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2265-9

Advanced School on Understanding and Prediction of Earthquakes and other Extreme Events in Complex Systems

26 September - 8 October, 2011

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Computational geodynamics as a component of comprehensive seismic hazards analysis[1]

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Abstract

This paper reviews, with a few out of many examples, recent advances in computational geodynamics related to modelling of stress localization and earthquake occurrence. These studies provide a basis for a comprehensive seismic hazard analysis. Several case studies are considered: tectonic stress modelling in the southeastern Carpathians and central Apennines; dynamics of the lithospheric blocks and earthquake modelling for the Sunda arc and the Tibetan plateau; and seismic hazard assessment for the Vrancea region. Possibilities for earthquake prediction, mitigation and preparedness based on the earthquake science and computer modelling are discussed.

1 Introduction

Recent advances in understanding Earth dynamics and in development of computational tools permit accurate numerical modelling and forecasting that are transforming the Earth sciences. These advances have a strong impact on studies of geohazards and show significant potential to be applied to serve the sustainable development of society. The International Year of Planet Earth had chosen Hazards as one of its main scientific themes. Four key research questions were identified (Beer 2007). Among these questions are the following: *What technologies and methodologies are required to assess the vulnerability of people and places to hazards and how might these be used at a variety of spatial scales? How do geo-hazards compare relative to each other regarding current capabilities for monitoring, prediction and mitigation and what methodologies and new technologies can improve such capabilities to help civil protection at local and global scales?*

To answer such questions, natural hazard and risk assessment should be considered from a holistic point of view (from the whole to details). Particularly, a holistic comprehensive quantitative assessment of seismic hazard should be based on multidisciplinary research in (i) geodynamics (to reveal zones of tectonic stress localization), (ii) present and historical seismicity (to localize areas prone to strong events), (iii) nonlinear dynamics of the lithosphere (to analyse statistical properties of the earthquake sequences, their clustering and critical transitions), (iv) soil property (to analyse liquefaction and seismic shaking), and (v) classical hazards assessment (to determine peak ground acceleration, response spectra amplitude, and seismic intensity). This approach to seismic hazard should be accompanied by a holistic approach to earthquake prediction (e.g., Keilis-Borok and Soloviev 2003) and by a

[1] The paper is published as a chapter in: Beer, T., 2010. Geophysical Hazards: Minimizing Risk, Maximizing Awareness, Springer, Heidelberg, p. 161-177.

holistic approach to seismic risk (e.g., Beer and Ismail-Zadeh 2003; Cardona 2004), when a convolution of hazard, vulnerability and exposure (as functions of space and time) should be viewed also from social-psychological (e.g., resilience of community to extreme seismic events) and legal (e.g., role of law in risk reduction; see Paterson 2003) points of view.

The vulnerability of human civilisations to natural disasters is growing due to the proliferation of high-risk objects, clustering of populations, and destabilisation of large cities. Today a single earthquake may take up to several hundred thousand lives, and cause material damage up to several billions EURs (see Munich Re. 2009) with a possible chain reaction expanding to a world-wide financial crisis and economic depression (comparable and even more severe than the 2008 financial crisis and economic recession). A large earthquake in (or close to) Tokyo might result in a world financial crisis, because many Japanese companies, which invested considerable funds in foreign enterprises, will withdraw these funds to rebuild or to restore the city infrastructure after the disaster. A large earthquake can trigger an ecological catastrophe (e.g. Chernobyl-type calamities) if it occurs in close vicinity to a nuclear power plant built in an earthquake-prone area (e.g., in Azerbaijan, Iran or elsewhere).

About a million earthquakes with magnitude greater than 2 are registered each year; about a thousand of them are large enough to be felt; about a hundred earthquakes cause considerable damage, and once in a few decades a catastrophic event occurs. The 26 December 2004 earthquake with magnitude greater than 9 that occurred in the Aceh-Sumatra region of the Indian Ocean generated great tsunamis, which killed more than 270,000 people and caused billions of dollars of damage (UN/ISDR Platform for the Promotion of Early Warning 2008). The occurrence of a particular earthquake is associated with dynamics of the lithosphere.

Extreme seismic events (e.g., 1755 Lisbon, 1906 San Francisco or 2004 Aceh-Sumatra earthquakes) are a manifestation of the complex behaviour of the lithosphere structured as a hierarchical system of blocks of different sizes. Driven by mantle convection these lithospheric blocks are involved in relative movement, resulting in stress localization and earthquakes. Despite the lithosphere behaving as a large non-linear system, featuring instability and deterministic chaos, some integral empirical regularities emerge, indicating a wide range of similarity, collective behaviour, and the possibility for earthquake prediction (e.g., Keilis-Borok et al. 2001). These great earthquakes, when they occur, are surprising, and society is poorly prepared to deal with them. Protecting human life and property against earthquake disasters requires an uninterrupted chain of research and civil protection tasks: from (i) understanding of the physics of earthquakes, their analysis and monitoring, through (ii) interpretation, modelling, seismic hazard assessment, and earthquake prediction, to (iii) delivery of the scientific forecasts to local authorities, public awareness, preparedness, and preventive disaster management.

The OECD Global Science Forum workshop *"Earthquake Science and its Contribution to Society"* (Potsdam, Germany, 2006) focused on the analysis of recent achievements in earthquake physics, seismic hazard and risk assessment, and earthquake prediction as well as on the role of science in increasing of awareness of governments and society on earthquakes to mitigate aftermaths of natural hazards. It was highlighted that modern super-computer facilities provide useful tools in modelling of geodynamical processes leading to earthquakes; modelling of extreme seismic events; monitoring of seismic hazard; earthquake forecasting; and modelling of seismic risks.

This paper reviews recent studies in computational geodynamics by the author and his colleagues. These studies provide a basis for a seismic hazard analysis. Section 2 presents studies on tectonic stress localization. The studies on dynamics of the lithospheric blocks and faults as well as occurrences of large events are reviewed in section 3. Quantitative seismic hazard assessment is presented in section 4. Moreover, possibilities for improvement of earthquake prediction are discussed in section 5 and possibilities for earthquake mitigation and preparedness based on the earthquake science and computer modelling are discussed in section 6.

2 Modelling of lithospheric stress

Models of stress generation in the lithosphere are now widely used in geosciences to identify areas of stress localization and their correlation with observed seismic events (e.g., Bird and Baumgardner, 1984; Ismail-Zadeh et al., 2000, 2004, 2005a, 2005b; Aoudia et al., 2007). In this section I review models of tectonic stresses in the mantle beneath the south-eastern Carpathians (the Vrancea region) and central Apennines (the Umbria-Marche region). The tectonic stress is generated as a result of heterogeneous movements of the crust and mantle. The movements can be described by a mathematical model using the equations of momentum and mass conservation with relevant boundary conditions. A discretization of the mathematical model results in the computational model, which is solved by relevant numerical methods (e.g., Naimark et al., 1998 in two-dimensional case studies; Ismail-Zadeh et al., 2001 in three-dimensional case studies).

2.1 Southeastern Carpathians

Repeated large intermediate-depth earthquakes of the southeastern (SE) Carpathians (the Vrancea region) cause destruction in Bucharest (Romania) and shake central and eastern European cities several hundred kilometres away from the hypocenters of the events. The epicentres of the mantle earthquakes in the Vrancea region are concentrated within a very small area (marked in Fig. 1). According to the historical catalogue of Vrancea events (e.g., Radu 1991), large intermediate-depth shocks with magnitudes $M_W>6.5$ occur three to five times per century. In the 20th century, large events at depths d of 70 to 180 km occurred in 1940 (moment magnitude $M_W=7.7$, $d=160$ km), in 1977 ($M_W=7.5$, $d=100$ km), in 1986 ($M_W=7.2$, $d=140$ km), and in 1990 ($M_W=6.9$, $d=80$ km) (e.g., Oncescu and Bonjer 1997).

The intermediate-depth large earthquakes gave rise to the development of a number of geodynamic models for this region. McKenzie (1972) suggested that this seismicity is associated with a relic slab sinking in the mantle and now overlain by continental crust. A seismic gap at depths of 40-70 km beneath Vrancea led to the assumption that the lithospheric slab had already detached from the continental crust (Fuchs et al. 1979). Oncescu (1984) proposed that the intermediate-depth events are generated in a zone that separates the sinking slab from the neighbouring immobile part of the lithosphere rather than in the sinking slab itself. Linzer (1996) explained the nearly vertical position of the Vrancea slab as the final rollback stage of a small fragment of oceanic lithosphere. Sperner et al. (2001) suggested a model of Miocene subduction of oceanic lithosphere beneath the Carpathian arc and subsequent soft continental collision, which transported cold and dense lithospheric material into the mantle.

