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OVERALL SEISMOTECTONIC MODELLING - A POWERFUL TOOL IN SEISMIC HAZARD ANALYSES: TWO APPLICATIONS IN CENTRAL ITALY AND CALIFORNIA (U.S.A.)

Abstract. A keystep in seismic hazard analyses is the assessment of the maximum potential earthquake which could occur in a studied area. For a world-wide application, use is made of empirical relationships between some characteristics at the surface of active faults and the surface-wave magnitude of the maximum related earthquakes. But the use of these relationships presents problems in terms of applicability and reliability, which are due mainly to the following factors:

- the difficulty of finding on the ground the key elements required as input to these relationships (active faults and/or seismic ruptures); this task is all but easy, especially when making only superficial geological surveys in tectonically complex areas, where brittle-faulted basements (and consequently most of the relevant seismic sources) are often hidden by disharmonic ductile sediment covers;
- the virtual exclusion in these relationships of the most significant parameters required by the Geomechanic for a correct location and evaluation of the maximum potential earthquake of a fault (respectively the deep geometry and the frictional strength of a fault plane).

For these reasons, at ENEL (National Electric Generating Board of Italy S.p.A.), in order to improve these relationships, a methodological approach has been developed, which is more suitable for tectonic settings such as the Italian one and which allows complete seismic hazard analyses (assessment of the earthquake sources and prediction of earthquake effects), where geological, mechanical and geophysical characteristics of the crust are taken into account at the same time to formulate an *overall seismotectonic model* of a given area which explains all the available tectonic and seismological information. In this new methodological approach, evaluation of the seismic sources is done maintaining the basis of the existing relationships (which is to relate an active tectonic feature to the potential earquake); this basis has been made more effective by giving particular attention to the rheological conditions of the rocks involved in active strain, and by considering the resistant that, obstructing the motion of the brittle portion of an identified tectonically active structure, allows an accumulation of elastic energy from which, if suddenly released, earthquakes can be generated. So, seven main categories of three-dimensional tectonic structures, to be filed on the basis of their seismotectonically relevant characteristics, have been proposed as reference for creating a seismotectonic data-bank of the most common active tectonic structures in the world. Thus, in the future, instead of referring only to one or more characteristics at the ground surface of an active fault (as is done when applying the existing fault/magnitude relationships), a more complete comparison could be done with all active 3D tectonic structures, including their physical properties. It is hoped that such an approach, will be carefully evaluated by the existing Regulatory Commissions, and be as widely adopted as possible by the researchers so as to create seismotectonic data banks wherein world-wide seismically active structures can be filed on the basis of their overall seismotectonic characteristics. To give an example of the noteworthy possibilities of the method, two overall seismotectonic models are proposed: one for the central part of Italy and one for the western U.S.A. The guidelines of the *overall seismotectonic models* used to explain the seismic patterns in these two areas are:

- in the first case, the presence of a large zone with thin brittle crust softened by a geothermal positive anomaly, which is the residual effect of uprisen mantle material that at present is acting against a slab of continental lithosphere on the NE, E and SE borders of the warm area;
- in the second case, the resistance given by a rooted cold body (probably correlated to the outcropping Sierra Nevada batholith) to the relative movement between the Pacific and North American Plates (in part taking place along the famous San Andreas fault), and the probable presence of soft crust in correspondence to areas with high heat flow densities in Oregon, Southern Idaho, Western Utah and Arizona. In this second case, the suggested model should only be considered very preliminary, due to the lack of sufficient information about the geometry and strength of the rocks belonging to active tectonic structures down to the maximum depth of the known seismicity; if studies aimed at completing the data set required by the present seismotectonic methodology were carried out, a remarkable improvement in the reliability of the western U.S.A. seismic hazard assessment could be obtained.

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INTRODUCTION

Relevant buildings or other critical facilities at risk (like for instance nuclear power plants, Liquefied Natural Gas (LNG) plants, large bridges and dams, important buildings, etc.) must be designed to maintain conditions of absolute safety, even if the site where they are built is subject to earthquakes. To achieve this, the planners must be provided with the Design Basis Ground Motions, characterized by the maximum ground acceleration which may be induced at the site by the largest future event generated during the plant's lifetime by the strongest seismic source existing in the area around the site.

As is obvious, defining such an acceleration (that together with the related site specific response spectra is usually called - by the nuclear power plant planner - the SSE: Safe Shutdown Earthquake) is an extremely delicate task, because the need for safety must be reconciled with containment of expenses at the plant (or building) under construction. The seismic hazard analyses necessary to estimate the SSE (or any kind of Design Basis Motions on the ground given to the planner) can be made both in a probabilistic or deterministic way.

The **probabilistic approach** is a very powerful and attractive method that can take into account various geological/seismological data and/or models of differing uncertainty; whenever necessary, it can be used to define the occurrence probability of different magnitude earthquakes, and then to perform risk analyses. For these reasons it is very useful when defining the earthquake hazard assessment over wide areas, for instance for entire countries (McGuire, 1993). It should be noted however that many difficulties are met when applying the probabilistic approach even in a country, like Italy, where one of the richest historic earthquake catalogues in the world is available.

The **deterministic approach** is a highly regarded method for assessing the seismic hazard of a specific site, but it requires (Reiter, 1990) that discrete, single-valued events or models be available for the seismotectonically relevant area under study.

In both the probabilistic and deterministic approaches, an assessment of the maximum potential earthquake that could occur during the lifetime of the plant (or building) in the area around it is required.

There are numerous empirical relationships in the literature that give, starting from one or more parameters of an active fault (see the "*capable fault*" of USNRC, 1978 (1)), the largest earthquake that the identified fault could generate. The surface-wave magnitude of such an earthquake can be obtained from the following fault parameters: length, surface displacement, surface rupture length, downdip rupture width, surface rupture length times surface displacement, and so on.

The relationships giving the most reliable future potential earthquake of a particular fault are those utilising the surface rupture lengths; but it is extremely difficult to find reliable geological data for evaluating the presence and length of fault ruptures on the ground related to a single historical earthquake. In fact, geomorphologic and anthropic agents work incessantly to hide such evidence and, in a very short time (from a geological point of view) it is practically impossible to find it. Of course we can carry out very refined studies and establish to a certain extent if some displacement on a fault is given by one or more coseismic events, but everybody working in seismotectonics know how difficult such a task is. Consequently the fault/magnitude relationships are entered essentially by the length of active fault instead of surface rupture lengths. But there is a big problem related to this parameter: once a fault has been ascertained to be certainly active, how much of the fault will rupture in the case of the largest future seismic event? Generally researchers choose one half.

Thus, we see, that the seemingly good idea to relate fault parameters to the maximum earthquake potential of the fault needs improvement, especially when we consider that the existing

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(1) In the USNRC regulations the definition "capable fault" refers to a fault which has been displaced towards the surface at least once in the last 35,000 years or which has undergone recurrent motions in the last 500,000 years. In the most recent edition of these regulations (USNRC, 1992) "capable fault" has been replaced with "capable tectonic source", defined by the presence of near-surface deformation of landforms or geologic deposits of a recurring nature within the last approximately 500,000 years, or at least once in the last approximately 50,000 years.

relationships between fault and magnitude cannot be used for magnitudes less than 6.0 (Wells and Coppersmith, 1994).

INCONVENIENCES CONNECTED WITH ASSESSMENT OF THE FUTURE EARTHQUAKE PONTENTIAL OF A TECTONIC STRUCTURE BY MEANS OF THE EXISTING FAULT/MAGNITUDE RELATIONSHIPS

As most people were doing at that time for similar cases, ENEL started in the 1970s by trying to apply some of the fault/magnitude relationships to define earthquake sources when siting nuclear power plants in Italy. Soon they had to face the difficulty, discussed in the previous Chapter, of locating with certainty active faults (representing the basic element for applying the relationships concerned) in a territory like Italy, which has a rather complex tectonic setting, unsuitable for detecting them (Patacca and Scandone, 1986).

Owing to the widespread, and sometimes high seismicity recorded in Italy, some active faults should easily have be found there. But in fact this was not so, despite the co-operation between some of the foremost international experts and the creation of extremely demanding initiatives by ENEL, among which the following are worth mentioning:

- the setting up of a pioneering list of the Neotectonic Elements in Italy (to which more sophisticated researches, carried out by the CNR-Italian National Research Council, followed without any appreciable results in detecting active faults);

- the detection of the tectonically relevant Pliocenic and Quaternary geological structures of the Po Plain and the Venetian Plain (Northern Italy) by means of a large number of seismic reflection profiles;

- the execution of extensive geological field surveying (photo-interpretation of more than 20,000 km^2, and ground survey over several zones for a total of about 10,000 km^2), of the main neotectonic structures in central-northern Italy, carried out from 1983 to 1984, within the studies for locating nuclear power plants in the Po Plain, and with the help of the most actively involved university experts.

Thus at ENEL, which in the meantime had made a complete Italian National Earthquake Catalogue, the firm belief was reached that some other methods had to be found to identify seismic sources in territories, like Italy, where the widespread presence of areas with ductile sedimentary cover hides the motion of stiff structures at depth, where the majority of the most relevant seismic events normally take place.

During the 1980s, a particular seismotectonic approach (to which experts from ENEA-DISP and most of the talented university researchers operating in the Earth Science field in Italy provided ideas and suggestions) was applied by ENEL in siting two nuclear power plants in the Po Plain (Northern Italy). This approach, very similar to that called the *seismotectonic provinces* one (or, better, the *localizing structures* approach as defined in Reiter, 1990) was progressively improved to become a new methodology, extensively described in the following Chapter "Characteristic steps of the methodology here proposed", in which the surveying of characteristics of active faults on the ground surface is considered only one of the elements (even though important, not necessarily decisive) which must be taken into account when identifying the relevant seismic sources in an area under examination.

