1. INTRODUCTION.

An earthquake (EQ), in terms of physics, is an abrupt, strain energy release in the form of kinetic energy that had been accumulated in a seismogenic area. The science which studies these physical phenomena is called “seismology”. This term is formed by the combination of two Greek words. The first one is the word “seismos” which stands for the word “earthquake” and the second one is the verb “lego” which in the Greek language means “talk about”. Seismology, at its early stages, developed from the necessity of people to know in advance when an earthquake is going to occur, since strong earthquakes hit, some times, abruptly, devastating populated areas, damaging cities, villages and moreover killing people. Seismology, in the course of its evolution, was divided into two main branches. The first but less developed, is its initial main task, namely the prediction of an earthquake. The second one, which developed rapidly and in great depth, is the study of the Earth’s interior through the analysis of the propagation of the seismic elastic waves in the ground, waves generated by the occurrence of earthquakes.

Although seismological observations are referred back to ancient Greek writers, its scientific effectiveness was boosted during the last 100 years, when instrumental seismology was introduced. The mechanism that controls the generation of an earthquake is not yet well known. Many theories have been suggested, starting with the early “Elastic Rebound Theory” (Reid, 1911), SOC theories (Main 1995, 1996), where the seismogenic area can produce an earthquake by a slight variation of its stress level, up to the latest one which states that an earthquake is “a frictional phenomenon rather than a fracture one” (Scholz, 1998). In any case, it is generally adopted that when the stress of a seismogenic area exceeds a threshold level then, regardless the mechanical procedure followed for the specific rock fracture / friction slip, an earthquake takes place. The absence of a physical model for the process of seismogenesis poses more difficulties in the solution of the particular problem of earthquake prediction in terms of Classical Seismology or Statistical Physics.

The term “earthquake prediction” refers to the knowledge of the earthquake prognostic parameters that is the location, the time of occurrence and its magnitude, for some time before it takes place. According to the prognostic time window it is distinguished as: long-term, referring to a time window of some decades of years, medium-term, referring to a time window of a few years (2-3) and short-term, referring to a time window of the order of up to a couple of months, while sometime the term “immediate” is used when the time window is of the order of a few days.

The scientific literature which concerns the topic of earthquake prediction has to present a very large number of papers which deal with it. Each one of them deals with some “predictive” technique or probable physical observation which could help in to the solution of this problem. There is no point to refer to them in this book, since these can be found easily in almost all the seismological, scientific journals, published internationally. Furthermore, a search in the bibliography indicates that a lot of monographs exist which deal with this topic, either in the form of textbooks or as proceedings of scientific meetings, dedicated, to this specific topic. After a quick survey in public libraries and bookstores through their web portals, the following bibliography was traced under the title “Earthquake prediction”, or very similar to this one: Tsuboi et al. 1962, Rikitake 1976, Wyss et al. 1978, Vogel 1979, Wyss 1980, Keilis-Borok, (1980), Rikitake 1981, Asada 1982, Simpson and Richards 1982, Toshi and Ohnuki 1982, Vogel and Itsikara 1982, Rikitake 1982, Rikitake 1984, Mogi 1985, Stuart 1985, Shimazaki and Stuart 1985, Guha and Patwardhan 1985, Tyckoson 1986, Kisslinger 1986, Association for the Development of Earthquake Prediction (Japan) 1986, Keiiti and Stuart 1988, Stuart and Aki 1988, Ma et al. 1990, Dragoni et al. 1992, Tazieff 1992, Shih-jung 1993, Hayakawa et al. 1994, Lomnitz 1994, Bonnet et al. 1995, Gokhberg et al. 1995, Lighthill 1996, Dmowska 1997, Keilis-Borok et al. 2003, Donnellan 2004, Varotsos 2005, Saumitra 2006, Mukherjee 2006 just to name the textbooks found which were published during the last 45 years that, more or less, represent along time, the advances in the topic of earthquake prediction.

The earthquake prediction evolution in time is described in details by Geller (1997), who concludes that despite research has been conducted for more than 100 years, “no obvious” success has resulted. The question that arises is what the cause of this failure is. In a very general approach this is discussed and commented with the use of the following sketch **(fig. 1.1)**.

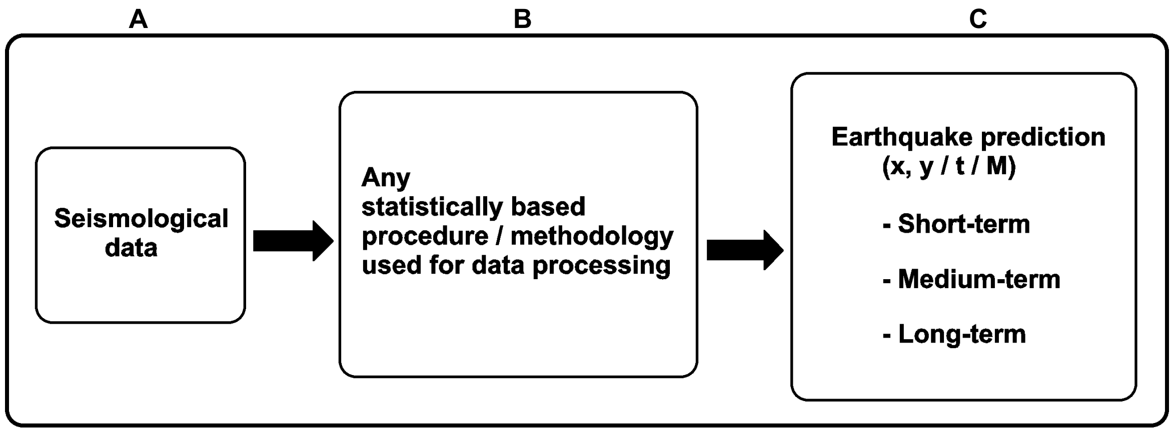


Fig. 1.1. Generalized flow chart indicating the procedure followed towards the earthquake prediction. **A** = input data, **B** = methodology used / physical model etc, **C** = wanted output, **x, y, t, m** are the prognostic parameters for all the types of EQ prediction (**x, y** stand for EQ coordinates in any appropriate coordinating system, **t** stands for the time of the EQ occurrence and **M** stands for the EQ magnitude).

Figure **(1.1)** shows the generalized procedure, used to date, by the various researchers to solve the earthquake prediction problem. The wanted output **(C)**, that is the prognostic parameters of the output of the system (EQ prediction), depends on the procedure / methodology **(B),** used, and the input data **(A)**. So far this system has failed or has presented very limited success. Therefore, its failure must be attributed either to part **(A)** or to part **(B)** or to both of them. It is suggested that, part **(B)** is highly unlike to fail, since it consists mainly of mathematically validated, robust, statistical methods. At the same time part **(A)** is valid, too, since it consists of the seismological data, collected, by the different seismological observatories and there is no doubt about their validity. This peculiar non-conformable situation can be explained only with the assumption **that part (A) and (B) are not compatible in terms of physical laws**. In other words these refer to different physical quantities/procedures that cannot be interrelated with any rational physical / mathematical model.

The incompatibility of figure **(1.1)** leads us to the selection: at first of a new data set as **(A)** and secondly to a different methodology / procedure **(B)** which will be used for the processing of the input data. The latter, additionally, dictates new physical models to be adopted and to be used in the physical / mathematical analysis of the earthquake prediction problem. If all these are valid and true, then the relation between **A, B, C** will be a valid one and the problem will have, in principle, been solved. A final remark to be made is that **the data used as input must intrinsically, even in a hidden way, convey the information of location, time and magnitude of a future earthquake**.

The aim of this book is exactly this: to present the implemented earthquake prediction deterministic, specific procedure, which fulfills the layout diagram, presented in figure **(1.1)**. To this end, different physical models are introduced, which are related to the seismicity of a seismogenic area and allow us to use conventional, physical laws and mathematical analysis for the calculation of the individual prognostic parameters.

The main difference between this book and the aforementioned bibliography is that in this book all the prognostic parameters (time, location, magnitude) are concerned with deterministic methods, while traditional, statistical methodologies are used at minimum and only for the purpose to analyze the validity of the obtained results from the postulated, physical models. Moreover, it analyses the earthquake prediction topic in the range of what is called by the seismologists as “short-term prediction” and considered, by them, as an impossible target. On the contrary, in the existing to date bibliography, just one monograph was traced which refers to “medium term prediction” (Kejiti and Stuart, 1988), while the majority of these books is related to time prediction, some times the topic of location, in terms of a regional seismogenic region, is treated, in a stochastic way and very rarely to the prognostic parameter of magnitude. It is hoped that other researchers will follow this research path and will improve and refine the topics which are presented in this book.

In all these years of my involvement with earthquake prediction, the people who were interested in this topic put a question to me quite frequently. Are all the earthquakes predictable? Well, the answer is definitely, no. First of all, magnitude plays a great role in predictability. As long as the magnitude of a future earthquake increases, more energy is going to be released, the more the physical properties of the seismogenic area are affected prior to the seismic event and therefore, there is larger probability, for the affected physical properties of the seismogenic area, to become observable above ambient noise. The depth of occurrence is another parameter that affects the earthquake predictability. The depth of occurrence of an earthquake is of vital importance for the generation of precursory physical variations in the seismogenic area, since the physical parameters that prescribe the underground status of the Earth change drastically according to the depth. Consequently, the earthquakes which occur in favorable depth and geological / tectonic environment, capable of producing valid, precursory phenomena, are predictable. We will come back on this topic in the course of this presentation.

The implementation of the prediction of a strong earthquake depends on the generation of the appropriate precursors before its occurrence. These precursors must convey or must be capable of providing, probably after appropriate processing, at least one of the prognostic parameters of the pending earthquake. Therefore, in the course towards a successful prediction, it will be necessary to use different types of precursors and / or different analyzing procedures, as well as different physical models that will be interrelated, so that a valid prediction may be achieved. The writer followed this philosophy, which is presented in details in this book.

In the course for the earthquake prediction and particularly in the search for an effective earthquake precursor, many different physical quantities and mechanisms have been studied. Some of the observations which had been made before strong earthquakes occurred are: the **seismic gap**, that is the absence of normal seismicity in a seismogenic area for a long period, the **seismic quiescence** that is the drop of seismicity below its normal level, the **doughnut feature** of spatial distribution of earthquakes around the epicenter area, the **earthquake swarm** that precedes a large earthquake, the **change in Vp / Vs** ratio over the seismogenic area, the various **time-spatial statistical earthquake patterns,** observed, the **change in Earth resistivity**, the **change of b value** of the Gutenberg-Richter law, the **emission of electro-magnetic waves,** the **increase of Radon emission** from the ground, the **geodetic variations (abnormal ground elevations),** the **change in the chemical composition of the underground waters,** the **change in temperature** of the aquifers, the **changes of the Earth’s magnetic field**, the **changes of the Earth’s electric field**, the observed **changes of the plasma density in the ionosphere**, the **strange animal behavior,** to name some of the most important and well-known of them.