Continental convergence in the SE-Carpathians ceased about 10 Ma (e.g., Jiricek, 1979). At present the relatively cold slab beneath the Vrancea region sinks due to gravity. Hydrostatic buoyancy forces promote the sinking of the slab, but viscous and frictional forces resist the descent. The combination of these forces produces shear stresses at intermediate depths that are high enough to cause earthquakes. This was shown in two-dimensional numerical models of mantle flow and tectonic stress by Ismail-Zadeh et al. (2000). These authors recognized that the depth distribution of the annual average seismic energy released in earthquakes has a shape similar to that of the depth distribution of the modelled stress magnitude in the slab.

To evaluate the role of slab detachment in stress evolution, Ismail-Zadeh et al. (2005a) developed two-dimensional thermo-mechanical finite-element models of the post-Miocene subduction of the Vrancea slab subject to gravity forces alone. The models predicted lateral compression in the slab that were in agreement with those inferred from the stress axes of earthquakes. It was found that the maximum stress occurs in the depth range of 80 km to 200 km and the minimum stress falls into the depth range of 40 km to 80 km, which corresponds to the seismic gap. It was also shown that high tectonic stress (leading to seismic activity) is preserved in the slab for a few million years, even after detachment. The two-dimensional numerical studies revealed the principal features of mantle flow and tectonic stresses induced by a simple model of the descending slab, but they could not show a correlation between the descending high-velocity body, tectonic stress, and the locations of the Vrancea intermediate-depth earthquakes in any detail.

To analyse processes of stress generation and localization in and around the descending slab, Ismail-Zadeh et al. (2005b) developed a three-dimensional numerical model of contemporary mantle flow and stress beneath the Vrancea region. The input data of the model consisted of temperatures derived from seismic P-wave velocity anomalies and surface heat flow, crustal and uppermost mantle densities converted from P-wave velocities obtained from seismic refraction studies, geometry of the Vrancea crust and slab from tomography and refraction seismic data, and the estimated strain rate in the slab (as a result of earthquakes) to constrain the model viscosity. Ismail-Zadeh et al. (2005b) showed a correlation between the location of intermediate-depth earthquakes and the predicted localization of maximum shear stress (Fig. 2). Modelled tectonic stresses also predict large horizontal compression at depths of about 70 to 220 km beneath the Vrancea region, which coincides with the stress regime defined from fault-plane solutions for the intermediate-depth earthquakes. This implies that buoyancy-driven descent of the lithospheric slab beneath the Vrancea region is directly linked to intermediate-depth seismicity.

Mantle heterogeneities imaged by seismic tomography in the SE-Carpathians contain information on the present thermal state of the mantle. Ismail-Zadeh et al. (2008) developed a model of the present mantle temperature beneath the region based on *P*-wave seismic velocity anomalies (Martin et al., 2006) and combined the model with a model of crustal temperature constrained by heat flow data (Demetrescu et al., 2001). The modelled temperatures have been assimilated into the geological past using the information on the regional movement in the Early and Middle Miocene. Prominent thermal states of the lithospheric slab descending in the region have been restored from its diffuse present state. In Miocene times the slab geometry clearly shows two portions of the sinking body. The northwest-southeast oriented portion of the body is located in the vicinity of the boundary between the East European (EEP) and Scythian (SCP) platforms, and this portion of the sinking body may be a relic of a cold lithosphere that has travelled eastward. Another portion has a northeast-southwest orientation and is related to the present descending slab. Above a depth of 60 km the slab had a concave thermal shape, confirming the curvature of the Carpathian arc, and a convex surface below that depth. The slab maintained its convex shape until it split into two parts at a depth of about 220 km. Ismail-Zadeh et al. (2008) proposed that this change in the slab geometry, which is likely to be preserved until the present, can cause stress localization due to the slab bending and subsequent stress release resulting in large mantle earthquakes in the region.

2.2 Central Apennines

Central Mediterranean geology has been mainly shaped by the interplay between the Eurasian and African plates. The extremely variable structure of the lithosphere–asthenosphere system in the region is the result of its complex geodynamic history. The Cenozoic to Quaternary regional evolution has been marked by the coexisting compression and tension developed at the same time between converging continental plates (e.g., Doglioni et al. 1999; Faccenna et al. 2004). However, the rate of convergence between the plates has been less significant than the east-west extension (e.g., Mantovani et al. 2002). The latter has been migrating from west to east and has been positioned behind a compression front migrating in the same direction. As a consequence, a number of extensional basins have formed behind the Apennines-Maghrebian compression front.

The eastward migration of the Apennines compression front is accompanied by a fragmentation of the Apennines lithosphere, with progressive ending of the active subduction zone from the Northern Apennines to the south. Fragmentation of the Apennines lithosphere created sectors that had an independent evolution (Locardi 1993; Sartori 2003). This may explain the variable lithosphere-asthenosphere structure in the region. The juxtaposed contraction and extension observed in the crust beneath Central Apennines has, for a long time, attracted the attention of geoscientists and is a long-standing enigmatic feature. Moreover, Selvaggi and Amato (1992) showed the sub-crustal seismicity in the Umbria-Marche geological domain (UMD) is not associated with the dipping seismic (Wadati-Benioff) zone. Several models, invoking mainly external forces, have been put forward to explain the close association of these two end-member deformation mechanisms observed by seismological and geological investigations (e.g. Frepoli and Amato 1997; Montone et al. 1999; Doglioni et al. 1999). These models appeal to interactions along plate margins or at the base of the lithosphere, or to subduction processes (e.g. Negredo et al. 1999; Wortel and Spakman 2000; Carminati et al. 2005).

The geodynamic complexity of the Central part of Italy makes the kinematics of the present day deformation and its relationships with the recent magmatism and seismicity less well understood. To unravel some of these aspects, higher resolution geophysical models of the earth structure compatible with gravity, heat-flow, petrological and geochemical data have been required to investigate the deformation. Recent Earth structure velocity models (e.g. Chimera et al. 2003; Mele and Sandvol 2003) provide the required resolution. These models exhibit clear evidence of lithospheric roots without any continuous slab. This would imply that the slab has been eroded and no engine is left to drive relative subduction processes.

Ismail-Zadeh et al. (2004) and Aoudia et al. (2007) modelled the contemporary regional tectonic stress along a west-east transect crossing the Peninsula from the Tyrrhenian coast, via the UMD, to the Adriatic coast. They used a crust/lithosphere-asthenosphere structural earth model by Chimera et al. (2003). Although external forces must have been important in the building up of the Northern Apennines, Aoudia et al. (2007) investigated the contribution of buoyancy forces with respect to the ongoing slow and complex lithospheric deformations, as revealed by very recent GPS measurements and by the unusual sub-crustal seismicity distribution. They showed that the buoyancy forces that result from the heterogeneous density distribution in the lithosphere govern the present day deformation within Central Italy and can explain regional coexisting contraction and extension at shallow depth and mantle seismicity in the UMD (Fig. 3).

3 Modelling of earthquake occurrence

Stress accumulation and its release in earthquakes are governed by non-linear hierarchical systems, which have a number of degrees of freedom and, therefore, cannot be understood by studying them piece by piece (Keilis-Borok and Soloviev 2003). Since an adequate theoretical base has yet not been well elaborated, theoretical estimation of statistical parameters of earthquake sequences is still a complex problem. Studying seismicity using the statistical and phenomenological analysis of earthquake catalogues has the disadvantage that instrumental observations cover, usually, too short a time interval compared to the duration of the tectonic processes responsible for seismic activity. The patterns of earthquake occurrence identifiable in a catalogue may be apparent and yet may not be repeated in the future. Moreover, the historical data on seismicity are usually incomplete. Numerical modelling of seismogenic processes allows overcoming these difficulties. Synthetic earthquake catalogues formed via numerical simulations may cover very long time intervals and, therefore, provide a basis for reliable estimates of the parameters of the earthquake flows (Ismail-Zadeh et al., 1999, 2007a; Soloviev and Ismail-Zadeh, 2003).

It is difficult to detect the impact of a single factor on the dynamics of seismicity by analysing seismic observations, because seismicity is impacted by an assemblage of factors some of which may be more significant than that under consideration. It is also difficult (if not impossible) to single out the impact of an isolated factor by using seismic observations. This difficulty may be resolved by numerical modelling of processes that generate seismicity and by studying the synthetic earthquake catalogues thus obtained (e.g., Shaw et al., 1992; Gabrielov and Newman, 1994; Allegre et al., 1995; Newman et al., 1995; Turcotte, 1997; Keilis-Borok and Soloviev, 2003).