In the new methodology, particular attention is also given to considering in the right light the physical conditions able to generate an earthquake: that is, all the elements which allow us to understand if in the studied area there are forces which can obstruct the motion of the active tectonic structures. In fact, for instance, it is not sufficient to study the kinematics of a fault and to establish whether it is active or not to assess its seismic potential: if the slip along the detachment surface were completely free, there would not be elastic deformation (build-up of strain in rocks) and, consequently, no sudden movement able to generate earthquakes would occur; see among others Hooke (1668) and particularly Reid (1911) with his widely accepted *Elastic Rebound Theory of Earthquakes*.

It must be noted that while working on this new methodology, besides the already mentioned difficulty in detecting active faults on the surface of tectonically complex areas, further inconveniences also arose connected with the above mentioned fault/magnitude relationships, and above all, with the way they are usually adopted world-wide.

The most important of these inconveniences are listed here below:

a) The *extremely conclusive role given by the fault/magnitude relationships* to the presence or lack of active faults at the ground surface: as will be better seen later, there are several other geological-geophysical aspects which can be profitably utilised for arriving at an evaluation of the seismotectonic conditions in a specific area. Therefore, concentrating primarily on the detection of any surface appearance of active faults may lead to erroneous conclusions. Moreover this can limit the search for seismogenic structures, whenever blind faults exist in the subsurface (see the following).

b) The *high standard of professional expertise* required to establish whether or not a fault is active, and to ascertain how large a part of it may rupture while producing the maximum potential earthquake: it is all but easy to assess, according to the USNRC definition, whether a fault produced motions, taking into account also the need for reliable dating methods and of samples which permit their application. Thus this work often requires the intervention of top-level specialists who are forced, every now and then, to resort to their professional judgement; this is especially so when there is the need to establish whether the supposed active fault will move over its full length or only partially, and, if the latter, which section of the fault will produce the potential earthquake forecast by the relationships.

c) The *uncertainty in transposing the fault/magnitude relationships* to situations often differing from those which generated them, when referring to tectonic features: some authors (see e.g. Bonilla et al., 1984) have faced this problem and, starting from a very scattered data set for several of the world's tectonic provinces (see Fig. 1), worked out a series of relationships dividing the fault types according to the particular tectonic settings. In this way they managed to strongly reduce the data scattering: a praiseworthy but not conclusive operation, since earthquakes produced by different types and values of stress acting on lithotypes with different shear strengths may easily co-exist in the same tectonic province. The reliability of some of the straight regression lines may thus be rated as poor, in cases where they originate either from a limited number of samples or from very scattered values.

In one very recent paper (Wells and Coppersmith, 1994) an appreciable effort has been made in improving the transposibility of the new empirical fault/magnitude relationships presented in it by utilizing source parameters from historical earthquakes world-wide. It is easily seen that about one third of the data comes from the Californian tectonic setting. This ratio increase up to one half of the total if we also consider earthquakes from areas of Turkey and China having a tectonic setting dominated by transcurrent faults and thus very similar to the Californian one. This is not surprising if we take into account the fact that in tectonic settings where most of the faults are of the strike-slip type it is quite easy to find surface elements related to active faults. The Authors confirm such an opinion, candidly declaring that in their database earthquakes associated with subduction zones are excluded.

It is worth while noting that one of the existing fault/magnitude relationships and the 1,100 km long *subduction* fault at the boundary between the Gorda-Juan De Fuca Plates and the North American Plate was used to predict that in the near future an enormous earthquake of M=9 or greater could hit the Oregon coastal area (Wuethrich, 1994).

d) The *little attention given to the basic parameters* required in geomechanics for a correct evaluation of the seismic potential in a tectonic structure, such as:

- the maximum depth where the rocks involved in active tectonic processes remain in a brittle condition (or where the deepest brittle/ductile transition is); this depth can vary greatly from site to site, depending on the nature of the rocks, on their temperature and on the tectonic strain rate to which they are exposed;

- the frictional strength along a fault plane (of course only for rocks in a brittle regime): this strength varies greatly with depth (and sometimes also appreciably in a horizontal direction, in the case of crooked faults), depending on the normal stress across the fault, and on the friction

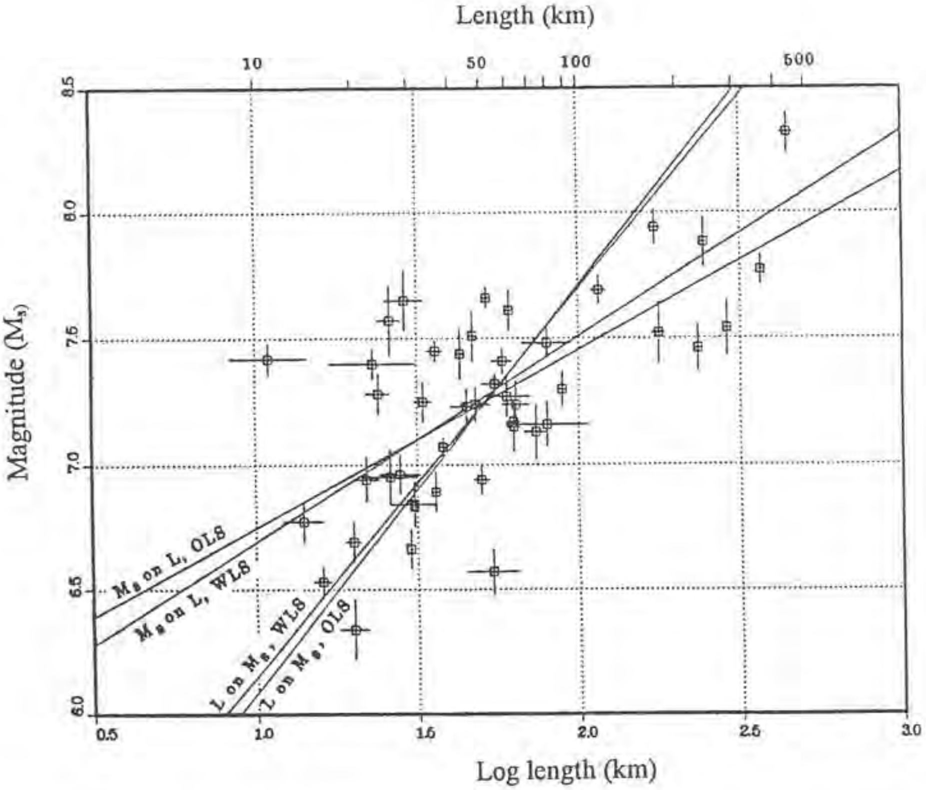


Fig. 1 - Length of surface rupture versus surface-wave magnitude (after Bonilla et al., 1984). M_s on L = regression of magnitude on log length; L on M_s = regression of log length on magnitude; OLS = ordinary least squares; WLS = weighted least squares. Error bars are shown for each event.

coefficient present in the various sectors of the fault itself; and these require knowledge of:

- the entire geometry of a fault, and not only of its expression at the ground surface;
- the frictional coefficient of the rocks crossed by the fault;
- the lithostatic load;
- the tectonic stress;
- the fluid pressure across the fault plane.

e) The *association of the potential earthquake with a point on the emergent part of the fault* or on its vertical: this operation, which should be considered completely incorrect, is at present carried out every time a map of earthquake epicenters is superimposed over a geological map showing the location of the faults (anybody interested in seismotectonics must have done it or seen it being done at least once); it can be particularly grave, since it may lead to erroneous conclusions, especially when possible relationships between ground surface evidence of non-vertical faults (as in the case of listric faults or of thrust detachment surfaces) and deep earthquakes are being evaluated (see the following).

This mistake, rating among the most frequent, is evidenced in Fig. 2, where two faults of the above mentioned type are shown: one traceable in areas characterized by extensional-type tectonics and the other in areas affected by compressive tectonics. From the two examples given in this figure, an attempt was made to check the position of the characteristic sites of the two faults, where it is presumed the conditions of highest frictional strength would be attained: that is, where the maximum amount of energy would accumulate under elastic strain, and then where it would be released in the form of a maximum (future) seismic event. Note that the sole aim of the conclusions given in the figure is to generalise the problem (the assumption that the friction coefficient does not vary along the fault surface is very over-simplified), but it is possible to carry out more accurate evaluations in a real case: see Cocco and Rovelli (1989) for the computational approach.

What clearly emerges from Fig. 2 is that the more risky areas occur where the faults reach their maximum depth (in case of normal faults) or immediately before reaching it (in case of thrust or reverse faults), even if the magnitudes of the tectonic forces acting cannot be assessed with the same accuracy as can the loads on the rocks involved. It follows that the epicentral zone of the heaviest earthquake due to a fault of this type is distant from the zone where the effects at the surface of this fault could be detected (i.e., the fault rupture at the ground surface required by the existing fault/magnitude relationships): as Fig. 2 shows, this distance can be at least equal to the depth reached by the fault surface or, possibly, to the hypocentral depth of the heaviest events associated with it (in the cases shown the rocks traversed by the faults are assumed to remain in a brittle condition also at the maximum depth).

f) The *false sense of security given to experts by the fault/magnitude method*, and in particular by a certain way of applying it, especially if, when working in areas with an incomplete seismic history and where cover hides stiffly faulted basements, they do not use deep data (from geophysics and deep wells). In fact, if active faults are not detected, simply because they are masked by the cover, very disastrous consequences could follow a wrong seismic hazard assessment (see also the following).