All these observations indicate that earthquake precursory phenomena are generated in most of the physical – geological processes on Earth, in the seismogenic region, due to the fact that the strain accumulation in it changes its physical – geological / tectonic properties. The real problem with the detectability of the various precursors lays in the fact that the precursors, in most cases, are of low level, relatively to ambient conditions, and therefore, they are masked by this noise or lay out of the available, instrumental capability to detect them, very easily. This leads to the necessity to develop new precursory signals, processing procedures, as it has been done in the case of seismic precursory, electrical signals and will be presented in the sections to follow.

2. VARIOUS TOPICS IN SEISMOLOGY – TECTONICS PERTAINING TO EQ PREDICTION.

There is a general notion, in the seismological community, that earthquakes can occur in a random way in every place in a large area that exhibits seismicity. This is corroborated by the existing theories with regard to the generation mechanisms of earthquakes and the strain charge conditions held in such places. The Self Organized Criticality (SOC) theory, proposed by Bak (1966); Bak; Tag; and Wiesenfeld (1988), indicates that physical systems, like the seismogenic areas, are at critical state or instability and therefore, any small earthquake has some probability to cascade into a large earthquake. Other researchers (Otsuka 1972a, b; Vere-Jones 1976; Bak and Tang 1989; Ito and Matzutaki 1990) concluded that the generation of a strong earthquake depends on very small variations of stored elastic energy, fault strength or variations of the elastic properties of the seismogenic region, therefore, statistically, a strong earthquake can take place anywhere.

Since all the latter theories are combined to the fact that the Earth, as it is deduced from the geological, tectonic maps, compiled by the geologists, is highly fractured, then it is justified to conclude that strong earthquakes can, in a random way, occur almost anywhere. However, as the following analysis will demonstrate, the localization of strong earthquakes follows a scheme which is prescribed by the deep tectonics and the intense fracturing of the lithosphere, as far as it concerns the shallow earthquakes which occur in the crust.

2.1 Spatial distribution of strong EQs.

Before any attempt is to be made for any earthquake prediction, it is required to be known at least the general tectonic setting for the area under study. This is justified by the fact that EQs are the results of intense, tectonic processes which take place in the lithosphere. In this work a different approach, in relation to EQs, was adopted. Applied geophysical (gravitational) methods have been used in an attempt to explain the spatial distribution of strong EQs and to prove that **these occur only on predefined narrow faulting - fracture zones of the lithosphere, detectable in a deterministic scheme**. The theory of lithospheric plates and their motion is well known and has been adopted by the seismological community. A generalized picture of the Earth's lithospheric plates is presented in figure **(2.1.1)**.

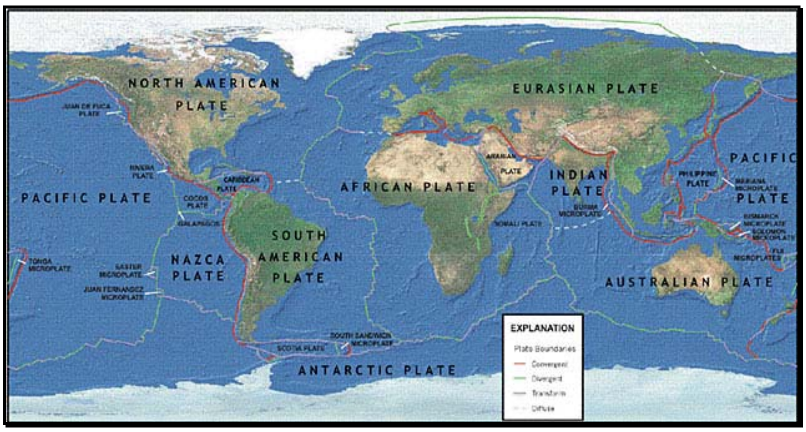


Fig. 2.1.1. The Earth's lithospheric plates (after USGS).

The main lithospheric Earth's plates are subdivided in smaller ones. McKenzie (1972, 1978) presented a small-scale lithospheric model for the particular case of the Greek territory. This is presented in the following figure **(2.1.2)**.

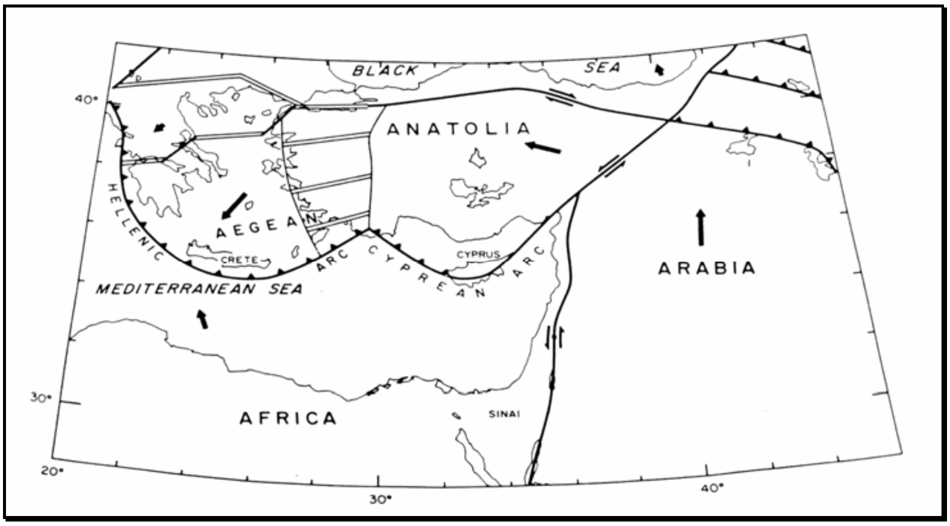


Fig. 2.1.2. McKenzie's (1972, 1978) lithospheric, plate model, proposed for the Greek territory.

As these plates are in continuous motion, due to applied forces from the surrounding larger plates, extension or compression is applied on them as a result. Therefore, extensional or compressional fracture zones are formed. The kinematics of the Greek territory tectonic plates was studied by Papazachos et al. (1996) and is presented in the following figure **(2.1.3)**. It is understood that strong seismic events are expected to occur where large tectonic activity takes place.

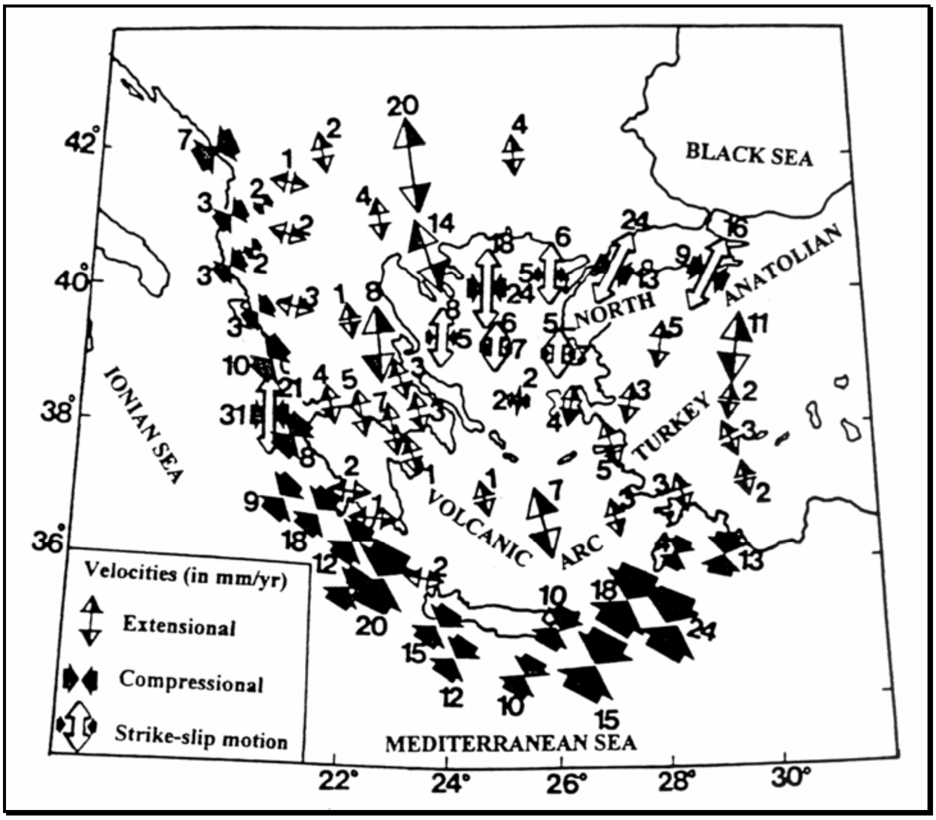


Fig. 2.1.3. Kinematics of the Greek territory tectonic plates proposed, by Papazachos et al. (1996).

The main features of this map are the areas which are characterized by compressional, extensional and strike-slip motion. As it will be explained later on, this plays an important role in the kinematics of the Aegean area and moreover facilitates the calculation of its angular, rotational velocity.

2.1.1 Mapping of major, seismic fracture zones – faults.

Mapping of fracture zones - faults is of great importance in seismological studies. These are the places where earlier EQs took place and most probably future EQs will occur. Therefore, the accurate mapping of these fracture zones - faults is of highest priority. The problem that arises is: what kind of faults - fracture zones must be mapped and is it always possible?

Earlier studies have revealed rather broad, seismic zones of increased, seismic risk, based, on the Greek seismicity history. In next figure **(2.1.1.1)** De Bremaecker et al. (1982) divided the regional, Greek area into smaller blocks which generally move towards southwest with different velocities in respect to the plate of Eurasia.