Mathematical models of lithosphere dynamics are also tools for studying earthquake preparation processes and are useful in seismic hazard and earthquake prediction studies (Gabrielov and Newman, 1994). An adequate model should indicate the physical basis of premonitory patterns determined empirically prior to large events. Note that available data often do not constrain the statistical significance of premonitory patterns. The model can also be used to suggest new premonitory patterns that might exist in catalogues of seismic events.

A block-and-fault dynamics (BAFD) model exploits the hierarchical block structure of the lithosphere (Alekseevskaya et al., 1977). The basic principles of the model have been developed by Gabrielov et al. (1990); the blocks of the lithosphere are separated by comparatively thin, weak, less consolidated fault zones, such as tectonic faults or lineaments. In seismotectonic processes, major deformation and most earthquakes occur in such fault zones.

A seismic region is modelled by a system of perfectly rigid blocks divided by infinitely thin plane faults. Displacements of all blocks are supposed to be infinitely small relative to their size. The blocks interact with each other and with the underlying medium. The system of blocks moves owing to prescribed motions of boundary blocks and the underlying medium. Blocks are perfectly rigid; hence deformation takes place only in fault zones and at block bases in contact with the underlying medium. Relative block displacements take place along fault zones. Strains in the model are accumulated in fault zones. This reflects strain accumulation due to deformations of plate boundaries. Considerable simplifications are made in the model, but they are necessary to understand the dependence of earthquake flow on the main tectonic movements in a region and on its structure. This assumption is justified by the fact that the effective elastic moduli in the fault zones are significantly smaller than those within the blocks.

Lithospheric blocks interact visco-elastically with the underlying mantle. The corresponding stresses depend on the value of relative displacement. This dependence is assumed to be linearly elastic. The motion of the medium underlying different blocks may be different. Block motion is defined so that the system is in quasi-static equilibrium. The interaction of blocks along fault zones is visco-elastic ("normal state") while the ratio of stress to pressure remains below a certain strength level. When this ratio exceeds the critical level in some part of a fault zone, a stress drop ("failure") occurs (in accordance with the dry friction model), possibly causing failure in some parts of other fault zones. These failures produce earthquakes. An earthquake starts a period where the affected parts of fault zones are in a state of creep. This state differs from the normal state by faster growth of inelastic displacements lasting until the ratio of stress to pressure falls below some level. Numerical simulation of this process yields synthetic earthquake catalogues.

3.1 Sunda arc

The Sunda island arc marks an active convergence boundary between the Eurasian plate, which underlies Indonesia with Indian and Australian plates (Fig. 4a). A chain of volcanoes forms the topographic spine of the islands of Sumatra, Java, and Sunda. The Indian and Australian plates subduct beneath the southwestern part of the Eurasian plate along the Sunda arc. The tectonic deformation and associated stress localization in the Sunda trench caused the 2004 Aceh-Sumatra earthquakes. Seismic tomographic imaging revealed anomalies of seismic waves beneath the Sunda island arc suggesting that the lithospheric slab penetrates to the lower mantle (Widiyantoro and van der Hilst, 1996).

Soloviev and Ismail-Zadeh (2003) presented a BAFD model of the Sunda arc region. The HS2-NUVEL1 global plate motion model (Gripp and Gordon, 1990) is used to specify the movements. The dynamics of the lithosphere was modelled for 200 years for various parameters of the BAFD model. For the preferred case study, the regional seismicity (a) is compared with the modelled seismicity (b) in Fig. 4. This model has identified two epicentral areas prone to huge earthquakes. The first area is related to the Aceh-Sumatra region, where the magnitude 9+ mega-thrust earthquake occurred. Another area is predicted to be located between the Borneo, Sulawesi, Sumbala, Lombok, and Bali islands. Figure 4c presents the cumulative frequency-magnitude plots for the observed (solid line) and modelled (dashed line) seismicity. The slopes of the curves are close within the magnitude range from 5.5 to 8.1, and shifted to the larger magnitudes in the case of modelled events. Rundquist et al. (1998) determined that earthquakes with magnitude ≥ 6 observed in the Sunda arc region migrate from the eastern to the western part of the arc. The synthetic earthquake catalogue revealed a similar migration of the modelled earthquakes with magnitude ≥ 7.

Despite the simplicity of the BAFD model of the Sunda arc, Soloviev and Ismail-Zadeh (2003) showed that the model with movements specified by the HS2-NUVEL1 global plate motion yields synthetic seismicity having certain common features with observations. These features include the locations of larger events, the direction of migration of earthquakes, and the slope of the frequency-magnitude plot.

3.2 Tibet plateau

Following the closure of the Mesozoic Tethys ocean, the India-Asia collision initiated the development of the Himalayan range and the Tibetan plateau and induced widespread strain in southeastern Asia and China. The Tibetan plateau is underlain by a thick crust (up to 70 to 80 km) as inferred from gravity anomalies and seismic profiles (Barazangi and Ni 1982; Le Pichon et al. 1992; Nelson et al. 1996). The Himalayan frontal thrust and the Longmen Shan represent abrupt and steep topographic fronts at the southern and eastern edges of the plateau (Fig. 5a).

There are three distinct views about the active deformation in Tibet that dominates the debate on the mechanics of continental deformation. One view is that the deformation is distributed throughout the continental lithosphere (e.g., Houseman and England 1996). Another view is associated with the crustal thinning and the deformation due to a channel flow within the mid-to-lower crust (e.g., Royden et al. 1997). Meanwhile there is growing evidence supporting the alternative view that a substantial part of the deformation of the continents is localized on long and relatively narrow faults and shear zones separating rigid crustal blocks (e.g., Tapponnier et al. 2001). Many of these zones cut the base of the crust (Vergnes et al. 2002; Wittlinger et al. 2004), and some extend to the base of the lithosphere (e.g., Wittlinger et al. 1998). Therefore, such deformations can be described by motions of crustal lithospheric blocks separated by faults.

Ismail-Zadeh et al. (2007a) developed a BAFD model for the Tibet-Himalayan region. They showed that the contemporary crustal dynamics and seismicity pattern in the region are determined by the north-northeastern motion of India relative to Eurasia and the movement of the lower crust overlain by the upper crustal rigid blocks. Variations in rheological properties of the fault zones and/or of the lower crust as well as in the motion of the lower crust influence the displacement rates of the crustal blocks and hence the slip rates at the faults separating the blocks. This may explain the discrepancies in the estimates of slip rates at major faults in the region based on different techniques.

Clustering of earthquakes can be considered as a consequence of the dynamics of the crustal blocks and faults in the region. The number and maximum magnitude of synthetic earthquakes change with the variations in the movements of the crustal blocks and in the rheological properties of the lower crust and the fault zones. As an example, a cluster of modelled events along the Longmen Shan fault was identified by the BAFD model (Fig. 5b). The 2008 M=7.9 Sichuan (Wenchuan) earthquake occurred along this fault killing about 70,000 in addition to about 400,000 injured and about 20,000 missing people.

4 Seismic hazard and risk

Primary models of geodynamics, stress generation, earthquake occurrences, and strong ground motions caused by earthquakes are important inputs for seismic hazard analysis. Seismic hazard assessment in terms of engineering parameters of strong ground motion (namely, peak ground acceleration PGA, response spectra amplitude RSA, and seismic intensity) is based on information about the features of earthquake ground motion excitation (source scaling), seismic wave propagation (attenuation), and site effect in the region under consideration. Ideally, all these factors should be studied on the basis of available regional earthquake ground motion data.

4.1 Quantitative seismic hazard assessment: Case study of the SE-Carpathians

Analysis of the macroseismic and instrumental data from intermediate-depth Vrancea earthquakes reveal several peculiarities of earthquake effects (e.g., Mandrescu et al. 1988; Ivan et al. 1998; Mandrescu and Radulian 1999; Moldovan et al. 2000). They may be summarized as follows: earthquakes affect very large areas with a predominant NE-SW orientation; local and regional geological conditions can control the amplitudes of earthquake ground motion to a larger degree than magnitude or distance; and strong ground motion parameters exhibit a large variability.