Jones et al. (1994) describing the tectonic setting of the the M 6.7 Northridge, California, earthquake of 17 January 1994, say that "... *Because no one fault dominates the Big Bend Compressional Zone, hazard mitigation efforts that focus on avoiding one or a few fault structures are not appropriate. With scores of faults, each moving no more frequently than once or twice a millennium, the approach to mitigation must be regionally based. The most active fault need not, and probably will not, be the fault that ruptures in our lifetime...*".

Note that a regional approach to seismotectonics it is just what ENEL has been doing since the beginning of the '80s in siting electric power plants.

See the following for the scheme that, following the seismotectonic methodology proposed in the present paper, has been drawn to explain the mechanical reasons for the Big Bend Compressional Zone (the bend in the San Andreas fault, just north of Los Angeles).

APPLICABILITY OF THE EXISTING FAULT/MAGNITUDE RELATIONSHIPS

Opinions on the applicability

The San Andreas fault structural system

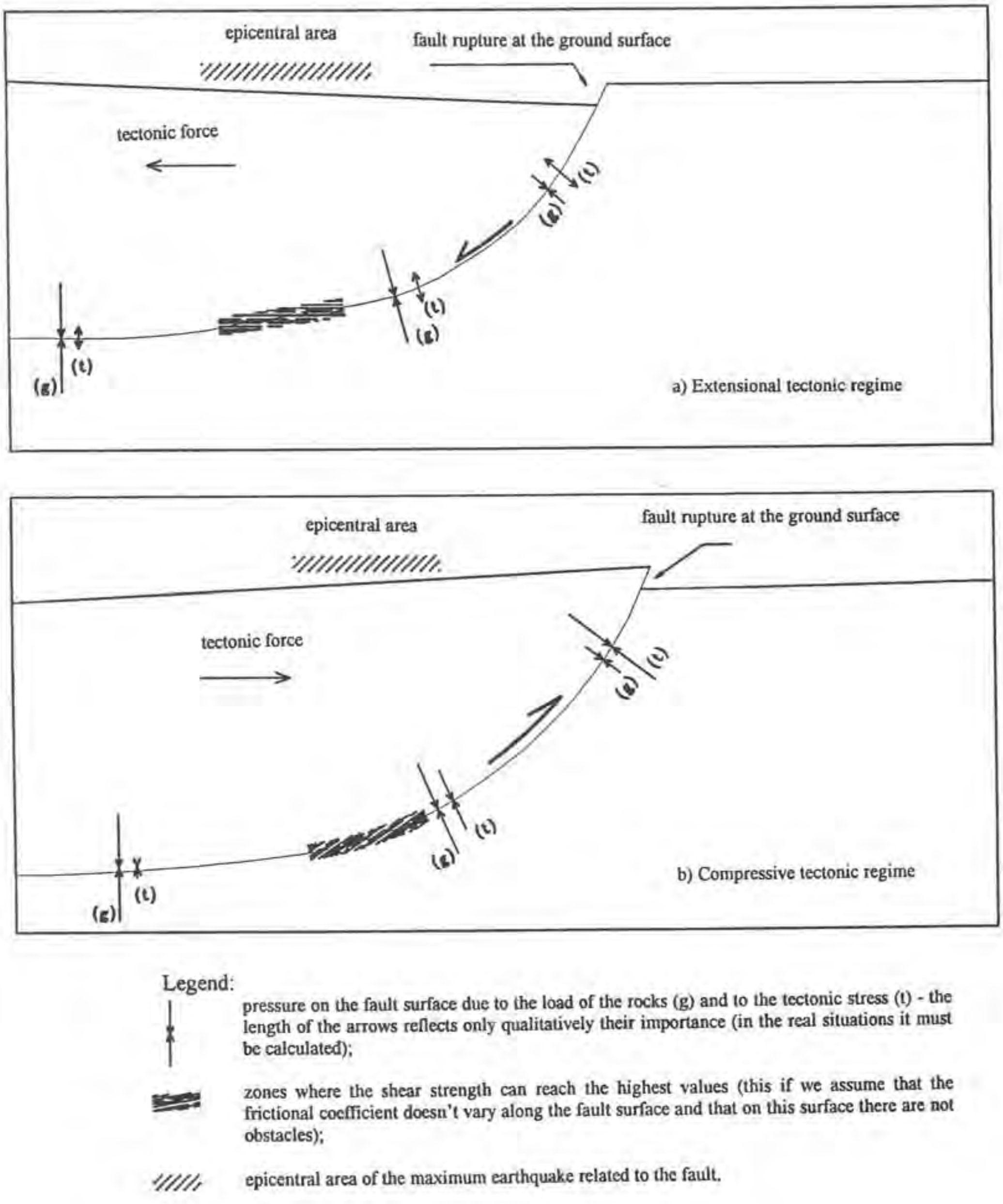
The large number of studies carried out by various scientists on the most famous fault in the world, the San Andreas Fault (California), have contributed decisively to neotectonics, seismology, seismotectonis, and engineering seismology. The results of these studies have been widely applied throughout the world:

(a) for seismic potential evaluation of tectonic structures (in defining position, size and potentiality of natural seismic sources);

(b) for seismic hazard analyses (in determining the ground effects, for engineering purposes, induced in sites or areas of interest by earthquakes generated in the defined natural seismic sources);

(c) for seismic risk analyses (probability of adverse consequences to buildings and human beings induced by earthquakes).

But very careful attention must be paid when applying fault/magnitude relationships derived from the specific Californian seismotectonic setting (Boschi et al., 1994). Sibson (1991), referring to the USGS Professional Paper 1515 titled "The San Andreas fault system, California", recalled in fact some notions about the San Andreas fault which are generally accepted uncritically:



Legend:

pressure on the fault surface due to the load of the rocks (g) and to the tectonic stress (t) - the length of the arrows reflects only qualitatively their importance (in the real situations it must be calculated);

▬ zones where the shear strength can reach the highest values (this if we assume that the frictional coefficient doesn't vary along the fault surface and that on this surface there are not obstacles);

//// epicentral area of the maximum earthquake related to the fault.

Fig. 2 - Fault zones where the shear strength can reach the highest value.

- the imperfect and atypical nature of the San Andreas tranform fault, which has no equal the world over, if only for the width of its deformation;

- the fact of it not being the only structural element in the area: the boundary between the Pacific and North American plates is not defined by a single fault, but by a complex fault system a hundred or so kilometres wide, in which the San Andreas fault accomodates only a part of the total plate boundary motion;

- the presence of mountains 3 ÷ 4 km high in an area generally considered to be characterized only by strike-slip tectonics (local irregularities in strike-slip systems transfer lateral by into vertical motion).

Earthquakes without surface faulting near the San Andreas fault

Stein and King (1984) studied the Coalinga 1983 earthquake of M=6.5, which occurred along the Anticline ridge (a structure running parallel to the San Andreas fault), and suggested that it was caused by the propagation of a "blind" thrust fault inside the nucleus of the anticline itself (see Fig. 3). The main reason why the authors resort to this explanation is that on the surface, corresponding to the earthquake concerned, which in their opinion "*was a shock to California*", no related active fault was detected. A deformation was spotted on the ground only, as revealed by a surface uprising of 75 cm and displacement in the direction of the thrust: but these elements could hardly be utilised for evaluating the seismic potential of the structure involved in the deformation by means of an over-simplified use of the existing fault-length/magnitude relationships[2].

In a recent paper (Bloch et al., 1993) the SE prosecutions of the Coalinga anticline, the Kettleman Hills and Lost Hills anticlines, have been studied. On these active tectonic structures, besides the aforesaid Coalinga 1983 (M=6.5) earthquake, other damaging seismic events have been localized, such as the New Idria 1982 (M=5.5) and Kettleman Hills North Dome 1985 (M=6.1) ones. The conclusion of the Authors was: *"it is clear that the seismic hazard is not confined to the San Andreas fault, but extends to the eastern limit of the deformed belt adjacent to that fault" (about 30 km distant)*. But along this belt, no ground surface evidence of fractures has been discovered until now, and the three earthquakes were related by Stein and Ekström (1992) to slips on blind thrust faults at depths of 9.7 to 14 km.

The same recently happened near Los Angeles for the Northridge 1994 (M=6.7) earthquake, which (see Davis and Namson, 1994) occurred along a fault that did not reach the surface and which had not been detected by traditional hazard methods (see also the quote from Jones et al., 1994 already cited).

These examples can be seen as a confirmation of the correctness of ENEL's decision in the early 1980s to revise the existing methodology using the length (or other characteristics) of the faults at the ground surface, and the surface-wave magnitude of the maximum related earthquake for defining the SSE acceleration when locating nuclear power plants.

At this stage it is advisable to compare Figs. 3 and 2 case a, to check the coincidence between the Coalinga fault setting, where the main event took place, and that supposed to hold the highest frictional strength of a hypothetic thrust. It should be also noted that, in order to reach their conclusion, Stein and King (1984) used a series of seismologic, geologic and geophysical data to assess that the fault acted down to 6-7 km from the ground surface, roughly the same as was done by Bloch et al. (1993) to understand the kinematic behaviour of the Pyramid Hills and Kettleman Hills South Dome.

But the rational exploitation of such a huge amount of data in seismotectonics, more than the mere application of the said relationships to the outline of the fault, is exactly what ENEL did to the seismic parameters for planning in its reports of 1983 and 1984 on siting nuclear power plants in the Po Plain, Italy. The decisive role played by ENEA-DISP (the Italian Nuclear Regulatory Authority) should also be recalled: its experts checked the siting operations and shared the opinion that little assurance could be offered by the methodologies correlating only superficial evidence of a fault to its seismic potential, when applied to the complex tectonics in Italy (where Coalinga-like situations are very frequent). Thus, the ENEA-DISP experts approved the approach philosophy chosen by ENEL as an alternative method for obtaining the seismic hazard[3]: this was also recalled by Serva (1990).