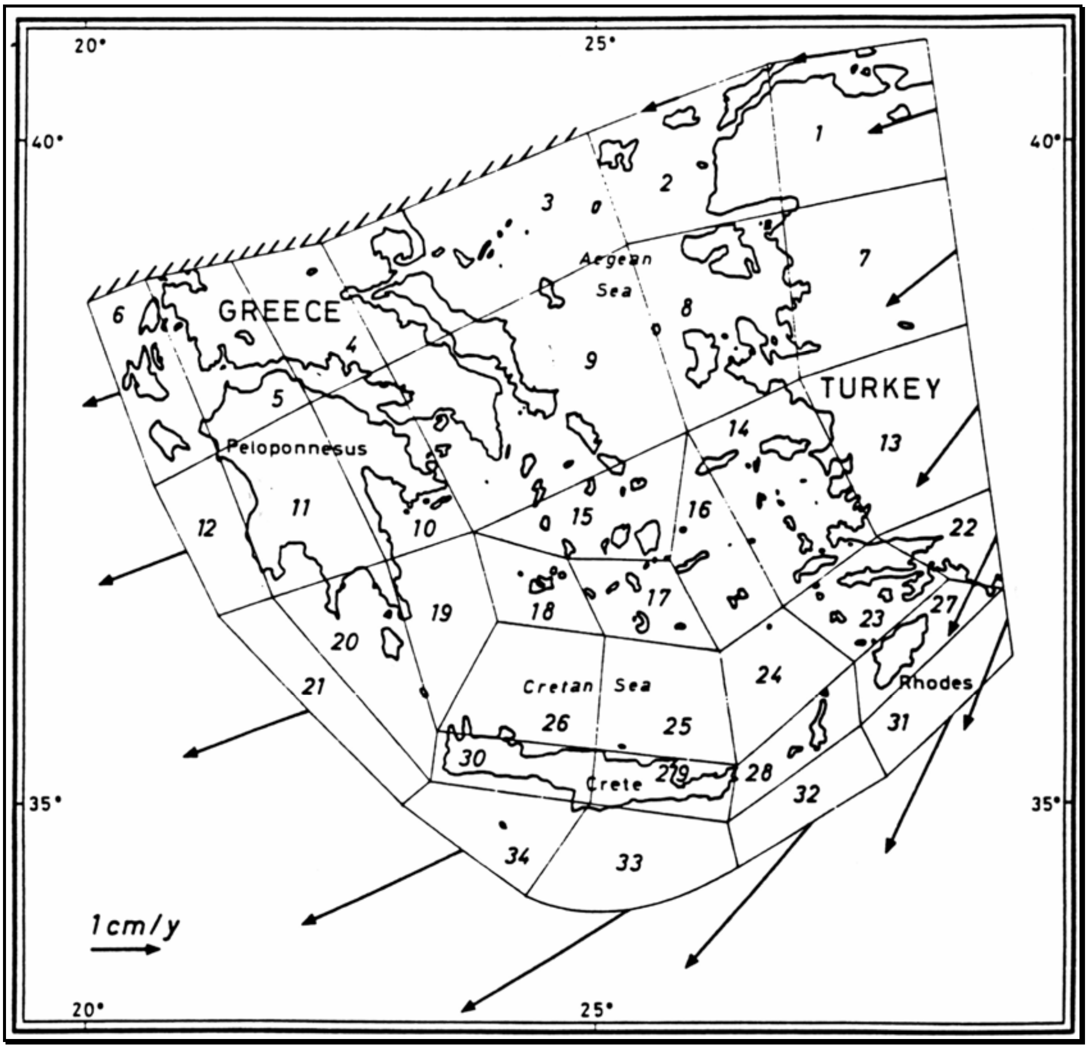


Fig. 2.1.1.1. Finite element network with boundary condition velocities, regarding European plate as proposed by De Bremaecker et al. (1982) for the Greek regional area.

In another study, Papazachos (1988) defined the most active seismic areas in Greece, based on the spatial distribution of the shallow earthquakes. The latter is shown in next figure **(2.1.1.2)**.

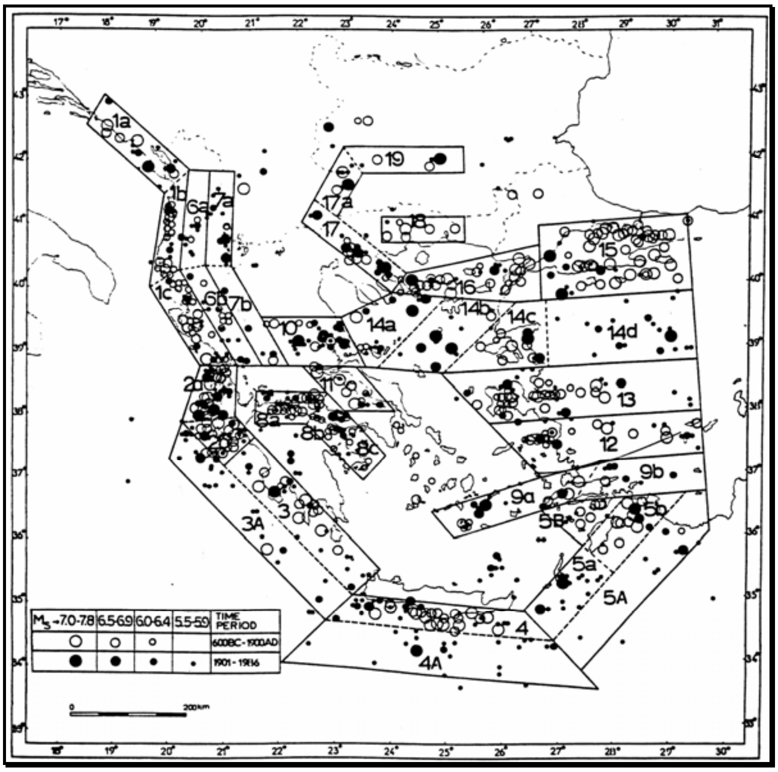


Fig. 2.1.1.2. Seismic zoning of shallow earthquakes in the Greek and surrounding areas (Papazachos, 1988).

Furthermore, the Greek territory was divided in specific zones according to the seismicity as it is expressed by the yearly released, seismic moment per 10000 Km^2 (Papazachos, 1989). This is presented in the figure **(2.1.1.3)**.

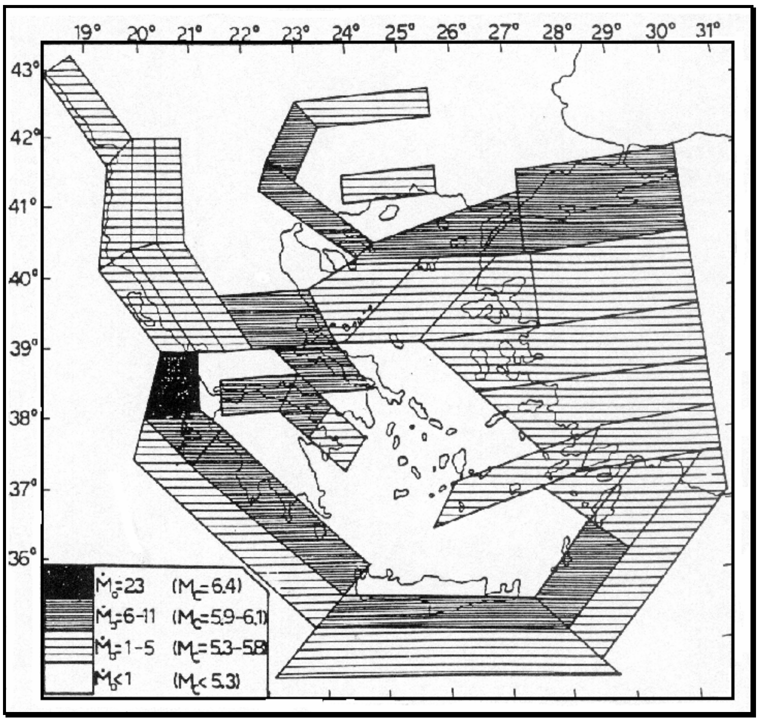


Fig. 2.1.1.3. Seismicity of the seismic zones of the Greek territory as it is expressed by the yearly, released, seismic moment per 10000 Km^2 (Papazachos, 1989).

In a more recent study, Hanus and Vanek (1993) presented another mapping of the active, seismic zones in the Greek territory which is presented in the following figure **(2.1.1.4)**.

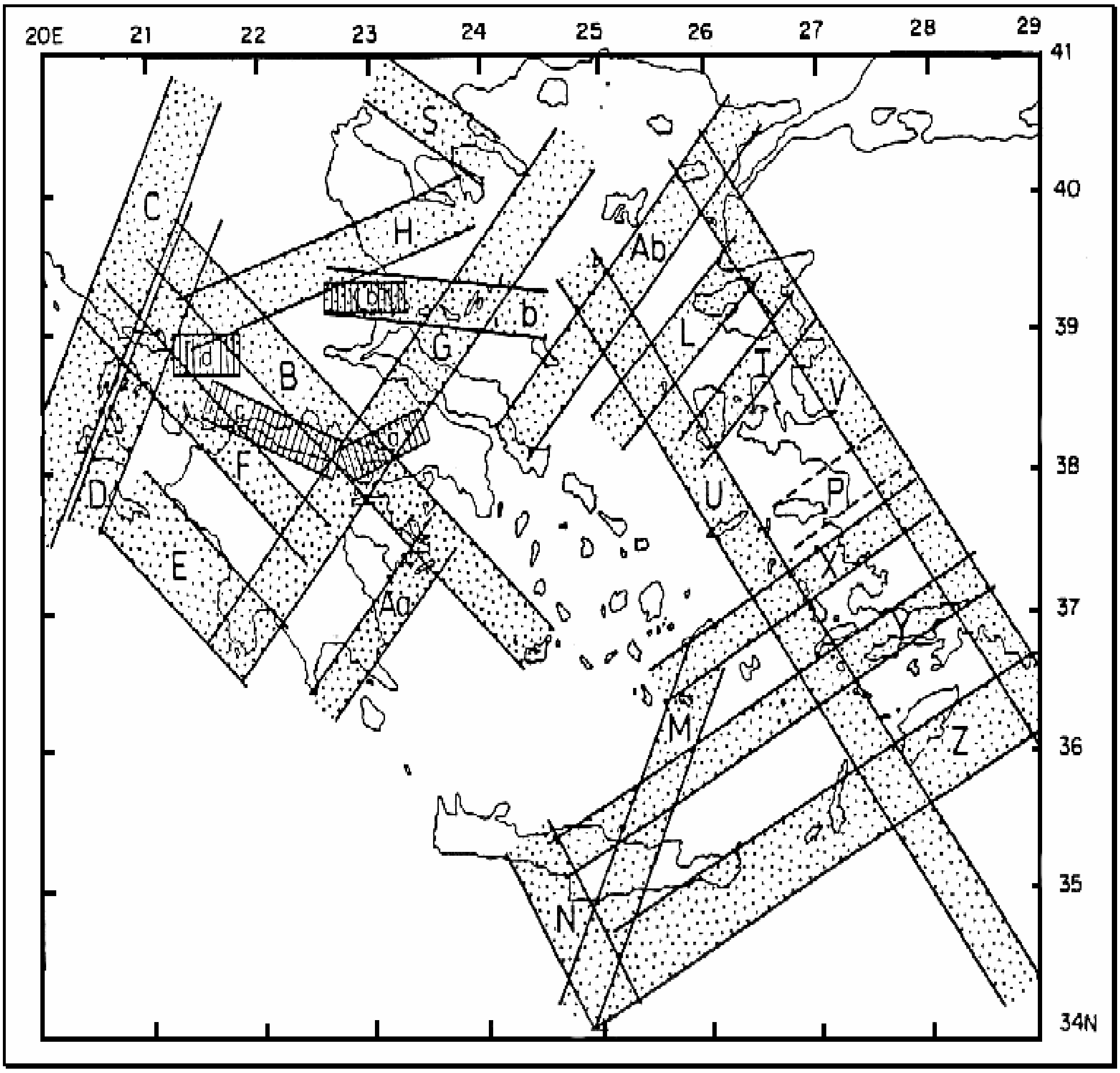


Fig. 2.1.1.4 Mapping of the active, seismic zones in the Greek territory as presented, by Hanus and Vanek, (1993).