To assess the seismic hazard in the SE-Carpathians, strong ground motion excitation and attenuation during the intermediate-depth Vrancea earthquakes were analysed (e.g., Oncescu et al. 1999; Radulian et al. 2000; Gusev et al. 2002). Several studies were carried out to estimate the seismic hazard in Romania using a probabilistic approach (Lungu et al. 1999; Musson 2000; Mantyniemi et al. 2003; Ardeleanu et al. 2005). The azimuth-dependent empirical attenuation models evaluated from regional strong motion data were used in some of these studies; however variations of the local site response were not taken into account.

Ismail-Zadeh et al. (2007b) performed probabilistic seismic hazard assessment (PSHA) for the region using knowledge of the soil conditions and basic features of local geology (properties of sediments down to bed-rock). Figure 6 shows results of the site-dependent PSHA for the SE-Carpathians in terms of PGA together with the PGA distribution during the large Vrancea earthquake (M_W = 7.2, 30 August 1986; Fig. 6a). There is a good agreement between observations and the site-dependent estimations predicted by the PSHA models both in the shape of contours and absolute values. For comparison, the PGA hazard model was also calculated without consideration of site response - for rock site conditions (Fig. 6b). Those PSHA results that do not consider geological factors have nothing in common with the distribution of ground motion amplitudes during earthquakes. Ismail-Zadeh et al. (2007b) concluded that geological factors play an important part in the distribution of earthquake ground motion parameters within the region analysed. These results can be considered as a basis for comprehensive site-dependent PSHA analysis in the region and as a basis for a new seismic code.

4.2 Seismic risk

Problems of estimating risks of natural catastrophes are becoming highly important. In the last few decades a number of concepts of risks of natural catastrophes have been suggested and a number of international projects on safety and risk management have been conducted. Serious difficulties in decision making in these fields are concerned with strong uncertainties in data and limitations in using mathematical tools for carrying out the historical analysis and forecasting.

Seismic risk can be defined as a measure that combines, over a given time, the likelihoods and the consequences of a set of earthquake scenarios (Beer and Ismail-Zadeh 2003). The risk can be estimated as the probability of harmful consequences or expected losses (of lives and property) and damages (e.g., people injured, economic activity disrupted, environment damaged) due to an earthquake resulting from interactions between seismic hazards (*Hs*), vulnerability (V), and exposed values (E). Conventionally, seismic risk (Rs) is expressed quantitatively by the convolution of these three parameters: $Rs = Hs \otimes V \otimes E$ (Kantorovich et al. 1973).

An estimation of seismic risk may facilitate a proper choice in a wide variety of seismic safety measures, ranging from building codes and insurance to establishment of rescue-and-relief resources. Different representations of seismic risk require different safety measures. Most of the practical problems require estimating seismic risk for a territory as a whole, and within this territory separately for the objects of each type: areas, lifelines, sites of vulnerable constructions, etc. The choice of the territory and the objects is determined by the jurisdiction and responsibility of a decision-maker. Each specific representation of seismic risk is derived from the models of seismic hazards, the territorial distribution of population, property, and vulnerable objects, and the damage caused by an episode of strong motion.

5 Earthquake prediction

Though the assessment of seismic risk is important in earthquake preparedness, it does not answer the question of *where* and *when* the next earthquake will occur. This question worries not only scientists, but also populations living in earthquake-prone regions. The catastrophic nature of earthquakes has been known for centuries due to the resulting devastation during some earthquakes. Their abruptness, along with the apparent irregularity and infrequency of large seismic events, facilitates a common perception that earthquakes are random unpredictable phenomena. For the last decade, earthquake prediction research has been widely debated: opinions on the possibilities of prediction varies from the statement that earthquake prediction is intrinsically impossible (Geller et al. 1997) to the statement that prediction is possible, but difficult (Knopoff 1999). To predict an earthquake, someone *"must specify the expected magnitude range, the geographical area within which it will occur, and the time interval within which it will happen with sufficient precision so that the ultimate success or failure of the prediction can readily be judged. Only by careful recording and analysis of failures as well as successes can the eventual success of the total effort be evaluated and future directions charted. Moreover, scientists should also assign a confidence level to each prediction"* (Allen et al. 1976).

Four major stages can be distinguished in earthquake prediction: (i) long-term (a decadal time scale), (ii) intermediate-term (one to several years), (iii) short-term (days to weeks and months), and (iv) immediate (seconds to hours). Long-term prediction of earthquakes is essentially based on the determination of probabilities of active fault segments to rupture for the next few decades (e.g., Working group on California earthquake probabilities 1999). This kind of prediction can guide engineering and emergency planning measures to mitigate the impact of the earthquake.

An intermediate-term prediction is an update of the long-term prediction brought about by some indicators (e.g., an increase in background seismicity, clustering of events in space and time, transformation of magnitude distribution and some others). For example, an intermediate-term earthquake prediction method was designed by retrospective analysis of the dynamics of seismic activity preceding the largest events worldwide (Keilis-Borok and Kossobokov 1990). Initially tested retrospectively, the method is subject to on-going real-time experimental testing, and the results of the prediction based on the method support the idea of predictability of great earthquakes (Kossobokov, 2006).

The feasibility of short-term earthquake prediction (days to weeks and months) is still controversial, and the major difficulty here is to identify short-term precursors in the background of intermediate-term alarms. One of the aims of intermediate- and short-term predictions of earthquakes is to reduce the number of false alarms and the number of failures to predict a strong event. A reduction of false alarms using, for example, the theory of optimal stopping (Feinberg and Shiryaev 2007) could improve the performance of prediction methods.

Immediate earthquake prediction is usually based on the first arrival of seismic waves and transmission of an electronic alert within a lead-time of seconds. It is used (e.g. in Japan) to shut down nuclear reactors, gas and electricity grids and to stop high-speed trains in the event of a strong earthquake.

Compared to the accuracy of weather forecasting (e.g., Kalnay 2003), the current accuracy of earthquake prediction is still too low. Our knowledge of earthquake physics and earthquake dynamics is limited to predicting strong earthquakes with a high accuracy. We do not know well (i) how earthquakes, especially large events, work; (ii) when an earthquake starts, when it stops, and what magnitude could be expected; (iii) how earthquakes cluster in terms of stress transfer; (iv) what were the initial conditions of stress state before a large event. Moreover, there is no quantitative description of earthquake physics, namely, no mathematical equations to describe non-linear dynamics of fault systems and earthquake "flow". The Navier-Stokes equations in meteorology describe atmospheric flow and hence allow weather prediction with a high accuracy for time scales ranging from one to several days.

The scientific community should use the full potential of mathematics, statistics, statistical physics, and computational modelling and the data derived from seismological (monitoring of physical parameters of earthquakes and tectonic stress, fluid migration, etc), geodetic (GPS, InSAR and other measurements of the crustal deformation), and geological (e.g., determination of the time intervals between strongest earthquakes using paleo-seismological tools) studies to improve intermediate- and short-term earthquake predictions.

Though the current accuracy of earthquake prediction is limited, any scientifically validated prediction can be useful for earthquake preparedness and disaster management, if the accuracy of the prediction (even though it is not high) is known. In this case an inexpensive low-key response to the prediction (e.g., to lower a water level in reservoirs located in the area of a predicted earthquake in order to prevent large flooding due to a possible damage of the reservoirs) would be well justified, if even a little part of the total damage due to a strong event is prevented.

6 Geoscience and preventive disaster management

Several extreme seismic events have struck the Earth and affected our society in recent times, among them: the October 2004 large Niigata earthquake (magnitude M=6.6) in Japan, the December 2004 great Aceh-Sumatra (M=9+) earthquake and devastating tsunami in the Indian Ocean, the October 2005 large earthquake in Pakistan (M=7.6), and the most recent May 2008 Sichuan (M=7.9) earthquake in China. Such natural events are rare, but not unexpected. The earthquake and tsunami in the Indian Ocean and the earthquakes in Pakistan and in China resulted in large humanitarian disasters because of weak preventive disaster management. Fortunately, the Niigata earthquake did not lead to extreme loss of human life, but became one of the costliest natural disasters of the XXIst century (economic losses were estimated to be US$ 28 billions; Munich Re. 2005).

Scientists know about historical devastating earthquakes and tsunamis, such as those, which occurred in the Indian Ocean region or earthquakes in Himalayas, Tibet, and the Japanese islands. Time is an important variable in natural disaster management, especially when it concerns extreme events. An extreme seismic event, in general, cannot be predicted in full details. So far, seismology can put confidence limits on uncertainty, although the limits are very wide in terms of the time, place and magnitude of an anticipated earthquake, which gives insufficient information for disaster management. Nevertheless hazard preparedness is vital for society. The less often natural events occur (and the large extreme events are rare by definition), the more often disaster managers postpone preparedness for the events.