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(2) This episode is probably the main reason for which the USNRC regulations were modified in 1992, replacing the pre-exiting definition "capable fault" with the more realistic new one "capable tectonic soource" (see also previous footnote 1).

(3) The method is also suggested by IAEA regulations that, starting in 1990 (IAEA, 2-4 April 1990: Earthquake and associated topics in relation to nuclear power plant siting - A NSSU Safety Guide, Revision 1), adds the possibility of utilizing for the evaluation of the seismic potential of a site a methodology similar to that shown in the present paper. Moreover, IAEA reported NEL to include the Author of the present note in the list of experts detailed to examine seismotectonic reports for siting nuclear power plants.

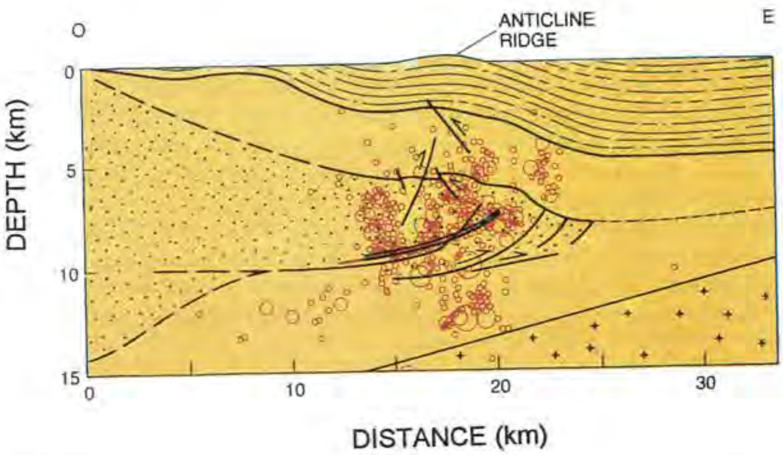


Fig. 3 - Structural setting of Coalinga anticline and location of 1983 (M 6.5) earthquake (main circle) and its aftershocks (after Stein and King, 1984).

The external thrusts of the Himalayan chain: clear evidence of the non-applicability of fault/magnitude relationships in seismic hazard assessment if only surficial data are considered

It appears evident from the examples given that if seismotectonics is practiced using uncritically the scientific results of studies done in the San Andreas fault area, there is the risk of overlooking its atypicality, or the seismotectonic peculiarities of the studied site. Thus, particular attention must be paid when using one of the fault/magnitude or acceleration/distance relationships available in literature, in which the starting data come essentially from the Californian tectonic environment.

Moreover it should be pointed out that if seismic forecasting is difficult in California, certainly one of the most surveyed region in the world from that point of view, as the faults appear on the ground surface with striking evidence, the task becomes even more hazardous if the above mentioned relationships are applied in areas where less information is available and/or where "plastic" materials (flysch, for instance) cover rigid basements, masking the state of tectonization of the deep rocks.

Supposing, however, that an optimal fault/magnitude relationship is available, especially worked out for the tectonic situation under survey, and that the position on the ground of the active fault has been exactly detected, there is still the need (1) to define how large a part of it may move during an earthquake, and (2) to choose the type of method most suitable for assessing the point on the fault where the potential earthquake could be released. The scheme in Fig. 2 shows the importance that this operation be carried out with extreme care, particularly if only the ground surface outline of the fault is available for plotting.

As said before, it is more frequent than may be expected to see the pattern of more - or - less active faults being laid on maps showing the distribution of earthquakes in a surveyed area: on the other hand, the existing fault/magnitude relationships have for years been applied almost in this way. In these cases it would be more profitable to gather in advance more complete information about the deep geometry of the fault and about its behaviour with regard to the depth of the frictional strength of the rocks under strain, unless extremely cautious procedures be decided due to the lack of reliable data.

An example is the episode which took place a few years ago in Pakistan, where ISMES (part of ENEL group) was charged with the task of doing the seimic assessment of a nuclear power plant located 3-400 km SW of Islamabad (the Chashma site). The power plant was considered to be in an extremely hazardous environment, from the seismotectonic point of view, since it was planned only a few kilometres from the front of the external thrusts of the Himalayan chain overlapping the Indian plate. Since these thrusts are certainly active tectonically and extremely long, applying one of the existing fault/magnitude relationships to the surficial fault underlining their front would give an overvaluation of its seismic potential, and severe doubts would remain as to the point in which the maximum earthquake should be applied. Unrealistic evaluations would arise by assigning a potential similar to that known for the Main Boundary zone of the Himalayan chain (more than 200 km away) to an area historically of low seismicity. One solution was to suppose that only part of the fault detected would rupture in the case of earthquake release, but this required a lot of professional judgement. Fortunately a commission of international experts from IAEA was called in to revise the seismic evaluations for the Chashma site. After a very thorough examination of the available data and documents, the IAEA experts chose, from among those put forward by other authorities, the seismotectonic scheme proposed by ISMES (and drawn up by the author of this paper), where the front of the external thrusts was considered seismotectonically insignificant.

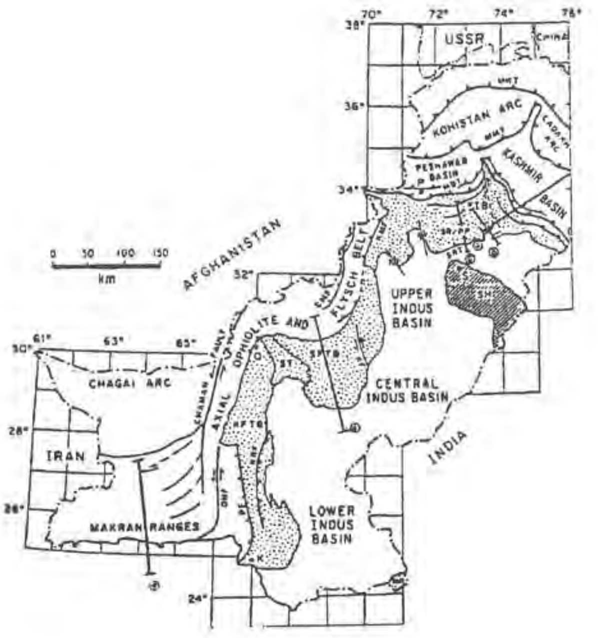
In fact it was a great oversight to consider the surface outline of this type of fault as being responsible for producing potential earthquakes of a magnitude close to 8, considering also that the thrust involved has the greater part of its detachment surface (sole thrust) dipping towards the Himalayan chain, with an inclination of a few degrees. Such a geometry, detected from seismic reflection profiles and drilling for oil exploration (see section Fig. 4c, after Yeats and Lillie, 1991) implies that values of confinement sufficiently high to increase the frictional strength necessary to accumulate the energy to be later released in the form of earthquakes can be obtained only in positions well back (even by hundreds of km) from the frontal emergence of the sole thrust (the confinement of the fault is mainly due to the pressure of the rocks, thus it increases with depth).

No doubt conclusive for the formation of a thrust with a detachment surface having so small an inclination was the presence of materials with very low resistance. The thrust gave birth to the hills called the Salt Range, and obviously shows only a sporadic low level of seismicity along its full extent. In fact (see Yeats and Lillie, 1991) the thrust forming the Salt Range has along its entire detachment surface a thick layer of halite, a salt (similar to that used in cooking) which provides an effective lubricating action, thus allowing the Salt Range to move forward over the Indian Plate (acting as the geological foreland of the thrusts) with negligible inclination.

Such a mechanism is all but rare in the area of the entire Pakistan foreland thrust belts (the Iranian Makran belts included, see again Fig. 4) where the detachment surfaces are always gently dipping; note also the position of the earthquakes (solid circles) in Fig 4e) with respect to the deformation front DF of the thrust and, above all, their distance from it of roughly 100 km.

At this point it is necessary to make the following observation: in a seismotectonic environment characterized by intense and deep plate indentation, as in the Himalayan region, inspection of only the outline on the ground of the thrust detachment surfaces, as is done when applying in a very over-simplified manner the methodology based on fault/magnitude relationships, frankly seemed to us insufficient for evaluating the seismic hazard in the area. The ISMES report, in fact, faced also a more relevant problem in the Indian Plate, where there is a rearrangement of the stress conditions of the Indian lithosphere. At present the latter, before being subducted under the Himalayan Range system, is forced to bend, forming possible weakness bundles, with faults sometimes even crossing the entire lithosphere. This flexure, which is present in the near foreland of the Himalayan frontal thrusts, increases towards the Himalayan chain and generates a peripheral bulge, a long-wave regional structure due to the deformation (build-up of strain) of the lithosphere, in the middle of the Indian Plate. The consequent accumulation of elastic energy is then able to generate significant earthquakes throughout the deformed plate (more frequently near the Himalayan chain, but also unfortunately very far from it: see for instance the recent disastrous earthquake of 29th Sept. 1993 in Latur, central India).

It is easy to see that this is one of the cases where the use of a methodology requiring the search for active faults from only surface evidence may even become misleading, and produce inexistent danger signals, while ignoring at the same time the real ones just mentioned: on the other hand, it is practically impossible to detect possible discontinuities in the basement of the Indian Plate continental lithosphere, where it is covered by recent alluvial sediments, without the aid of geophysics; this in particularly so if the rivers are very active and extend their alluvial



Generalized tectonic map of Pakistan and positions of cross-sections (a)-(e) portrayed on the right. CMF = Chukhan Manda Fault, IB = Islamabad, K = Karachi, KF = Kingri Fault, KFTB = Kirthar foreland fold-and-thrust belt, KMF = Kurram Fault, KRF = Kirthar Fault, NR = Nagarparkar ridge, ONF = Ornach Nal Fault, P = peshawar, PF = Pab Fault, Q = Quetta, S = Sangodha, SFTB = Sulaiman foreland fold-and-thrust belt, SH = Sargodha basement high, SR/RP = Salt Range-Potwar Plateau, SRT = Salt Range Thrust, ST = Sibi trough.