Comparing the latter three figures **(2.1.1.2, 3, 4)** it is shown that the mapping of the active, seismic zones in the Greek territory (concerning shallow seismicity) is very subjective to each researcher. The characterization of an area, as an active, seismic one, is based on subjective criteria of each scientist, who presents his work on this topic. The only common, broad feature between them is the absence of active, seismic zones in the central Aegean area (Cyclades). An objective, active, seismic zoning of the Greek territory can be obtained by taking into account the deep lithospheric fracture zones / faults.

As far as it concerns the detailed mapping of seismic fracture zones and faults, classical geological surface observations cannot detect all of them. This is especially true when no surface trace has been produced by any deep, subsurface, tectonic activity. Furthermore, it is difficult to assign a seismological significance, to a detected on surface fault, without any other deep tectonic knowledge. The previous problem has been overcome, partly, by studying the delineation of the seismic events over a certain area. An example of this procedure is presented in the following figure **(2.1.1.5)**.

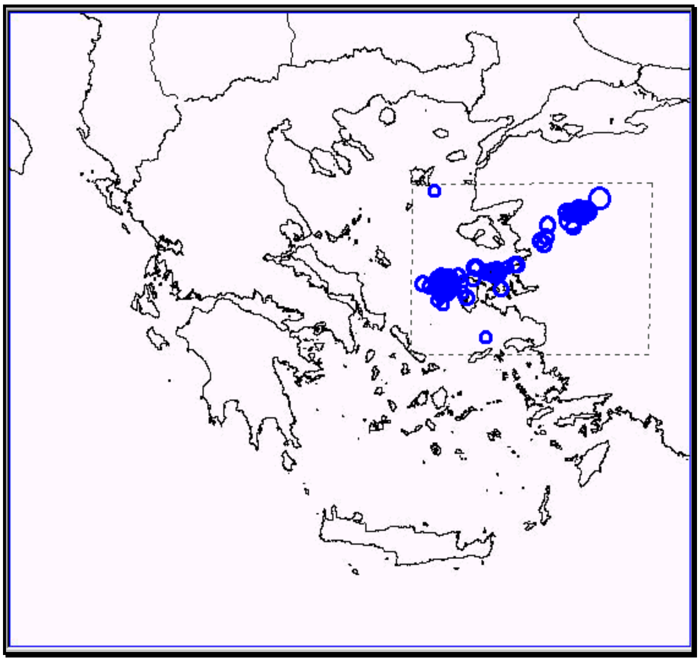


Fig. 2.1.1.5. Delineation of a deep fracture zone – fault from its seismic activity, mapped, over a certain period of time (June, 2001). The seismic activity for the assigned, spatial window (dashed square) was mapped in June 2001. It is obvious the delineation of the seismically activated fault. As a result of this activity a strong seismic event occurred at the lower left part of this fault (Psara EQ, Ms = 5.6R, June 10th, 2001).

2.1.2. Mapping of major, seismic fracture zones - faults from the study of the Earth's gravity field.

The creation of fracture zones and faulting of the Earth is due to the present stress field conditions which are applied in a particular area. Fracturing takes place in various modes (Mattauer, 1973), when extensional or compressional forces are applied on it. In the following figure **(2.1.2.1)** the black arrows indicate the applied forces, while the lines in the solid block indicate the various generated modes of fracturing. In case **(A)** there is block movement which creates a typical thrust fault combined with internal micro-fracturing typically normal and parallel to the direction of the applied stress field. In case **(B)** the generated, internal, micro-fracturing is interconnected and delineated diagonally in respect to the applied stress field direction, while in case **(C),** a characteristic strike-slip fault has been formed, due to exceptional type **(B)** stress field conditions.

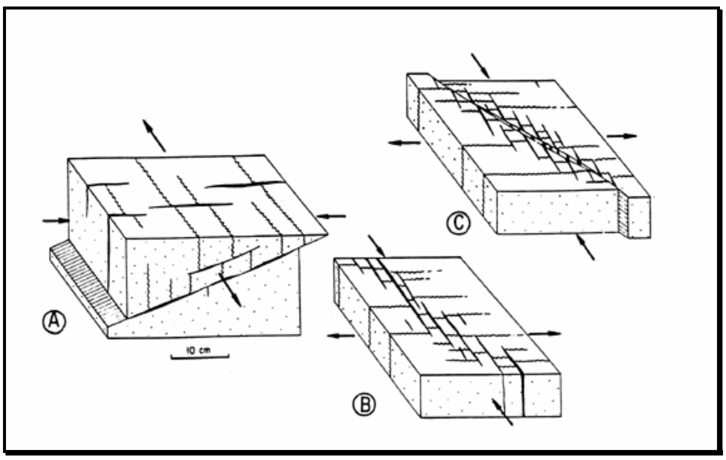


Fig. 2.1.2.1. Fracturing – faulting which is generated by applied stress (Mattauer, 1973). The arrows indicate the applied stress direction (compressional, extensional, shear-stress).

The form of a typical fault is presented in the following figure **(2.1.2.2),** regardless of its cause of origin. Typically, the ground is split into two parts through the fault plane, which exhibit a differential mode of relative movement to each other. The slip-vector of the generated fault, characterizes the latter.

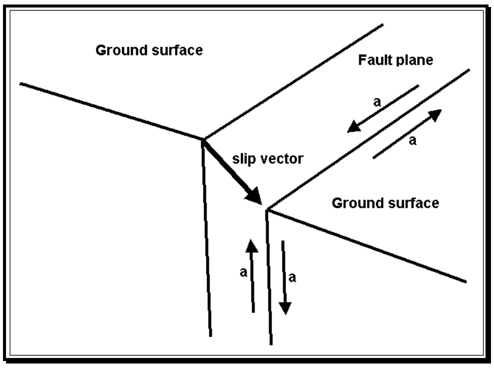


Fig. 2.1.2.2. Generalized sketch of a down-throw fault. The thick vector represents the slip vector; the thin vectors indicate the relative movement of each ground block to the other one. The down-throw block has slipped along the fault plane.

The slip-vector, that characterizes a fault, can be generally considered as the combination of its orthogonal components, when it is projected to an orthogonal coordinating system X, Y, Z. This is presented in the following figure **(2.1.2.3)**.

In each case, the interrelation of the magnitudes between these components can generate the various types of faulting which are observed in nature. Moreover, by accepting that the fault plane coincides with the **Z-X** plane, then the **SV-Y** component equals to zero. In such a case, (when **SV-Z = 0**), no thrust, neither normal faulting can exist. Since the slip-vector lays in the fault plane, then the only possible, ground block movement is along the strike of the fault. The latter is the case of a strike-slip fault and is characterized as sinister or dextral one depending on the direction of the block movement. In case **SV-X = 0,** then normal faulting or thrust faulting is generated, depending on the sign of the **SV-Z** component. In nature, faulting that exhibits both types of faulting modes, is, typically, generated. The type of generated faulting is characterized by the dominant and much larger component of the fault slip-vector.

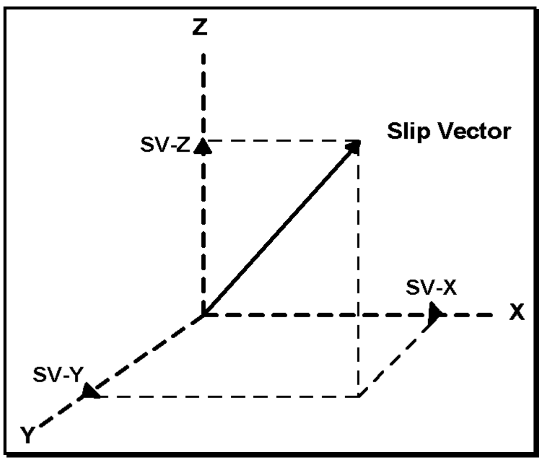


Fig. 2.1.2.3. Analysis of a vector into three orthogonal components. The fault slip-vector is analyzed into its orthogonal components **SV-X**, **SV-Y** and **SV-Z**.

In a most general case, the slip-vector is analyzed into orthogonal components, along the **X-Y** horizontal plane and the vertical to the ground **Z-axis**. In such a case the vertical component **VS-Z** plays a very important role in the overall tectonic and the stratigraphic conditions which characterize an area. A relative, vertical movement of the two ground blocks of the fault has, as a consequence, the stratigraphic modification of the overlaying geological formations. The latter has as an effect, the generation of ground lateral density discontinuities, and therefore, are generated changes in the intensity of the Earth's gravity field. This is the physical basis upon which the gravity methodologies for the study of the geology tectonics and stratigraphy of an area were founded.

Large tectonic fault / fracturing zones of the Earth are mainly reflected on the morphology of its gravity field. The wavelength of these features depends on the dimensions of the corresponding fault / fracture zones. Therefore, by studying the large wavelengths of the gravity field, we can obtain information for the deep large faulting / fractures zones of the Earth.

Moreover, by studying the horizontal gradient of the corresponding gravity field, we can locate the precise location of a fault / fracture zone quite easily. In the following figure **(2.1.2.4)**, **(a)** represents a geological fault of the Earth, **(b)** is the corresponding gravity field, while in **(c)** is presented the corresponding horizontal gradient of it. Details on this topic can be found in any geophysical gravity textbook.