Ismail-Zadeh and Takeuchi (2007) wrote: "The tendency to reduce the funding for preventive disaster management of natural catastrophes rarely follows the rules of responsible stewardship for future generations neither in developing countries nor in highly developed economies". The investment to avoid losses tends not to be easily accepted in political decision making as compared with that to gain positive benefits. It is because the benefit of preventing losses, however long lasting it is, is not easily visible while the positive benefit is obvious and can easily be agreed by people. A large investment is made, when a big disaster due to an earthquake occurs, and the investment decreases till the next large earthquake (Fig. 7). If about 5 to 10% of the funds, necessary for recovery and rehabilitation after a disaster, would be spent to mitigate an anticipated earthquake, it could in effect save lives, constructions, and other resources. The reaction of media and the societal attention to disasters follow the same cycle. Following V. Klemes and R. Tannehill (Tannehill 1947), we can call this cycle the “seismo-illogical cycle” meaning that a large investment is made when a big earthquake disaster occurs and the investment decreases till the next disaster occurs. If a seismic cycle is marked by an *increase* of tectonic stresses toward an earthquake (stress drop), the “seismo-illogical cycle” is characterised by a *decrease* of funding toward the next large seismic event.

How to convince disaster-management authorities paying forward, in advance of rare extreme events, to mitigate or even to prevent in some cases inflicting humanitarian disasters? What is the role of geoscientists in preventive disaster management of catastrophic events? Ismail-Zadeh and Takeuchi (2007) believe that science should provide the "brains" for preventive disaster management.

One of the roles of seismologists is to assist disaster managers in terms of timely delivery of reliable forecasts on potentially large earthquakes and on their possible aftermath. These forecasts should be based on physics of the seismogenic processes, statistical analysis of data, and computer models of stress generation and release in earthquakes. At present the role of science is limited by inaccurate (in a deterministic sense) predictions of earthquakes. But this fact should not push scientists to give up the predictions of extreme seismic events. They can enhance the study of accurate temporal and spatial prediction of such events, that is, prediction of the two important parameters for preventive disaster management: *where* and *when*. "The frequency and scope of loss of major natural catastrophes will continue to increase dramatically throughout the world. Unless drastic measures are taken soon to prevent it, this trend will be intensified considerably by the ever more evident warming of the atmosphere, the resultant increase in sea level, and the intensification of storm and precipitation processes. In its own interest, the insurance industry must assume a major role in implementing preventive measures in order to ensure that it can provide cover for natural hazards over the long term" (Berz 2004).

After the 2004 Aceh-Sumatra catastrophic event, the Commission on Geophysical Risk and Sustainability of the International Union of Geodesy and Geophysics recommended to develop multidisciplinary and multinational research programs and networks on geophysical hazards and risks in the affected countries in order to integrate diverse data streams, to improve understanding of the natural phenomena associated with the disasters, to enhance predictive modelling capability, and to generate and to disseminate timely and accurate information needed by decision makers and the public (IUGG GeoRisk Commission Statement, 2005). Scientists must act today and implement state-of-the-art measures to protect society from rare but recurrent extreme natural catastrophes. Otherwise we will witness again and again the tragic aftermaths of disasters that could have been avoided.

6 Conclusion

Advances in understanding of natural hazards and modern computational tools make considerable contribution to reduction of earthquake disasters, but their danger keeps escalating. This review illustrates that reversal of that trend does require a deep integration of knowledge on earthquake physics and analysis of seismic observation with theoretical development and numerical analysis. And computational geodynamics plays an essential role in identification of the places of large seismic events and in seismic hazard analysis.

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Figure Captions

Fig. 1. Topography map and seismicity (since 1950) in Europe.

Fig. 2. Predicted maximum shear stress beneath the SE-Carpathians at different depths. Isolines present the surface topography. Star marks the location of the Vrancea intermediate-depth earthquakes (modified after Ismail-Zadeh et al. 2007b).

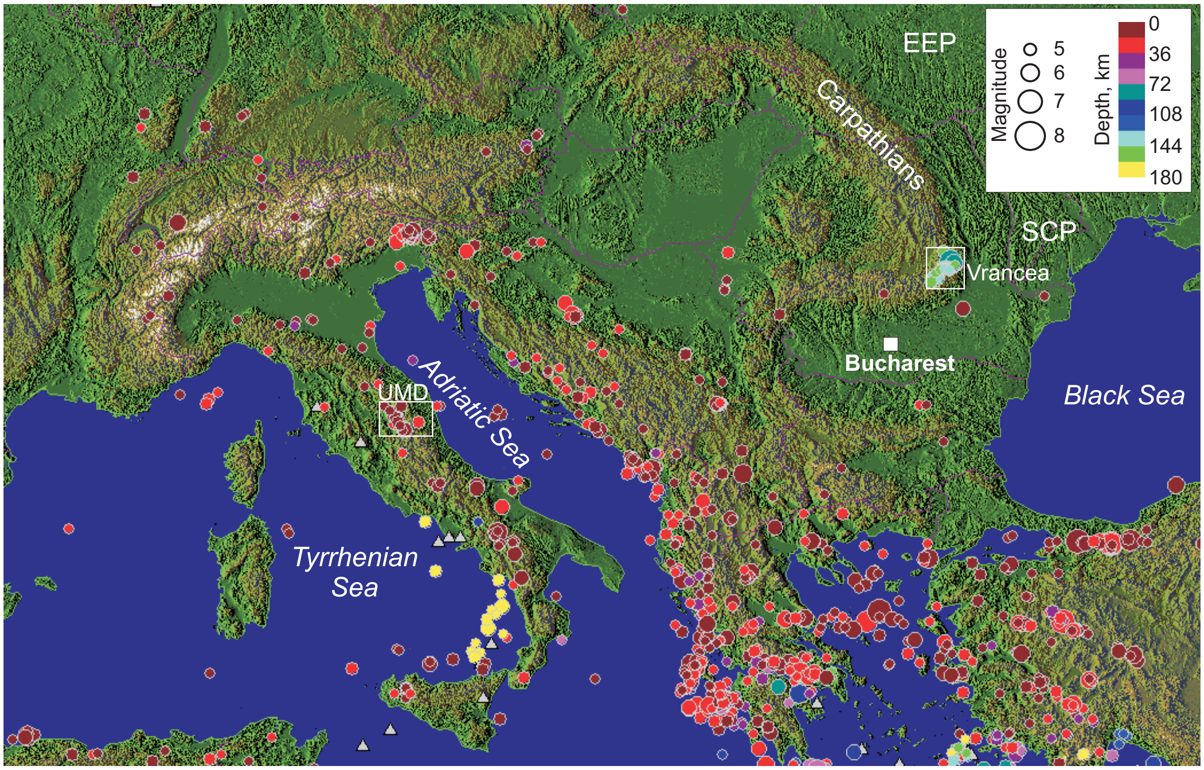
Fig. 3. Predicted maximum shear stress and compressional axes (ticks) along the profile (red line in the inset) (modified after Aoudia et al 2007). The horizontal ticks indicate thrusting and vertical ticks indicate normal faulting. Red stars mark the hypocentres of the sub-crustal earthquakes (vertical bars indicate the depth error) recorded in the period 1965-1998 within a stripe 150 km wide along the profile. The bold black segment indicates the Moho depth (Chimera et al. 2003).

Fig. 4. BAFD model of the Sunda arc. (a) Observed earthquakes from 1950 to 2000 with magnitudes greater than 6; (b) Modelled events with magnitudes greater than 7. Shaded domain represents the lithospheric block structure. (c) Cumulative frequency-magnitude plots for the observed and the modelled seismicity (modified after Soloviev and Ismail-Zadeh 2003).

Fig. 5. BAFD model of the Tibet-Himalayan region. (a) Observed earthquake since 1900. (b) Modelled events. (c) Cumulative frequency-magnitude plots for the observed and the modelled seismicity. Note that the frequency-magnitude plots for synthetic events are shifted upwards due to the larger number of the events compared to the number of seismic events in the region (modified after Ismail-Zadeh et al 2007a).