Look at section c) and try to evaluate the distance of the point where the thrust crosses the ground surface from the highly deformed zone left of Soan Syncline; see in section e) the distance of the same point from the seismic zone in the middle of the section.

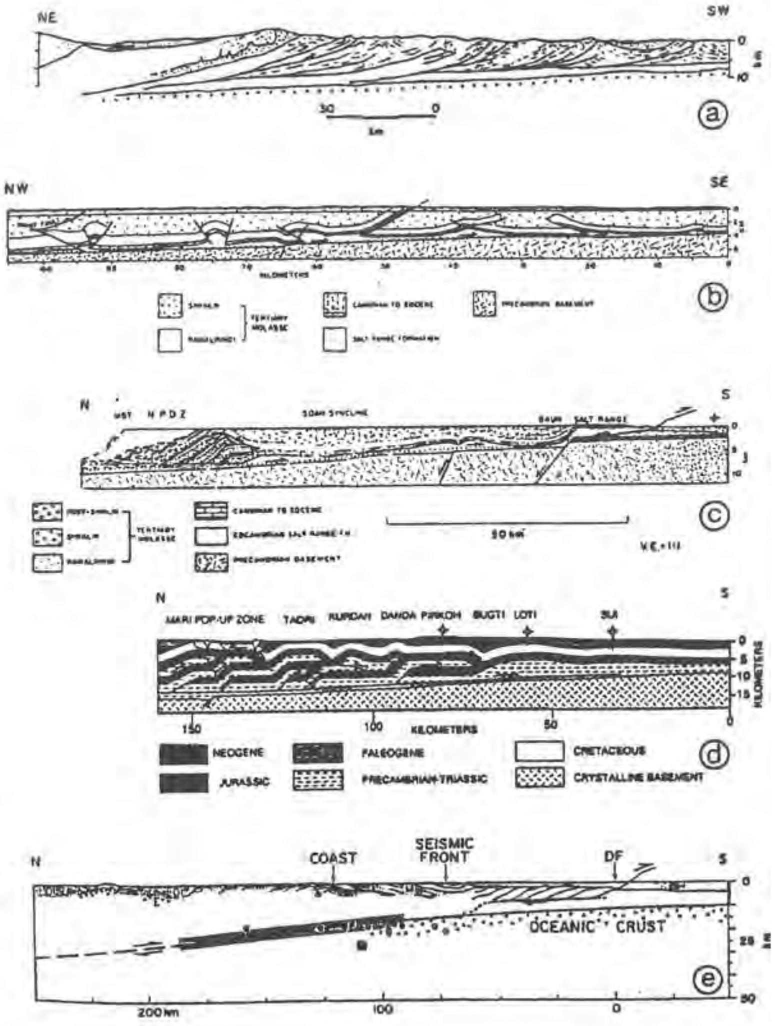


Fig. 4 - Active foreland thrust belts (stippled on the map) in Pakistan (after Yeats and Lillie, 1994, modified) characterized by very gently dipping detachment surfaces.

beds over large areas, as the Indus River does in the Punjab Plain.

The IAEA Commission therefore took the correct decision in considering the ISMES report as the reference one for the Chashma site and, with this experience, also included in the new IAEA regulatory guide a seismotectonic methodology similar to that used by ENEL and considered as equally conclusive as that based on the fault/magnitude relationships (see footnote n. 3).

Particularly from experiences of this type, ENEL made the decision to take part as promoters and financiers in the Italian CROP Project, a project of a wide scientific significance jointly being carried out with CNR (Italian National Research Council) and AGIP (Italian National Oil Company), and involving the entire Italian territory and surrounding seas. From a network of very deep seismic reflection profiles, information is expected on the geological and structural setting of the entire crust (and at least partially of the lithospheric mantle). This should give a better understanding of the mechanisms inducing seismic events in Italy.

CHARACTERISTIC STEPS IN THE METHODOLOGY HERE PROPOSED

Aims

As described before, the need for a methodology which eliminates the setbacks and difficulties in applying the existing fault/magnitude relationships in tectonically complex areas forced ENEL to start a series of suitable surveys for that purpose. The methodology arrived at is particularly suitable for application in areas where the cover is of considerable thickness and likely to hide the actual kinematics of the underlying rigid basement where normally the most dangerous earthquakes are generated. Experience in Italy and other countries of the Alpine Orogenic Belt (running from the Gibraltar Strait to the above mentioned Himalayan Range) would suggests its application in all the orogenically complex areas of the world as well.

Methodological approach

In the seismotectonic methodology presented here, the search for superficial evidence of active faults is considered only one of the elements (one of the most important, but not necessarily conclusive) concurring in the definition of an overall seismotectonic model for the studied site. In this methodology considerable importance is given to the definition of:

- the tectonic structures (in three dimension) of the seismotectonically relevant area;
- a kinematic-evolutive model for these structures;
- the strength of the rocks involved in active deformation;
- the space distribution of seismicity;
- an *overall seismotectonic model* which explains all the main geological, geophysical and seismological characteristics of the area;
- the most relevant seismogenic structures and their maximum potential (future) earthquake;
- the seismic ground motion induced in a site by such an earthquake.

Description of the basic steps

a) The **1st** step for arriving at a definition of the seismic hazard according to the present methodology is *to locate the seismotectonically relevant area and to define its geological structural setting.*

This area should include all the geological bodies which allow us to understand both kinematically and seismologically the seismotectonic characteristics of interest for the studied site. The extent of such an area can easily be defined by means of tectonic and seismological maps at a scale of 1:1,000,000 or less; its boundaries should be marked by known or seismotectonically insignificant structures for the site seismic phenomena.

The geological and structural characteristics (lithology and geometry) of the geological bodies present in the relevant area should be extended at least down to the maximum focal depths reached by local earthquakes. Each geological body, to define it in three dimensions, will normally be more and more detailed as the studied site or the main tectonic structures or seismic sources are approached. To achieve these goals, besides good geological maps at different scales, deep geophysical surveys and data from wells will be necessary.

b) The **2nd** step is *to define a kinematic-evolutive model of the geological bodies present in the relevant area.*

In this phase the neotectonic elements detected should be organically inserted into an overall kinematic model providing the necessary link between the last tectonic phase and the evolution of the current tectonics. Significant help in this phase can be obtained from a joint analysis of all signs left on the ground surface by the seismic activity, and of neotectonic, geological and high resolution geophysical maps (as in oil exploration, where it works extremely well to locate the geological structures of interest, decisive information can be derived from a correct interpretation of seismic reflection profiles).

In this way the kinematic evolution of each relevant structure can be drawn, and an evaluation of the slip-rate of the main faults or the strain rate of the more complex structures can be made, as is required for step f).

The ultimate aim of this step, which is strongly recommended because it constitutes one of the most powerful tools available today for obtaining a reliable seismotectonic study, is to detect the kinematics acting in the relevant structures (generally their importance depends mainly on their dimensions and on the distance from the area) and then, whenever possibile, the direction and speed of each structure undergoing a tectonic event must be defined.

Particular attention must be also devoted to locating the presence and establishing the importance of any bodies acting as obstacles to the motions of these structures. It has to be remembered that if there are no obstacles to obstruct the motion of a fault, no elastic energy (related to the elastic build-up of strain in the rocks) can accumulate and, consequently, no earthquakes are released by the tectonic structure. Thus, locating an active fault is not sufficient to establish the seismic potential of the fault itself; it should be noted by the experts who normally apply the existing fault/magnitude relationships (that, the present, relate more properly the ruptures at the ground surface to the magnitude).

c) the **3rd** step is *to assess the thickness and maximum depth of the brittle lithospheric layers under strain.*

Remembering that almost all known earthquakes derive from a sudden release of energy accumulated in elastic build-up of strain in the rocks, this step is very important to establish the extent of the brittle regime in the studied area. If we agree that the largest earthquakes should be located very close to the deepest brittle/ductile transition in the crust, making an effort to evaluate the depth of such a transition will give us an upper boundary evaluation of the maximum potential (future) earthquake, when assessing the seismic hazard of the area. To achieve this, formulas of the following type, describing the strength of the rocks at various depths, can usefully be applied:

$$\sigma_1 - \sigma_3 = \beta \varrho g z \, (1 - \lambda). \tag{1}$$

$$\sigma_1 - \sigma_3 = (\dot{\varepsilon}/A)^{1/n} \exp \, (Q/RTn). \tag{2}$$

The first, given by Ranalli and Murphy (1987), who modified a previous relationship reported in Sibson (1974), describes the brittle behaviour of the rocks; the second, provided by Weertman and Weertman (1975), the ductile one.

The meaning of the symbols used is the following:

$\sigma_1 - \sigma_3 =$ deviatoric stress in MPa (100 MPa=1kbar);

$\beta =$ coefficient taking values of 0.75, 1.2 or 3.0 according to whether we are dealing with a normal, transcurrent or inverse fault, respectively (4);

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(4) This is mainly a friction coefficient which helps to check the influence of the normal pressure on a fault plane, due to the different types of tectonic force acting on it, according to whether an extensional, transcurrent or compressive regime is deforming the structure (see also Fig. 2).