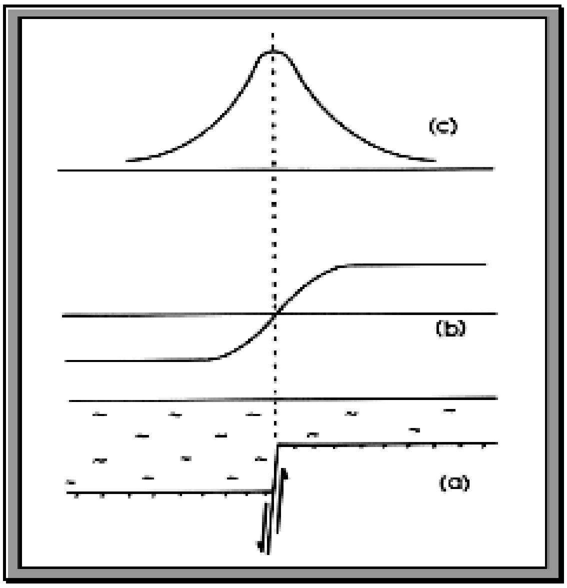


Fig. 2.1.2.4. **(a)** = Geological fault model, (**b)** = Corresponding gravity field, (**c)** = Corresponding gravity horizontal gradient.

Generally, the gravity method of Applied Geophysics is capable of tracing lateral density discontinuities of the underground, geological formations.

2.1.3 Application of the methodology in Greece.

On 13th May, 1995 a devastating earthquake (M=6.1R, Lat=$40^0.18$, Lon=$21^0.71$) occurred in "Grevena" area, northern Greece and caused many damages at the nearby towns and villages (some deaths were reported, too).

What is interesting, in this earthquake, is the fact of total absence of any statistical seismological indication that a strong EQ could take place, in an area like this, which was characterized as of very low seismic risk (zone **1**, out of **4**) and of total absence of any known, large, geological tectonic features to justify any possible strong seismic event.

The earthquake which occurred, the absence of statistical and geological - tectonic data which could reveal the seismically dangerous character of the "Grevena" area and the required, deterministic cause of this earthquake motivated the analysis to follow.

The very same scenario was replicated on 7th September 1999 in Athens, the capital city of Greece. Although Athens is located in an area which is characterized as "**zone 2**", as far as it concerns its seismic risk, the complete absence of knowledge of deep tectonics had postulated the notion that the capital of Greece is built over "safe" ground. Unfortunately, for the people (over a hundred) who died, apart from the very large damages in buildings, during this earthquake, this was proved to be totally wrong, after this earthquake.

So the question that arises is: Where do the strong earthquakes really occur?

The following analysis may be the answer to the above question.

It is well known that strong earthquakes occur when a fracture zone / fault releases its stress load and rupture occurs along a large part of it. The longest the fault / fracture zone has been activated, the largest the magnitude of the earthquake is.

The problem therefore, is formulated as follows: Is it possible to map the deep fracture zones, where strong EQs occur? The study of strong earthquakes in Greece, statistically treated, may vaguely reveal the large, deep, tectonic features that are prerequisites for its occurrence. The same problem, of the detection of deep tectonics of an area, faced from the view of Applied Geophysics, is rather simple, as it will be explained later on.

The key point of this study is that strong earthquakes must coincide in location with large tectonic faulting / fracturing systems of the lithosphere. Consequently, the specific target of this analysis is the location of these tectonic features, which locations can't be traced by other geological methods.

The following map **(fig. 2.1.3.1),** where is presented the location of the strong, (**M>=6R**), seismic events of the Greek territory, which occurred during the period **1900 – 1997,** has been compiled, in order to have a clear view on this topic. The circle, around each location, is the area defined by the (conservative) location estimation error (+/- 25Km).

It must be pointed out that the location of each earthquake can be anywhere in the error circle, without decreasing the validity of the map.

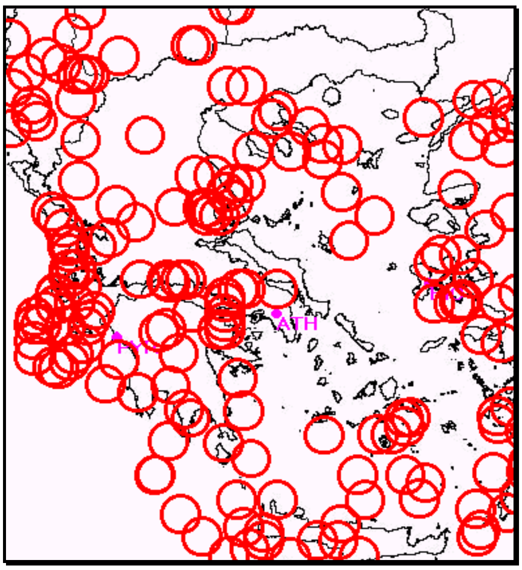


Fig. 2.1.3.1. Earthquakes with **Ms>=6R** which occurred in Greece during the period **1901 - 1997.** The red circle indicates the error, accepted, for the location determination that equals to **+/- 25Km**. The map correlates in size with the Bouguer Anomaly map of Greece (Makris, 1981).

The gravity field transformation approach into its gradient can be applied in two-dimensional form on the gravity field of Greece. A simplified presentation of the Greek gravity field, Bouguer anomaly (Makris, 1981) is presented in the following figure **(2.1.3.2)**.

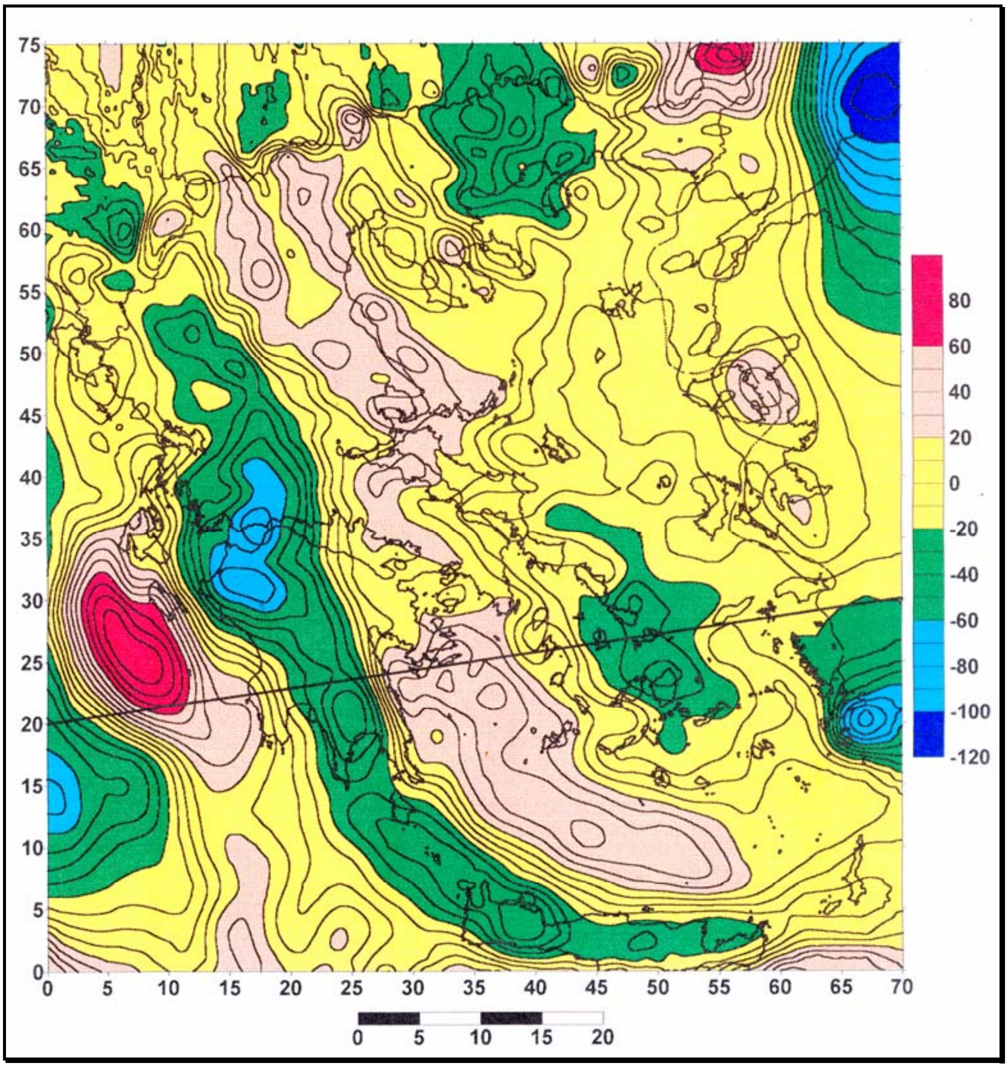


Fig. 2.1.3.2. Simplified (Thanassoulas, 1998) gravity (Bouguer anomaly) map of Greece (Makris, 1981). The scale is in mgals.

The following scheme has been applied in order to utilize the horizontal gradient transformation.

$$\mathbf{Grad_{x,y}(G) = G(x,y)*TL(x,y)} \qquad \mathbf{(2.1.3.1)}$$

Where: **G(x,y)** is the gravity field at point **x, y**

TL(x,y) is the operator, applied, for the transformation to be utilized

$\mathbf{Grad_{x,y}(G)}$ is the resulted, horizontal gradient

TL has been calculated analytically by the use of a polynomial surface of second order, fitted, to a progressively sliding window over the gravity field data.

In order to avoid near surface tectonic features, and targeting to the deeper structure of the Earth, a **2-D** "window" of **20 x 20Km** was used in all these transformations. The results of this operation are presented as photo relief map, illuminated, from **NE** direction. In the next figure **(2.1.3.3)** is shown the result of the transformation of the Bouguer anomaly map of Greece into a gradient one.