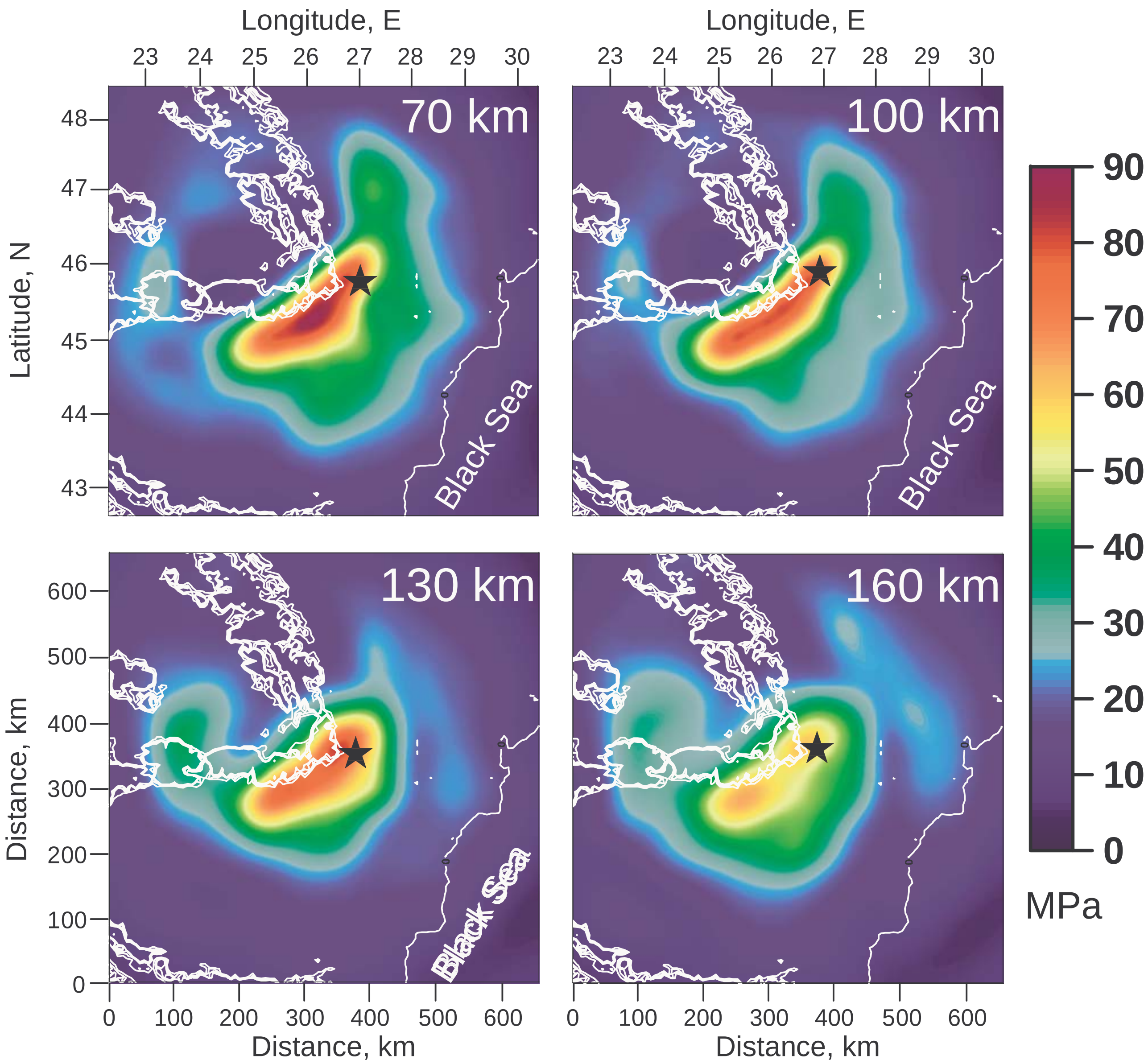
Fig. 6. Comparison of the peak-ground acceleration (maximum of two horizontal components) distribution during the M_W=7.2, 30 August 1986 earthquake in Vrancea (*a*) and the PSHA results evaluated for two types of site conditions (*b*: rock and *c, d*: soil and local geology) and for two return periods (*c*: T = 100 yr and *d*: T = 475 yr). Numbers at the contours are scaled in cm s^{-2} (after Ismail-Zadeh et al. 2007b).

Fig. 7. Diagram representing the seismo-illogical cycle in seismic risk and earthquake disaster management.



EEP
Carpathians
Magnitude
5
6
7
8
Depth, km
0
36
72
108
144
180
SCP
Vrancea
Bucharest
Black Sea
UMD
Adriatic Sea
Tyrrhenian
Sea

Fig. 1



Longitude, E
23 24 25 26 27 28 29 30
70 km
100 km
130 km
160 km
Latitude, N
48 47 46 45 44 43
Distance, km
600 500 400 300 200 100 0
0 100 200 300 400 500 600
Black Sea
90 80 70 60 50 40 30 20 10 0
MPa