ϱ= rock density ($g \cdot cm^{-3}$);

g= gravity acceleration (9.81 $m \cdot s^{-2}$);

z= depth (km);

λ= parameter accounting for the possible presence of circulating fluids (for $\varrho=2.75$ $g \cdot cm^{-3}$, $\lambda=0.36$);

$\dot{\epsilon}$= strain rate (which ranges from 10^{-12} to 10^{-15} s^{-1} when passing from tectonically very active areas to low active ones);

A = constant of the material (having a minimum for dry granites, of about 0.000002, and maximum for dunite of over 30,000);

n = constant of the material (having a minimum for granites and limestones, of about 1.8, and maximum for dunite of over 3.5);

Q = activation energy ($kJ \cdot mol^{-1}$) of the different creep processes (sliding through grains, intercrystalline or through atoms);

R = universal gas constant (8.31441 $J \cdot {}^{\circ}K^{-1} mol^{-1}$);

T = absolute temperature in °K.

From a combination of the previous eqns. (1) and (2) it is thus possible to know at which depth a rock remains under brittle conditions.

Note that applying this type of formula has particular relevance for explaining the seismic behaviour of those areas of high strain rate or high heat flow density; for similar regional tectonic stresses, in the first (second) case it will probably have higher (lower) seismic activity than normal.

d) The **4th** step is *to define a seismological picture of the seismotectonically relevant area.*

This step, which can start immediately after the first, is aimed at collecting as complete as possibile a seismological catalogue of the area; in this phase a revision of the historical sources should be carried out to get information on the positions and intensities of past seismic events; for instrumental earthquakes, besides the magnitude, their good hypocentral determination, and where possible their focal mechanisms (or other physical properties), should also be provided.

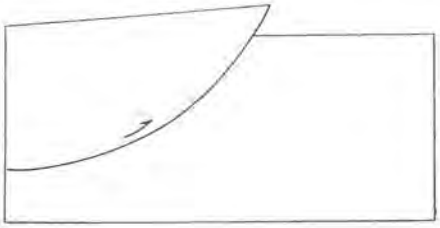
e) In the **5th** step *an **overall seismotectonic model** capable of explaining all the main geological, geophysical and seismological characteristics of the area* has to be created.

In this step, the most important and innovative of the methodology here discussed, a critical revision and synthesis of the most useful geological, geophysical and seismological information gathered so far for the relevant area defined as in step a), has to be made. To proceed to the outline of an ***overall seismotectonic model***, the geological-structural setting, the kinematic-evolutive model, the strength of the rocks involved in the deformations and the seismological layout must be considered together.

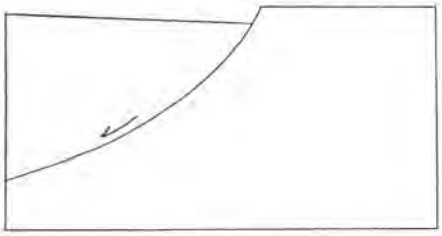
Since despite efforts to collect all possible data, a certain amount will still be lacking (due to the complexity of the seismotectonic phenomenon), the aim of the ***overall seismotectonic model*** is to complete each data set. So, active tectonic structures will show us where the seismological catalogue is incomplete and vice versa; tectonic structures with different strain rates and/or under very different thermal conditions will explain possible anomalous behaviours in the seismic pattern of the region; changes in the orientation of a tectonic structure (fault) with respect to the tectonic stress acting on it will indicate if part of the structure is only at the moment seismically silent or is undergoing creep; relevant clusters of known seismic events will require deeper geological studies, if the tectonic/rheological data are not sufficient to explain them; an so on.

In this step it is strongly advised to model the area under investigation with one of the existing mechanical programs (at present there are good programs also available for personal computers); in this way a scheme for the stress pattern can be obtained and the most relevant zones (the most stressed), detected and checked against the known distribution of active tectonic structures and seismological sources.

GROUP 1 (SINGLE FAULTS)

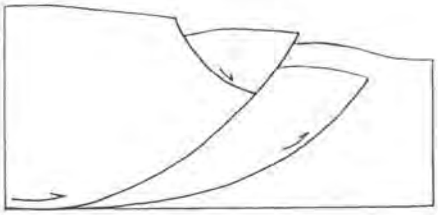


type a: reverse

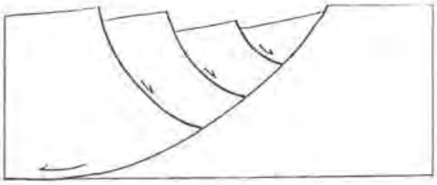


type b: normal

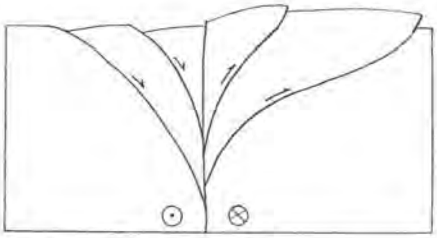
GROUP 2 (DEFORMATION ZONES)



type a: compressive



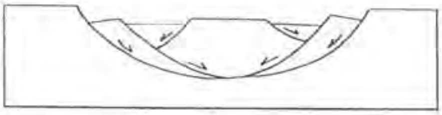
type b: extensional



type c: transform

GROUP 3 (COMPLEX STRUCTURES)

type a: mainly compressive



type b: mainly extensional

Fig. 5 - Proposed main categories of tectonic structures to be considered as reference in a WSSDB (World Seismogenic Structures Data Bank).

f) In the **6th** step *the most relevant seismogenic structures* are to be defined.

On the basis of the results of the previous steps, all the relevant seismogenic structures can at this point be detected in three dimensions; each seismogenic structure can be defined by a single fault or by fault bundles (the most frequent condition met) and/or by complex structures where coalescent faults alternate with slices of less deformed rocks.

Each seismogenic structure should be characterized by:

I - position and distance from the site of interest;

II - geometry (in three-dimensions including, of course, its depth); for this purpose it has to refer to one of the following categories related to the examples drawn in Fig. 5:

Group 1) single faults (type a or type b; respectively reverse or normal fault);

Group 2) deformation zones (type a, type b or type c; mainly formed by respectively reverse, normal or strike-slip faulted bundles);

Group 3) complex structures (type a or type b; respectively related to wide compressional or extensional zones);

(for all the Groups the presence and the position of any detected fault ruptures at the ground surface and/or landslides must be clearly evidenced and classified);

III - nature and meso-structural features at various depths of the rocks forming, or immediately surrounding, each of the seismogenic structure above indicated;

IV - kinematic; depending on the type of seismogenic structure considered, this must give (see again Fig. 5):

for structures of Group 1 (a or b types) the slip rate of the fault or, whenever possible, the slip during each earthquake (data on silent slip must be reported if available) and/or the slip trend over the last few million years;

for structures of Group 2 (a or b types) the strain rate of the whole faulted bundle under deformation or the slip rate of the main (master) faults of the bundle and/or the slip trend over the last few million years;

for structures of Group 2 (c type) the maximum uplift rate of the central flower shaped part of the structure, the maximum rate of the whole strike slip and/or the trend of these two rates over the last few million years;

for complex tectonic structures:

- (type a structure) the maximum uplift rate of the main thrust, the maximum lowering rate of the lower plate and the maximum movement rate towards the foreland of the external front and/or the trend of these three rates over the last few million years;

- (type b structure) the maximum lowering rate of the central portion of the graben, the widening rate of the entire extensional structure and/or the trend of these two rates over the last few million years;

V - frictional strength of the rocks forming the seismogenic structure; from eqns. (1) and (2) reported in the previous step c), the range of the brittle and/or ductile conditions will be drawn. Thus, for brittle rocks, the simple empirical shear failure criterion of Coulomb can be applied to a pre-existing fault:

$$\tau_f = C + \mu\ (\sigma_n - P_f), \tag{3}$$

where

τ_f is the frictional strength on the fault plane;

C is the cohesive or cementation strength;

μ is the static friction coefficient;

σ_n is the normal stress across the fault plane;

P_f is the fluid pressure in the rock mass.

The same equation can be used (Sibson, 1990) to evaluate the behaviour of an intact material (unbroken rock); in such a case:

τ_f becomes the shear failure strength of the intact rock;

C becomes the intact cohesive strength of the rock;

μ becomes the internal friction coefficient (Anderson, 1951).

The values of the static friction coefficient range from 0.6 to 0.85 (Byerlee, 1978), and those of the internal friction coefficient range for most rocks from 0.5 to 1.0 (Jaeger and Cook, 1979).

As can easily be observed from eqn. (3), the shear strength of most rocks strongly depends on the value of the stress across the fault (or the shear failure plane in the case of intact rocks), and therefore faults having similar lengths (or, more correctly, similar rupture areas) can give very different seismic release. As aforesaid in Fig. 2 it is possible to see the points where the normal components to the fault surface of the tectonic stress and of the lithostatic load give their maximum, and where the frictional strength will probably reach its highest values. Extremely low values of the frictional coefficient (as in the case of salt rocks) or the presence of significant fluid pressure, can strongly reduce these frictional strength values.