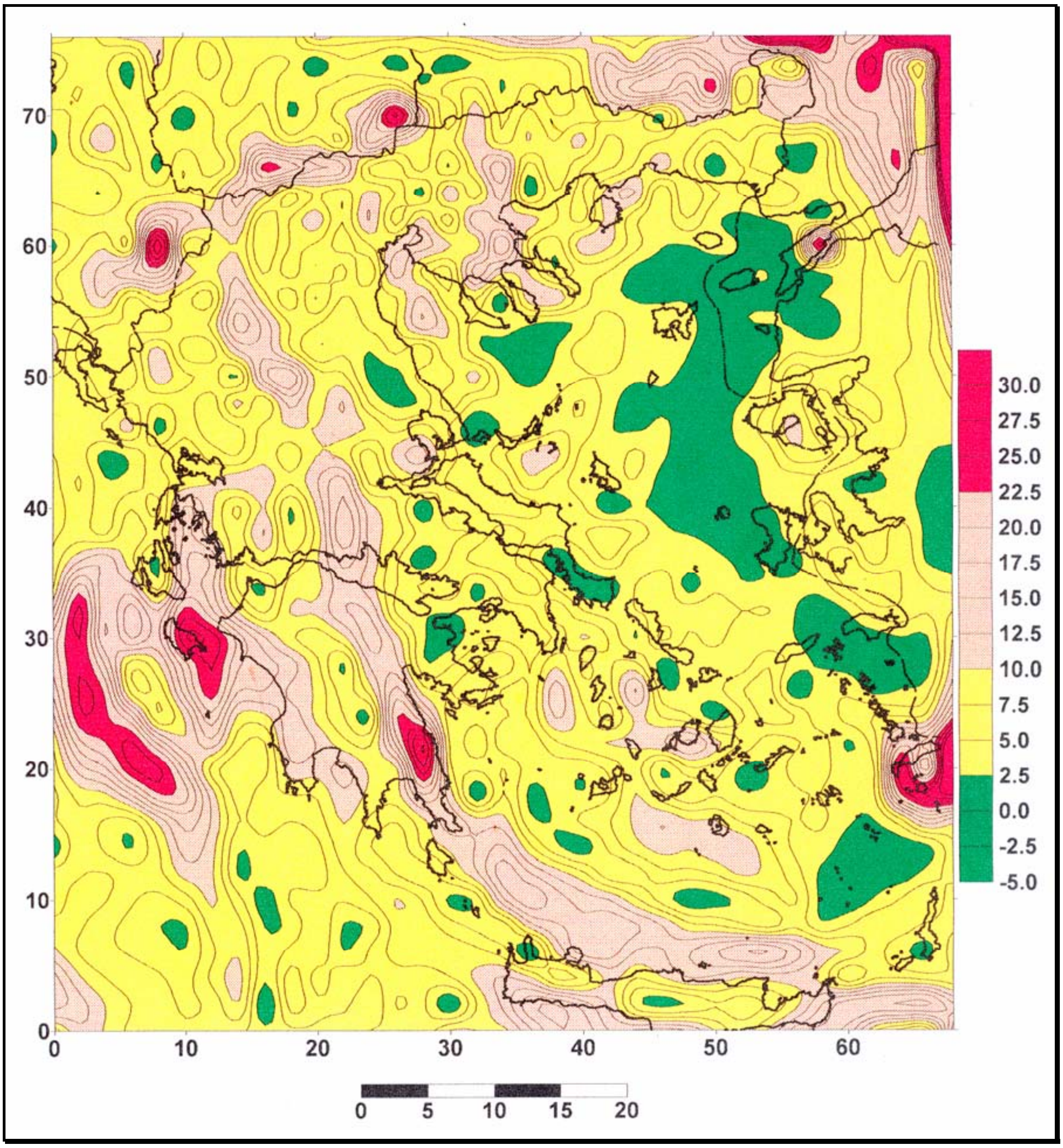


Fig. 2.1.3.3. Horizontal gradient map of Greece (Thanassoulas, 1998).

The latter map is presented in **3-D** photo relief **(fig. 2.1.3.4),** so that the high gradient value areas are better visualized.

Deep fracture zones express (horizontal gravity gradient ridges) themselves as the boundaries between dark black and white zones.

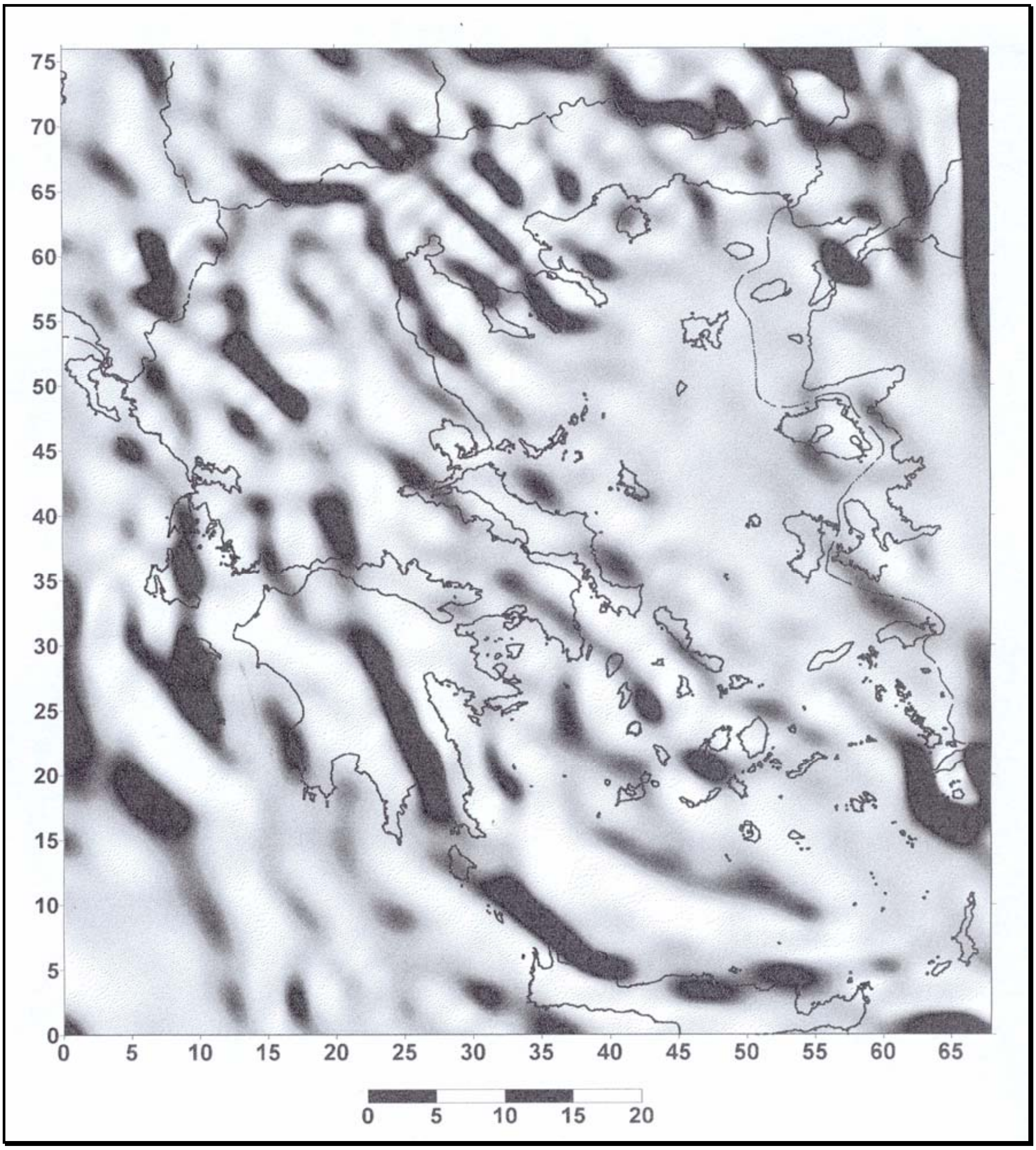


Fig. 2.1.3.4. **3-D** photo relief compiled gradient map of Greece. Each scale unit is 10Km. Lighting from **NE** (Thanassoulas, 1988).

It is very interesting to note the deep fracture zone, crossing in a **NW - SE** direction the Attiki area (X=32, Y=34), where Athens is located and the strong EQ of Athens took place. This feature, unfortunately, reveals the dangerous and seismically risky position, where the capital city of Greece is located.

The detailed fracture zones-faults (thick black lines) locations, determined by the latter method, are presented in the following figure **(2.1.3.5)**.

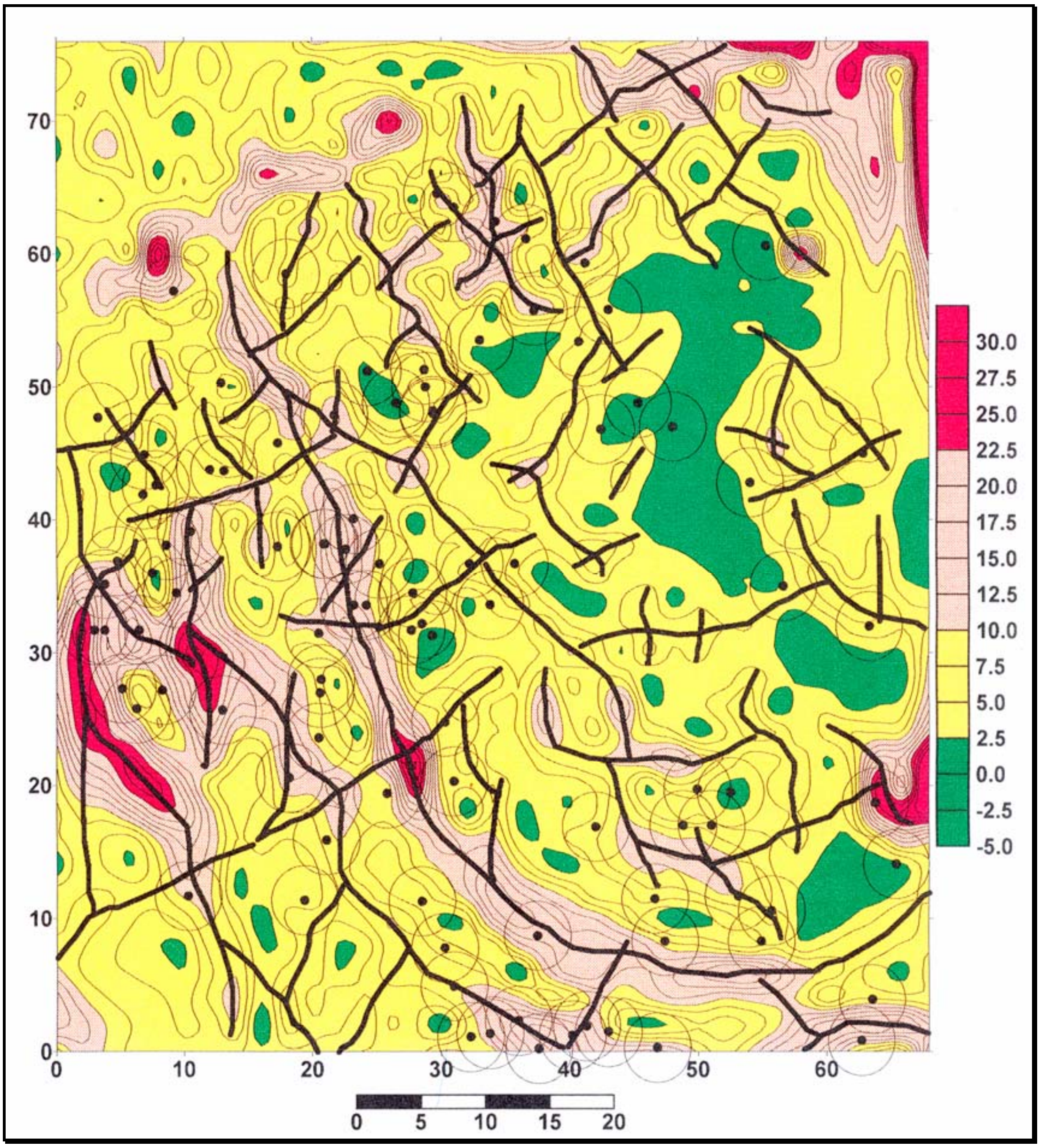


Fig. 2.1.3.5. Deep, lithospheric fracture zones (thick black lines) determined from the horizontal gradient map of Greece (Thanassoulas, 1998). The solid dots indicate the locations of strong (Ms>6R) EQs, which occurred during the period 1901 – 1997.