Fig. 2

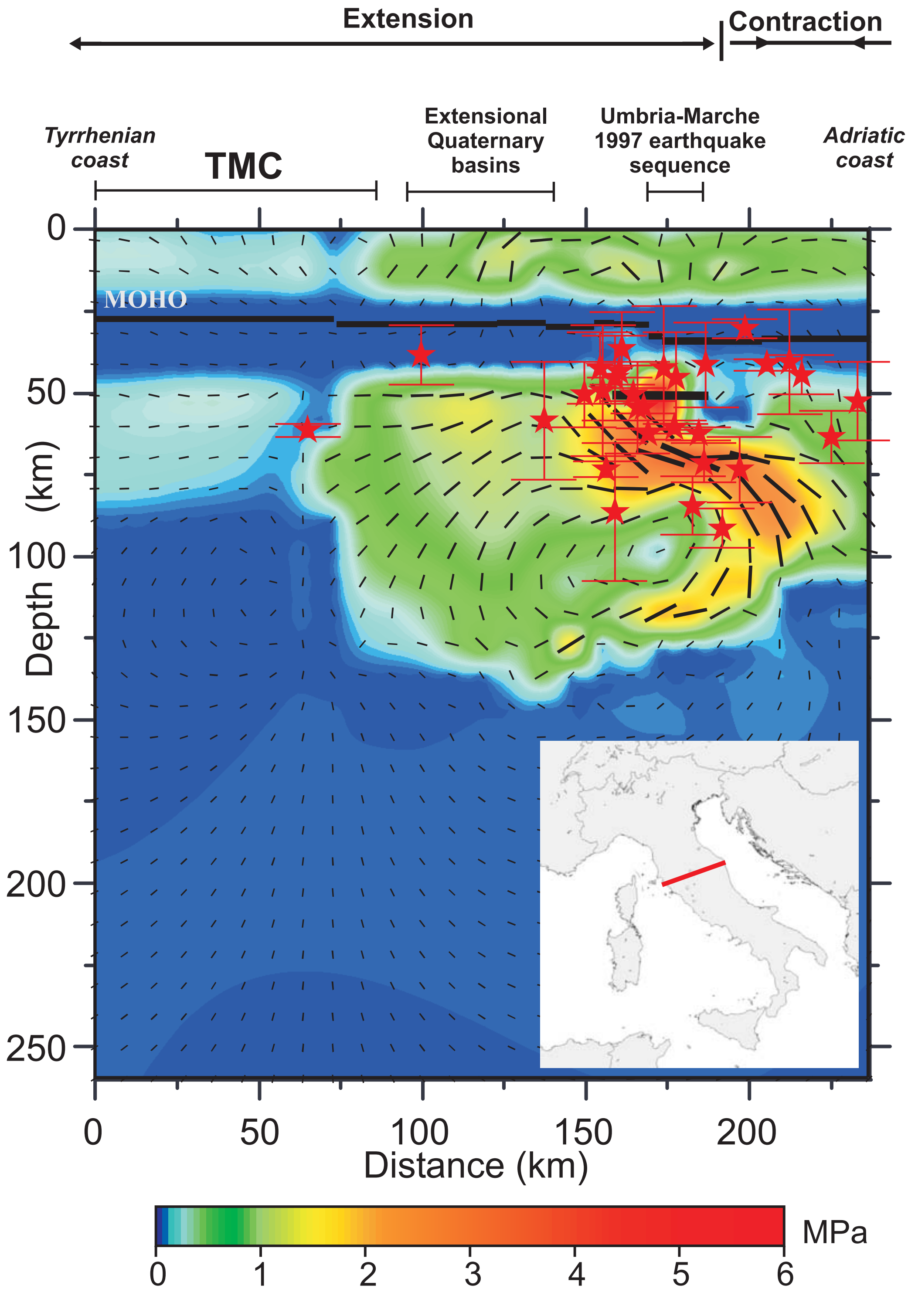
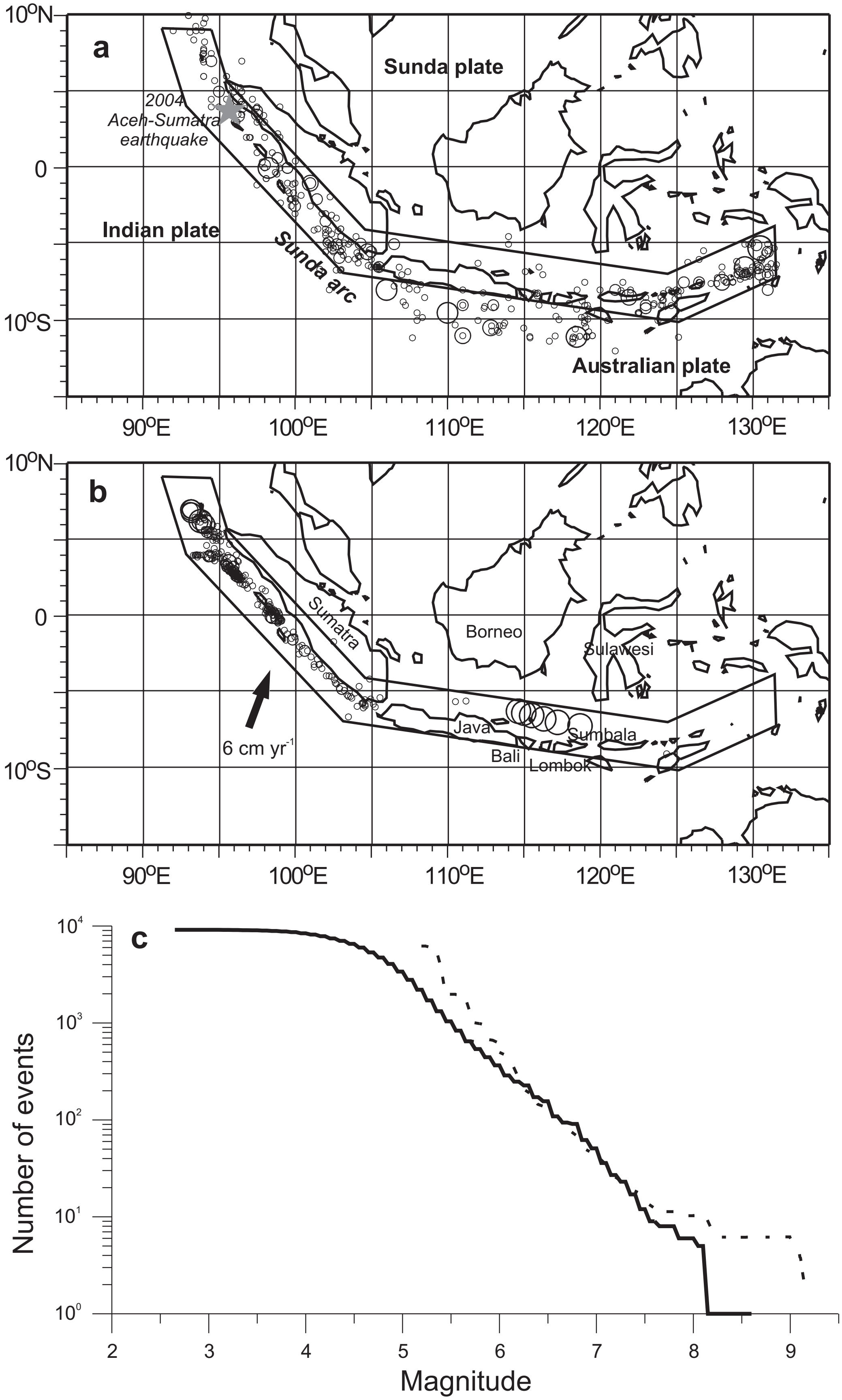
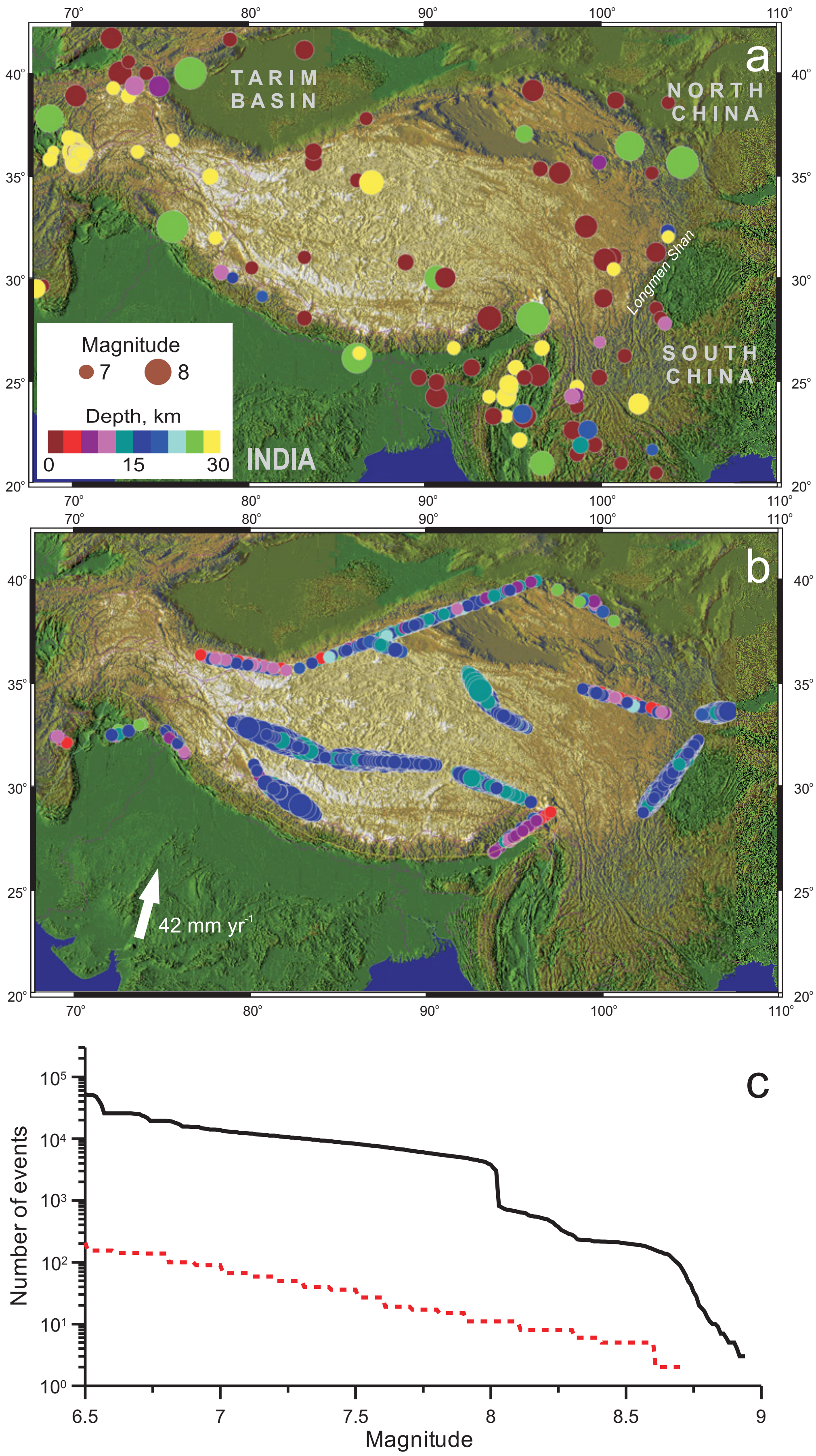

Extension
Contraction
Tyrrhenian coast
TMC
Extensional Quaternary basins
Umbria-Marche 1997 earthquake sequence
Adriatic coast
MOHO
Depth (km)
0
50
100
150
200
250
Distance (km)
0
50
100
150
200
MPa
0
1
2
3
4
5
6