(Note that this is not in accord with the current fault-length/magnitude relationships widely used in seismotectonics, which don't allow parameters other than one dimension of the fault);

VI - association with the seismogenic structure of all the earthquakes coming from step d) believed to pertain to it (on the basis of the location, focal mechanisms, energy, etc); in this step geological cross-sections will allow the researcher to match the tectonic features with the seismological evidence (it will be useful, for this scope, to draw the earthquakes as a function of their intensity or magnitude and of their focal mechanism). Doing this, and comparing with similar and/or near by seismogenic structures, it should be possible to understand the most significant relationships between tectonics and seismicity in the studied area;

VII - collection of the accelerograms, if available, recorded as a consequence of any earthquakes released by the seismogenic structure. Each accelerogram will be characterized by:

- the type of recording instrument;
- the distance of the instrument from the seismic source;
- the geological structure (even in a schematic manner) crossed by the seismic waves in their radiation from the focus to the recording point;
- the geomorphological and geothecnical setting at the recording point:

g) In the **7th** step *the maximum potential earthquake has to be assigned to each detected seismogenic structure.*

Each seismogenic structure should be given the value of the maximum earthquake related to it, and the point where the seismic release has the greatest chance of happening should also be defined; the method for obtaining this, having defined all the significant geological and geophysical parameters in a seismogenic structure, is comparison with other known world situations presenting similar characteristics (that is, the procedure will be done using a philosophy similar to that inspiring the pre-existing fault/magnitude relationships, but using a specific relationship for each of the detected structures, and considering the whole set of significant parameters described in the previous step f); among the structures having similar characteristics from the point of view mentioned above, the maximum earthquake recorded (for historic events attention must be given to the existing difficulties in relating intensity/magnitude) will be considered as the maximum potential (future) earthquake to relate to our seismogenic structure: it is easy to understand that the greater the number of similar structures found around the world, the better the reliability of the forecast potential earthquake to assign to our seismogenic structure; in this phase statistical relationships can be profitably applied if a sufficient number of reliable seismic events are available for the structures: this should be done taking particular care to use only earthquakes well defined in their location or magnitude and pertaining to one structure at a time. We must avoid using earthquakes related to different seismogenic structures: in a complex tectonic region, there are often a number of seismic sources having recurrence times and seismogenic potential also very different from each other; therefore, if we compute all the events at the same time, without any distinction between their provenance, we make an incorrect use of the statistical approach, which in turn will lead to estimations affected by notable errors (this is the same as if we wanted to foresee the flooding of a river using values from different rivers with only a poor relationship among them).

h) In the **8th** step *the geomorphological and geothecnical characteristics of the studied site* will be collected by means of an appropriate survey (boreholes, cross-holes, etc).

i) In the **9th** step *the more suitable accelerograms from those available in the world seismologic banks are selected*. In this phase one proceeds to the selection of the accelerograms considered most suitable for representing any seismic motion which might occur at the site under survey, should a potential forecast seismic event happen in the heaviest seismogenic structures detected: that is the accelerograms should be produced by seismic events of the same magnitude, with the same focal mechanisms and similar focal depths to the forecast potential earthquake for each relevant seismogenic structure; moreover they should be recorded at the same distance as the site from the seismogenic structure likely to release them; a check should also be done to ascertain if, in the path between the focus of the released earthquake and the site where it was recorded, the seismic wave crosses similar geological structures, at least with regard to the Q value (seismic attenuation). This last aspect, which is generally overlooked, may bear conspicuous influence on the concentration or dispersion of the seismic energy by the *lens effect* that geological structures, due just to their particular features, may have on the seismic wave propagation; for this reason it is suggested to use a computing program involving transmission of the seismic waves thoughout the rocks.

l) In the **10th** step *possible corrections will applied to the chosen accelerograms to take into account site conditions:* this is aimed at considering any possible disparities, from the morphologic and lithologic points of view, between at the recording point of the accelerograms, and the site being surveyed, capable of producing local amplification phenomena. The use of computer-aided calculation is strongly suggested to model at the same time all the possible effects induced in the seismic signal by local and/or regional peculiarities (see also the previous point i).

Finally, effort should be made to define suitable measuring points for plano-altimetric and microseismic monitoring of the area: in fact, it would be advisable to obtain data allowing a check of the conclusions arrived at when defining the ***overall seismotectonic model***.

Moreover, in the evaluation of the maximum potential earthquake as proposed in f) it will always be worthwhile to carry out a check with some other independent method, either probabilistic or deterministic. If an estimate is made by one of the length fault/magnitude relationships, pay attention however to avoid the errors pointed out previously.

Significant points of the methodology here discussed

Working in three dimensions and comparison with similar seismogenic structures

Besides having definitely established the need to operate in three dimensions, an outstanding improvement comes from assessing the maximum potential earthquake in a seismogenic structure by comparison among the various parameters characterizing it (geometry and kinematics of each structure, strenght of the rocks under deformation, etc) with seismogenic structures existing in other parts of the world and having as similar as possible seismotectonic characteristics: this simulates the availability of an earthquake catalogue for the seismotectonically relevant area to the site under survey, dating from a much earlier time than it is possible to recede to nowadays only using historical sources dealing with past events (research which normally only enables one to go back a few hundred years: a span of time clearly insufficient for the duration of geological phenomena which generally act over several thousands or even millions of years).

In this way, assessing the maximum potential earthquake in a seismogenic structure becomes more effective (an assumption already at the basis of the existing fault length/magnitude

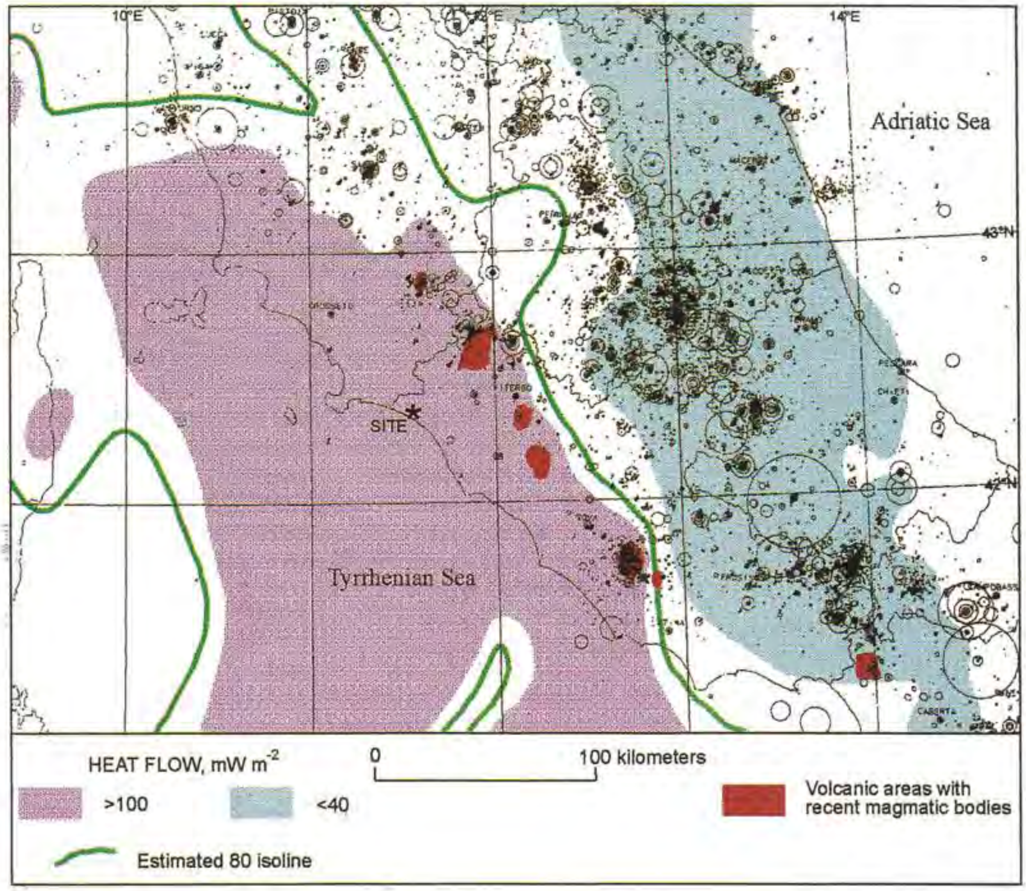


Fig. 6 - Relationship between heat flow density and earthquake pattern in Central Italy.

relationships). If the entire earth's crust is used as a natural experimental laboratory, besides the certainty of giving the variables involved their true weight, a considerable increase is obtained in the number of surveys on geological situations with structural and tectonic characteristics similar to those present in our seismogenic structures. Thus it is possible, as happens in a laboratory by increasing the number of measurements, to overcome the instrumental precision limits and obtain equally good results in fixing the parameter under examination.

It would be advisable to create a World Seismogenic Structure Data Bank (WSSDB) of well known geological structures (with geometries of the types suggested in Fig. 5) and their parameters which are seismotectonically significant, as described previously. An embryonal data bank of this type has been created in ENEL for the most relevant structures encountered during localizations of the most relevant power plants over the last two decades.

*The definition of an **overall seismotectonic model***

Defining an ***overall seismotectonic model*** of the area under investigation is one of the most difficult of the steps presented, but it is also the most exciting and powerful one in seismic hazard assessment. When an explanation is given to all the more or less relevant geological, geophysical and seismological data available for the studied area, the seismic hazard analyst will get a clear picture of the overall seismotectonic characteristics of it. If even the most insignificant pieces of the puzzle are correctly located, many doubts will be resolved.

In doing this, particular attention must be given *to evaluating, even in a qualitative or relative* *manner, the rheology (brittle or ductile behaviour) of the rocks.* Taking into account the mechanical resistance of the rocks under deformation in tectonically active areas allows noticeable improvements in the seismic hazard assessment.

To better explain such concepts, two cases are presented here below, one for central Italy and one for the western U.S.A.

Case a): Central Italy

The area in Fig. 6 has been studied by ENEL since the early 70s, first for siting a Nuclear Power Plant (NPP) and then, during the early 90s, when designing a Liquefied Natural Gas (LNG) plant. Since both these plants are considered under the regulations in Italy as subject to risk, site specific seismic hazard evaluations were carried out.

For the NPP first evaluations had been done using the fault length/magnitude relationships, but the results proposed by ENEL generated controversy, for almost 10 years, due to the difficulty often encountered by this method in detecting or excluding the presence of known active faults.