2.1.4 Strong EQs location map of Greece (1901- 1997).

It was stated earlier that strong earthquakes have their origin in deep and large faults / fracture zones of the Earth. In the following figure **(2.1.4.1),** is made a comparison between the location of the strong earthquakes, determined by seismological methods, and the location of the deep faults / fracture zones determined by the transformation of the gravity field into its horizontal gradient. The EQs catalog, which is used, is the one provided by the National Observatory of Athens **(NOA)**.

Therefore, it is expected that at least a fault zone crosses the error location circle of each strong earthquake, which is mapped. This fault zone is, presumably, the actual fault zone that was activated and generated the corresponding earthquake. Consequently, the "most probable true" location, of the corresponding earthquake, is not the one suggested by seismological methods, but the one which resulted by the projection of the "seismological" location of the epicenter, to the nearest fault / fracture zone.

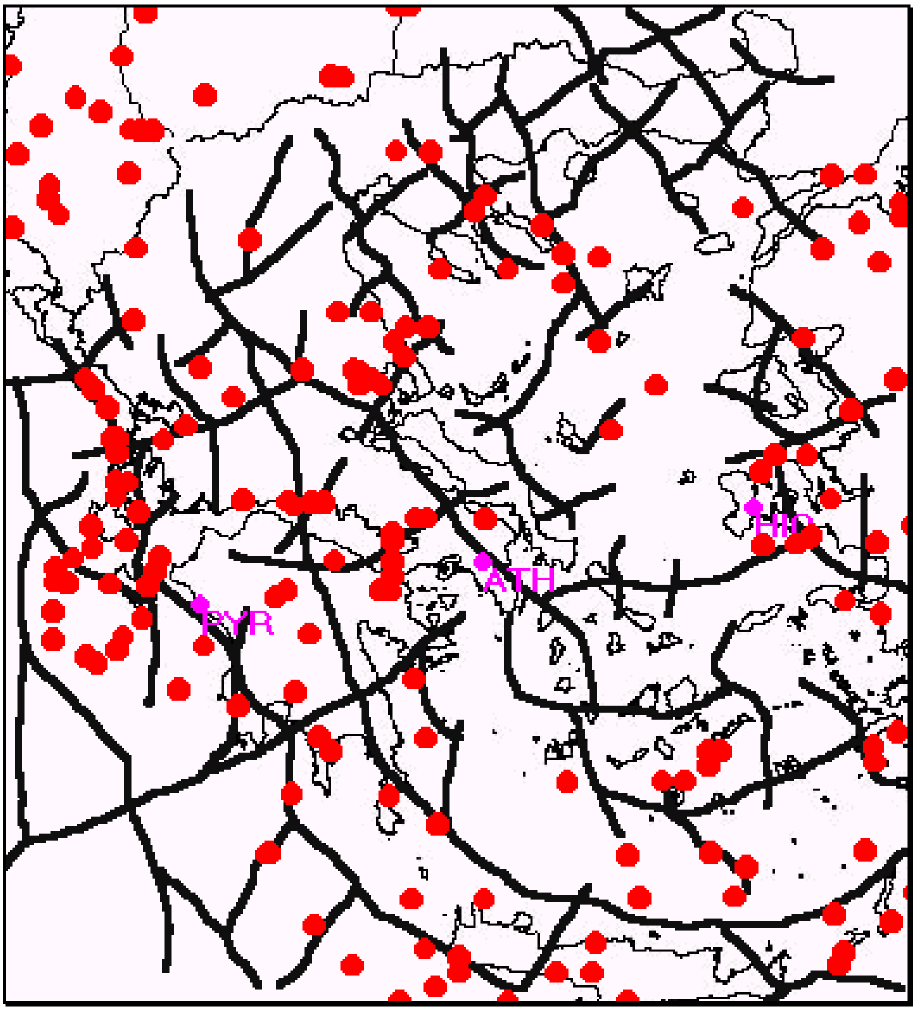


Fig. 2.1.4.1. Location of strong, seismic events (Ms>=6R, solid red dots) in Greece, for the period 1901 – 1997, in relation to the location of the fracture zones - faults (thick black lines), determined by the transformation of the corresponding gravity field.

A detailed examination of this map indicates that the vast majority of the earthquakes are located in a distance shorter than 25Km from the nearest fracture zone. Therefore, if the location of each earthquake is moved within its location error radius towards the collocated fracture zone, then the validity of the EQ location map does not change, while at the same time there is a very good coincidence of the EQ locations with the location of the fracture zones **(fig. 2.1.4.2)**. A very small number of EQs, mainly in the western part of Greece, do not follow this rule. This could be attributed either to missing existent fracture zones / faults which the transformation of the gravity field didn't succeed to identify or to the wrongly calculated, by the seismological methods, location of the deviating earthquakes. In either case the degree of correlation (statistically) is very high.

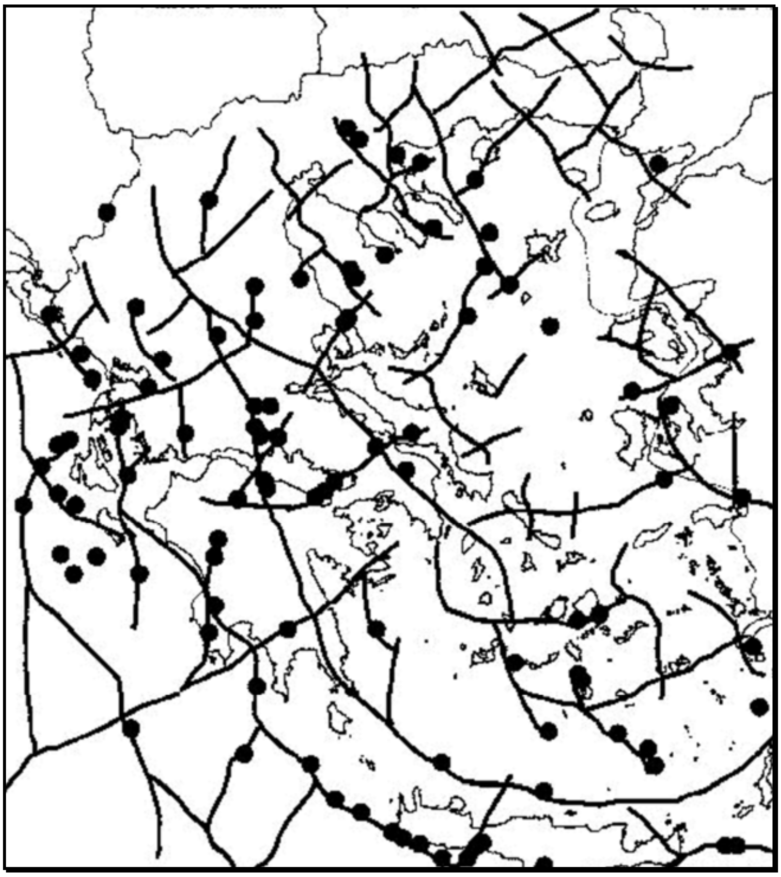
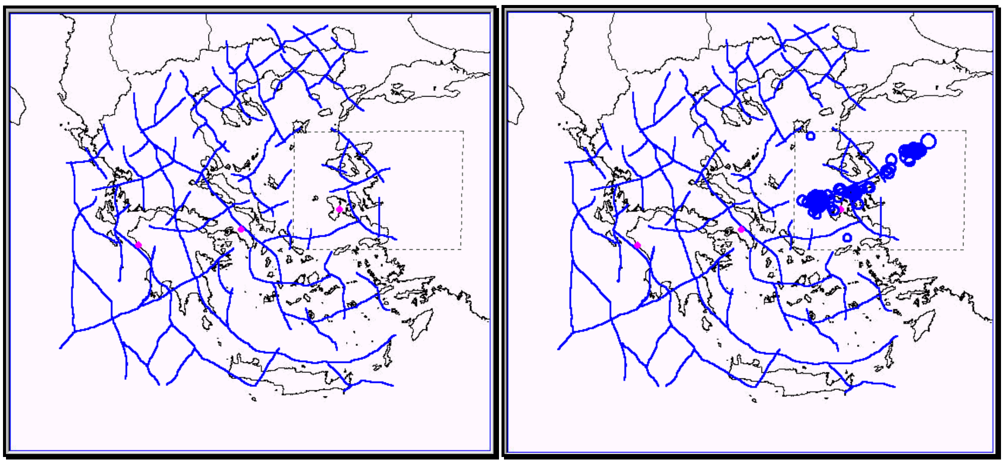


Fig. 2.1.4.2. Corrected location, of the presented EQs, according to the calculated fracture zones - faults from gravity map transformation. The EQs data file contains data from 1901 to 1997, when the original study was presented (Thanassoulas, 1997). The EQs, outside the gravity map boundaries, have been excluded.

A detailed example, showing the validity of the methodology, is presented in the following figure **(2.1.4.3)**.



A

B

Fig. 2.1.4.3. Delineation of a deep fracture zone - fault from its mapped, seismic activity over a certain period, compared with the one, calculated, by the gravity field transformation. **A (left)** = fracture zones, calculated, through gravity field transformation, **B (right)** = fracture zone, mapped, from its seismicity, which took place during June 2001. Comparison is made between the inset frames.

It is very interesting to see how the seismically, mapped, fracture zone in fig. **(2.1.4.3 - B)** coincides with the one which is mapped by the gravity method and is presented in figure **(2.1.4.3 - A)**. Further more the specific fracture zone extends towards **NE** in the area of Western Turkey. This fracture zone has already produced two strong EQs with **Ms >6R** in the past.