Fig. 3



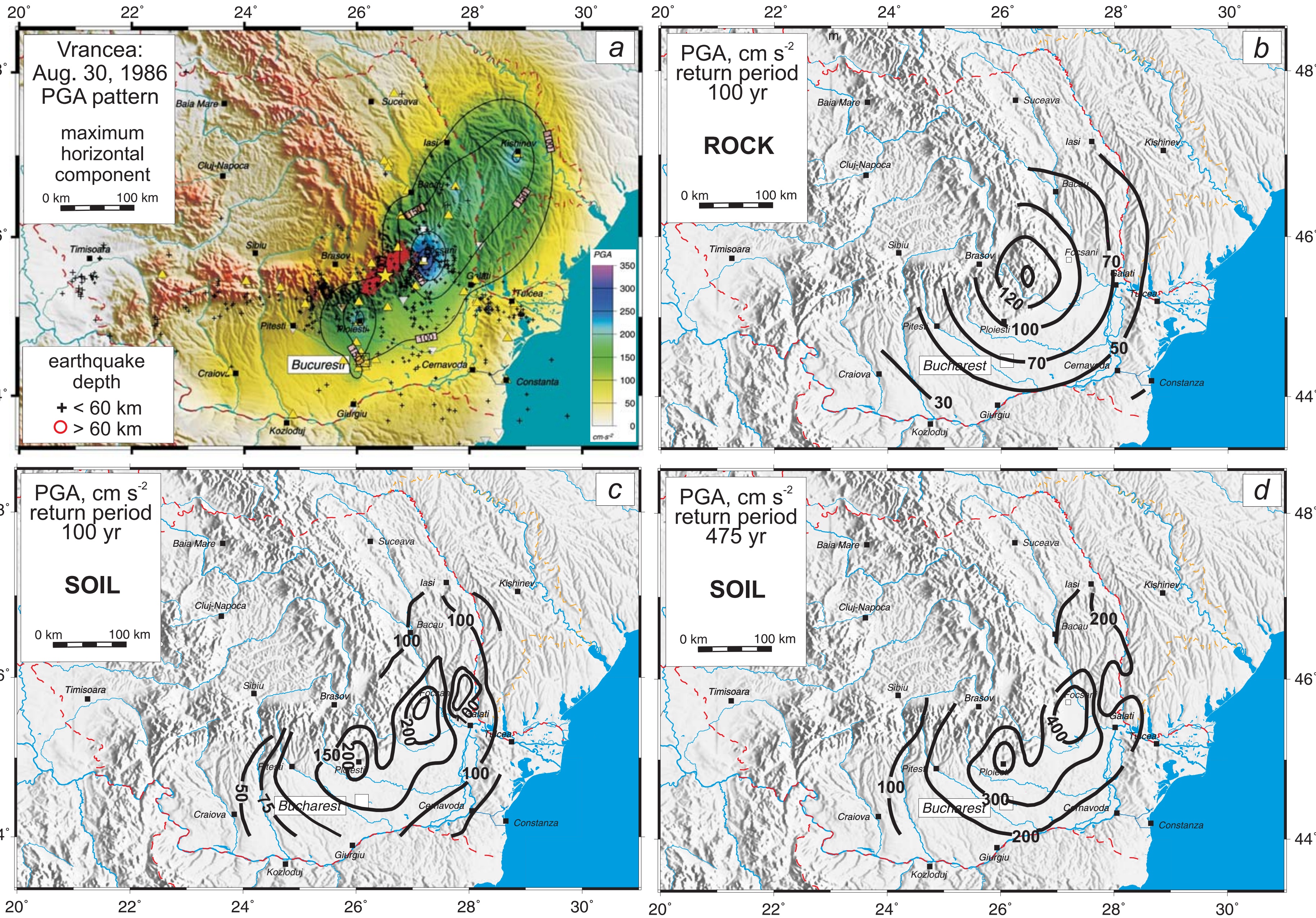
a
Sunda plate
2004
Aceh-Sumatra
earthquake
Indian plate
Sunda arc
Australian plate
b
Sumatra
Borneo
Sulawesi
Java
Sumbala
Bali
Lombok
6 cm yr-1
c
Number of events
Magnitude
10oN
0
10oS
90oE
100oE
110oE
120oE
130oE

Fig. 4



a
TARIM BASIN
NORTH CHINA
SOUTH CHINA
INDIA
Longmen Shan
Magnitude
7
8
Depth, km
0
15
30
b
42 mm yr⁻¹
c
Number of events
Magnitude

Fig. 5



a
Vrancea:
Aug. 30, 1986
PGA pattern
maximum
horizontal
component
0 km 100 km
earthquake
depth
+ < 60 km
○ > 60 km
PGA
cm s-2
b
PGA, cm s-2
return period
100 yr
ROCK
0 km 100 km
c
PGA, cm s-2
return period
100 yr
SOIL
0 km 100 km
d
PGA, cm s-2
return period
475 yr
SOIL
0 km 100 km
Baia Mare
Suceava
Iasi
Kishinev
Cluj-Napoca
Bacau
Timisoara
Sibiu
Brasov
Focsani
Galati
Tulcea
Pitesti
Ploiesti
Bucharest
Cernavoda
Constanza
Craiova
Giurgiu
Kozloduj

Fig. 6

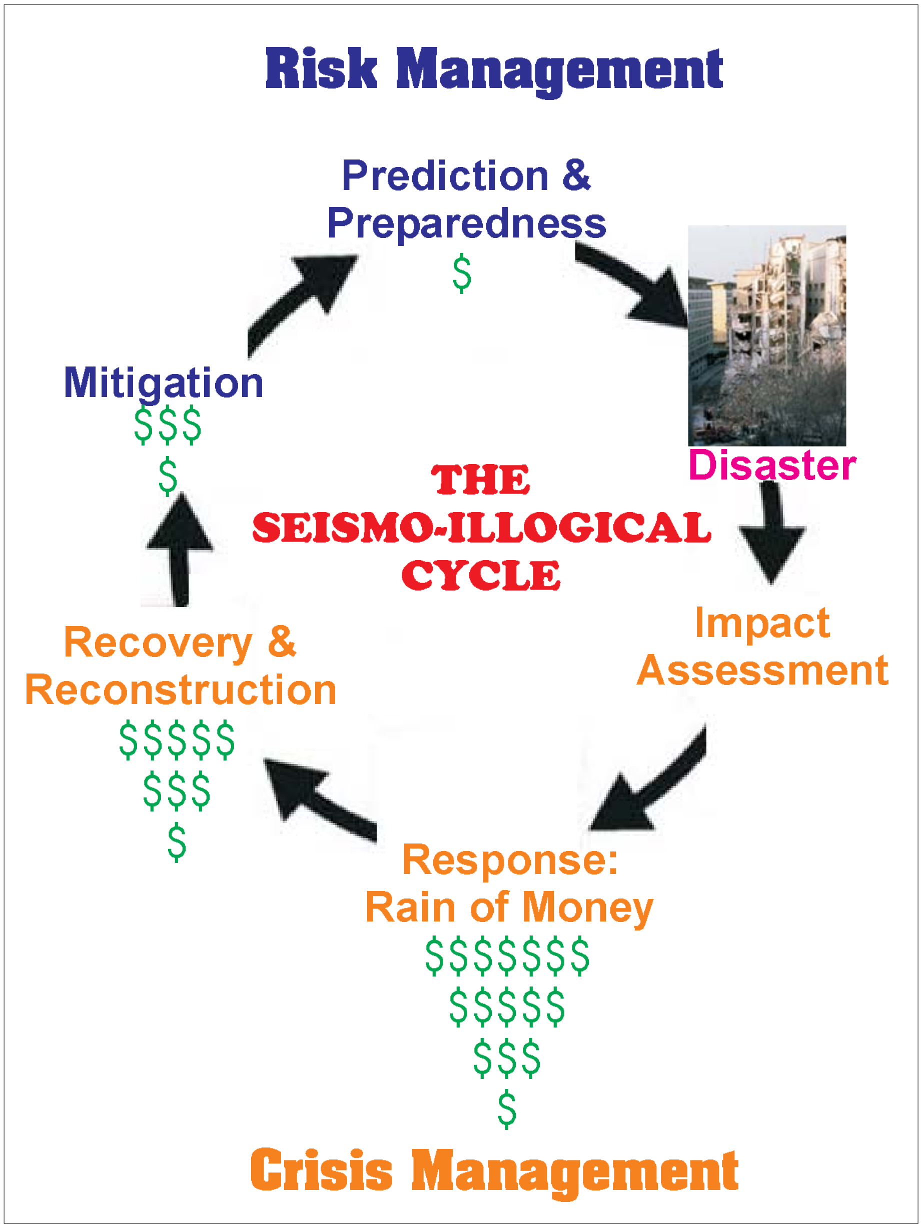

Risk Management
Prediction &
Preparedness
$
Disaster
Impact
Assessment
Response:
Rain of Money
$$$$$$$
$$$$$
$$$
$
Recovery &
Reconstruction
$$$$$
$$$
$
Mitigation
$$$
$
THE
SEISMO-ILLOGICAL
CYCLE
Crisis Management

Fig. 7