2.1.5. Verification of fault zones by strong EQs which occurred during the period 1998-2006.

Accepting the validity of the presented methodology, it is applied as a test on the earthquakes which took place during the period 1998-2006 in Greece. These earthquakes must coincide with the corresponding, deep, lithospheric fracture zones / faults.

In the following figure **(2.1.5.1)**, are presented for validation purposes the strong (Ms>=6R) earthquakes (solid red circles) which took place in Greece, after the completion of this study (Thanassoulas, 1998), that is the period 1998-2006, along with the determined fault / fracture zones.

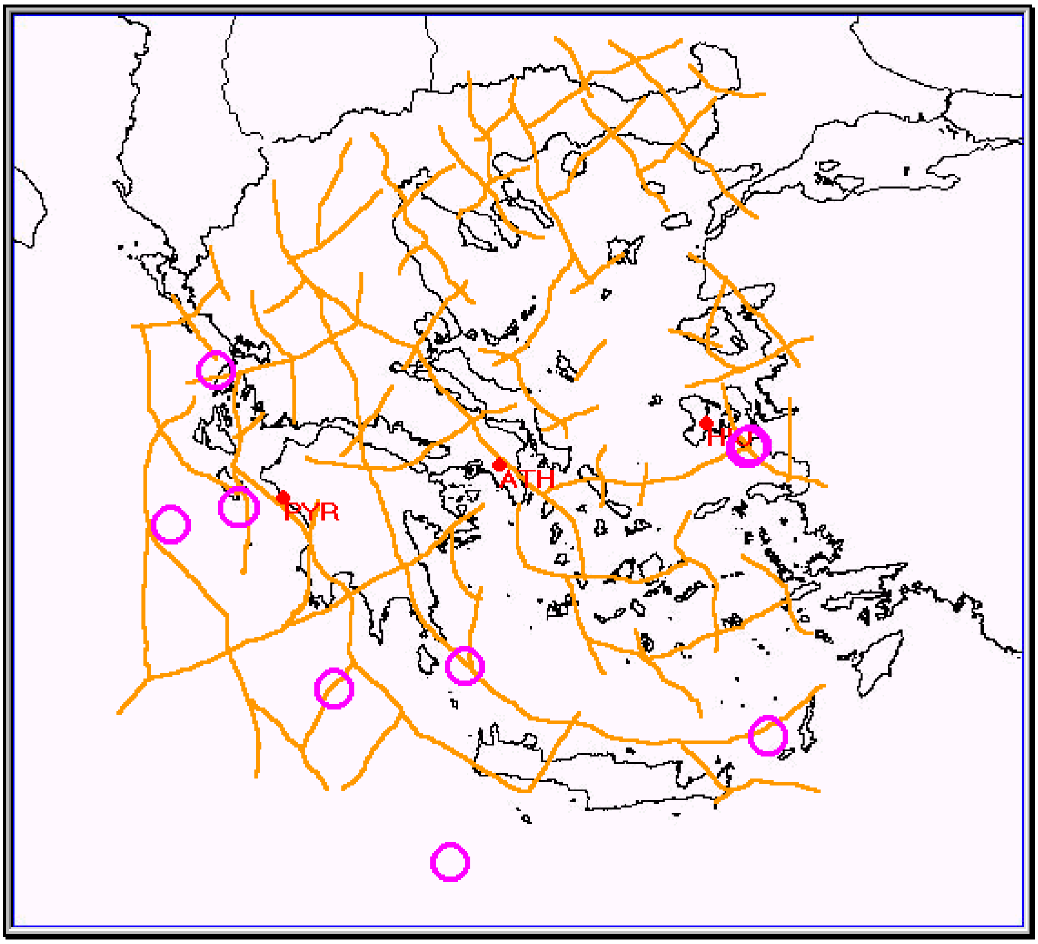


Fig. 2.1.5.1. Correlation of the location of recent strong (1998 - 2006, Ms>=6R) seismic events (red circles) to the location of the already calculated fracture zones - faults by the transformation of the Greek gravity field.

It has been made clear that all the latest, strong, seismic events coincide with the location of the fracture zones - faults which have been already calculated.

Two more examples, related to Lefkada EQ (2003/08/14, Ms = 6.4R) and Kythira EQ (2006/01/08, Ms = 6.9R), follow. Lefkada EQ caused large damages on Lefkada Island and is the most destructive recent one. The above mentioned EQ is presented in the following figure **(2.1.5.2)**.

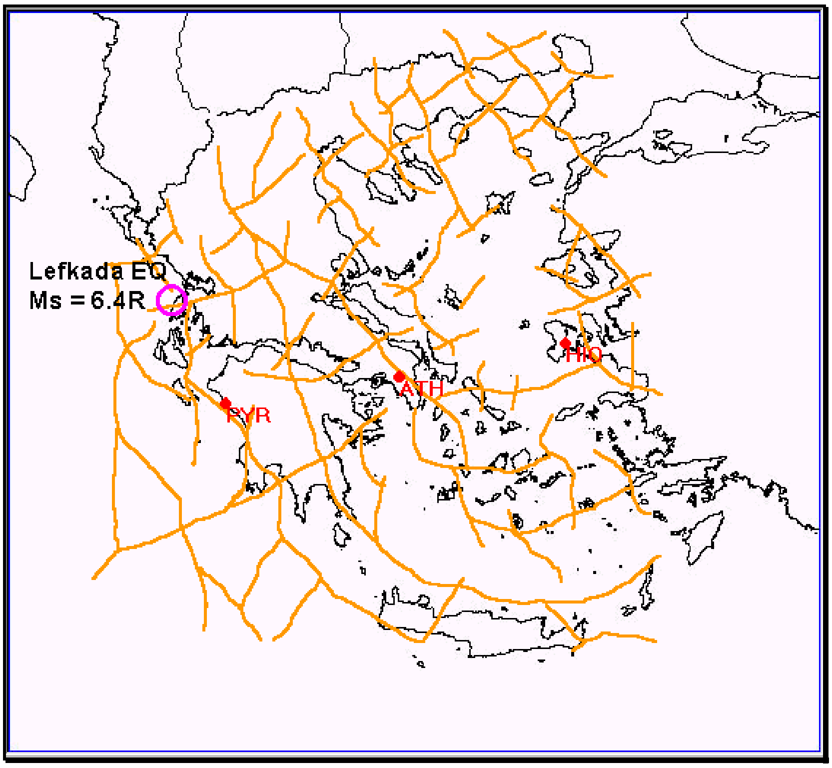


Fig. 2.1.5.2. Lefkada EQ, red circle (2003/ 08/14, Ms = 6.4R) in relation to the deep, lithospheric fracturing (brown lines), calculated by the gravity field transformation (Thanassoulas, 1998).

Kythira EQ is the strongest one which occurred in Greece, recently. It was felt almost allover Greece and the neighbor countries, too. Kythira EQ is presented in figure **(2.1.5.3).**

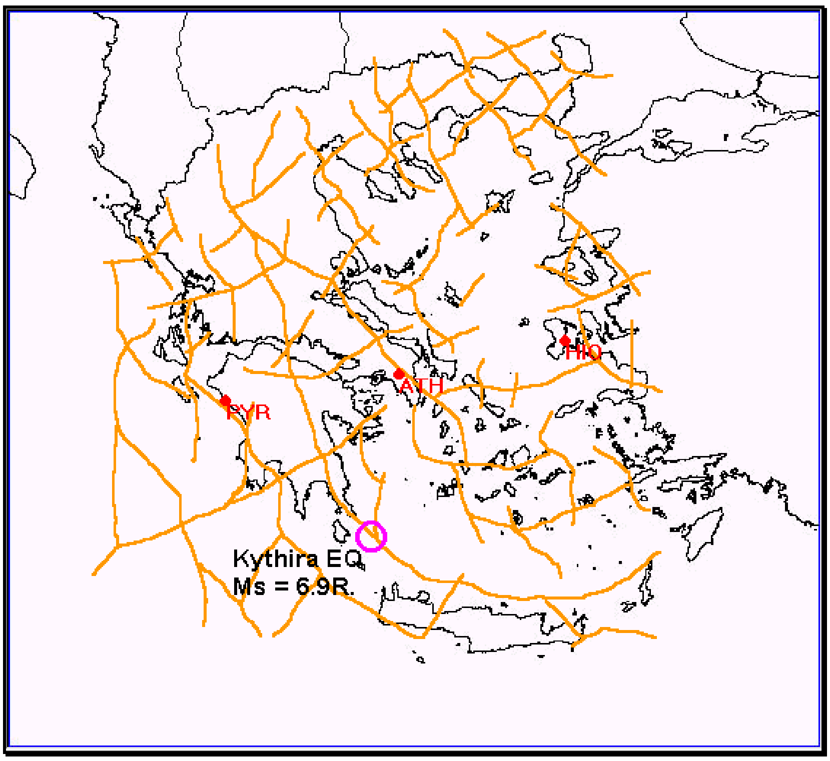


Fig. 2.1.5.3. Kythira EQ, red circle (2006/01/08, Ms = 6.9R) in relation to the deep, lithospheric fracturing (brown lines), calculated by the gravity field transformation (Thanassoulas, 1998).

The presented analysis of strong earthquakes' location which earthquakes occurred in Greece during the last 100 years (more or less) and the detailed examples, too, show clearly that, contrary to seismological notions that strong EQs can occur, statistically, in any place, these happened in specific, deep, lithospheric fracture zones / faults. These can be mapped by the use of applied geophysical methods, and in particular, through the analysis of the Earth's gravity field that is modified by these strong, tectonic, lithospheric anomalies. The methodology which is presented could be used to prepare more detailed maps of seismic risk for wider areas, even though seismological data of such areas are missing or are of limited extent. This is an advantage, compared to seismological methods which require a statistically large number of earthquakes to take place in order to evaluate the seismic risk. The case of the EQ in Grevena (seismic risk zone I) and the EQ in Athens (seismic risk zone II) are two characteristic examples, which justify the validity of this methodology.

In conclusion, taking into consideration the latest, increased, seismic activity of the Greek territory, it is justified to expect, strong earthquakes to occur along this faulting / fracture-zoning network in the future. Therefore, the State Authorities must take into consideration the fact that the seismic risk is enhanced along these specific fracturing / faulting zones. The fact that, in some of them we have not experienced a strong earthquake yet, does not justify, at all, the notion that it is an aseismic zone. On the contrary, it must be considered as a seismogenic area, potentially to be activated in the future. What is open, as a question, that is only the timing of the future strong EQ.