For the LNG design, ENEL decided to apply the Overall Seismotectonic Modelling presented here, and a comprehensive examination of the tectonic, geophysical and seismological characteristics throughout central Italy was carried out. The results of the model were included in a report (ENEL, 1993), given to the Italian Ministry of the Environment and, considered positively by a Commission of Experts charged with its examination. In Fig. 6, the main elements behind this model are very schematically given:

- the extensive warm area (underlined by heat flow density higher than 80 mW/m^2) in the middle of which is located the site of interest to ENEL;

- the pattern of known seismicity drapping the warm area on its NE, E and SE boundaries.

In the model, the warm area was considered as the residual effect of mantle material which uprose essentially in the Upper Miocene-Lower Pliocene, and which moved progressively towards NE, E and SE, where, at present, in the zone roughly delimited by the isolines between 40 and 80 mW/m^2, the mantle material is pushing against a lithospheric slab of continental type.

In the warm area, where a thickness of the brittle portion of the lithosphere of no more than about 6 km has been calculated from eqns. (1) and (2), we must assume the generation of earthquakes with only low magnitude and very shallow foci; moreover most are strictly linked to recent volcanoes, as shown in Fig. 6, and thus not necessarily of tectonic type (they could be generated by an uprising of molten material or by differential change in the rock volume due to thermal variations, etc). All the significant seismicity is consequently confined to the surrounding cold area, where the rocks remain in a brittle condition down to depths of about 20-25 km. In the meantime similar results had been found independently by Pasquale et al. (1993).

Case b): Western U.S.A.

Even in this, which is of the world's most studied areas (from the geological point of view) it is possible to improve our knowledge of the seismic characteristics, by trying to formulate, even though necessarily in a rough and very preliminary manner, an overall seismotectonic model. Instead of trying to calculate the seismic hazard from the fault/magnitude relationships only, let's try to combine the kinematics, the geometry of the deep geological structures, and the rheology of the main geological bodies in the western U.S.A., using the present approach (most of the data used are from Wallace, 1990, an USGS Professional paper especially devoted to the San Andreas fault system).

The kinematics are very simple at the regional scale: a SW motion of the North American Plate at a rate of 2.5 cm/year and a NW motion of the Pacific Plate at a higher speed (8 cm/year). This gives a deformation zone along the Pacific coast with a mainly trancurrent tectonic regime (see, for instance, the San Andrea fault system) accompanied by non-negligible compressive tectonics.

Structurally speaking, the Pacific Plate (with the Rivera Plate, at the southern end of the Gulf of California, and the Gorda-Juan De Fuca Plate, going north offshore from the State of

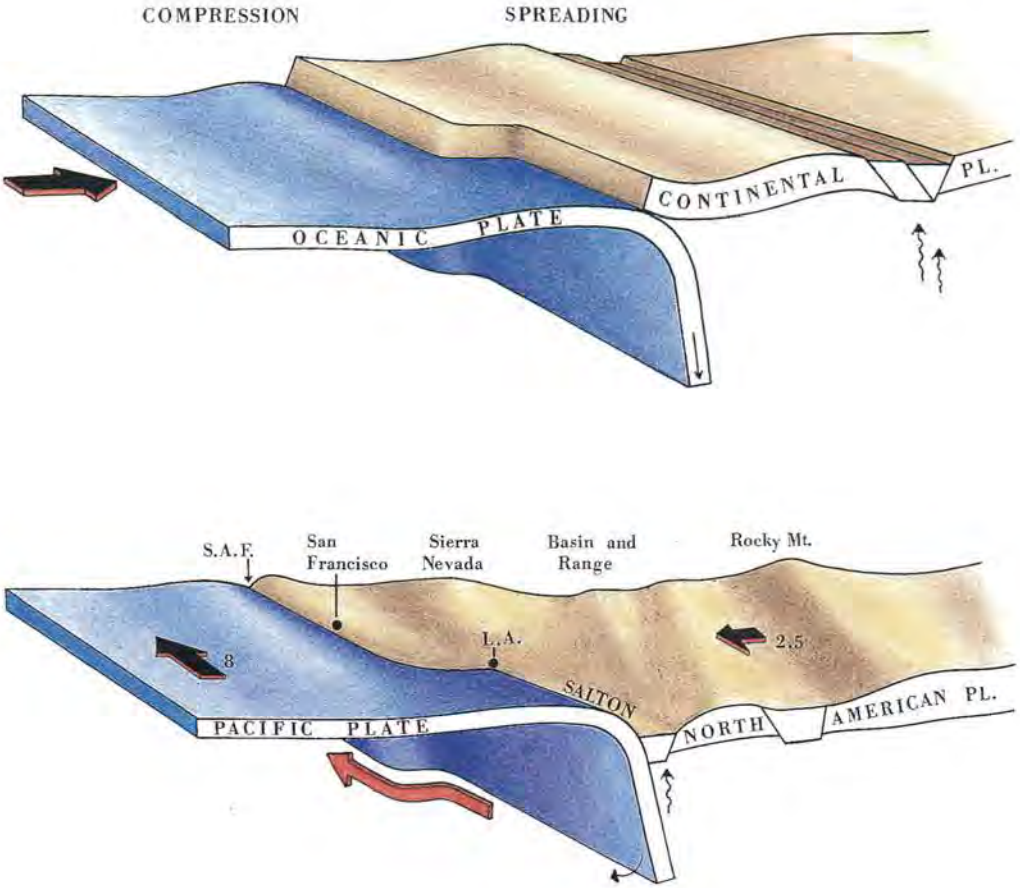


Fig. 7 - Postulated kinematics in the case of normal convergence between an oceanic plate and a continental one (up); aspected kinematics with an obstacle acting as buttress (the deep-rooted cold Californian body, or DRCCB of Fig. 8) to the relative movements between the Pacific and the North American Plates (down). The arrows give the direction and the rate in cm/y of the plate motions. L.A. = Los Angeles, S.A.F. = San Andreas Fault.

Oregon) is, at the same time, dipping NW along the Aleutian thrust and dipping NE under the North American Plate.

This very simple scheme becomes a little more complicated if we focus on the Californian area. In fact, a long strip of continental rocks pertaining to the North American Plate has been captured by the Pacific Plate and is now moving NW, as does the oceanic plate. The area affected by this phenomenon runs from the southern extremity of the Californian Peninsula up to the Mendocino Fracture Zone, near Eureka; its eastern side is delimited by the San Andreas fault. The latter shows a prominent bend very near Los Angeles, a few kilometres north, in the zone of S. Fernando (the S. Fernando Bend in the following).

Now, let's try to consider, at the same time, the following elements:

- the regional kinematics of the Pacific and North American Plates;
- the S. Fernando Bend in the San Andreas Fault;
- the kinematics of the strike-slip Garlock Fault (left-lateral), with respect to the right-lateral kinematics of the San Andreas;

- the presence of a thrust fault, about 50 km long, exhibiting evidence of Quaternary displacement, at the southern part of the San Joaquin Valley; this thrust, which runs roughly parallel to the Garlock Fault and is located about 30 km north of it, is characterized by a NNE-ward movement;

- the presence of many spreading (pull-apart) centres along the San Andreas fault, but only south of the S. Fernando bend, which we can to some extent relate to the tectonics from which the large Gulf of California originated;

- the presence of a large, deep-rooted and cold body below the Great Valley, just north of the S. Fernando bend, with a length of about 800 km and more than 200 km wide, as revealed by a very low heat flow density (less than 63 mW/m^2) (see Sass et al., 1994) and high seismic velocities (see Humphreys and Dueker, 1994). The body (which in the following we will call the Deep Rooted Cold Californian Body or DRCCB), which runs parallel to the coast, is bordered to the SW by the San Andreas Fault, and is probably related to the batholith and to the metamorphic belt of the Sierra Nevada;

- the sigmoidal shape of the DRCCB, which is similar to that of a mega-lithon;

- the distribution of the earthquakes in the area, most of which are located just on the border of the DRCCB;

- the lack of significant earthquakes in most of Oregon, despite the presence of a 1100 km subduction zone (Wuethrich, 1994) between the Gorda-Juan De Fuca Plates and the North American Plate.

Most of these geological and geophysical data are easily explained by an overall kinematic model in which the DRCCB, being the body offering the strongest resistance in the area, acts as a buttress(5), forcing the Pacific Plate slab to rearrange arround it (Fig. 7). The Pacific Plate, being forced to turn around the DCCB, will cause:

- left-lateral strike slip tectonics north of the S. Fernando bend, with a small compressive component;

- strong compressive tectonics, just around the S. Fernando Bend, with a small component of strike slip movement;

- extensional tectonics, south of the S. Fernando bend, with a appreciable amount of strike slip movement.

Thus, at a glance, we can understand the main reasons for the seismicity pattern shown in Fig. 8, considering the San Andreas fault north of the S. Fernando bend as the western boundary of the DRCCB, and the Sierra Nevada Faults up to the White Mountains as the eastern one.

But it is also very interesting to see how the main thermal bodies throughout the western U.S.A. are able to modify the pattern of known sismicity in this large region. In Fig. 9 the seismicity taken from Wallace (1990) and the geothermal heat flow densities taken from Humphreys and Dueker (1994) are presented, the latter slightly modified to evidence the supposed trend of the 80 mW/m^2 curve. As we can easily see, the presence and/or absence of the known seismicity is strongly related to the thermal bodies and, in particular, besides the cold body previously mentioned (the DRCCB), others can be outlined:

- the warm body affecting a large area comprising most of Oregon, southern Idaho, western Utah and Arizona, where the seismicity is almost absent or of low level;

- the large cold body running from northern Arizona to central Wyoming passing through southeastern Utah, and in particular its northwestern boundary (roughly following the 80 mW/m^2 curve) which depicts the seismicity in the region in a very clear manner for a length of over 1000 km;

- the various cold bodies, small but mechanically very efficient, in NE Nevada and around Los Angeles, which rearrange the stress and consequently the local seismicity.

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(5) Anderson (1972) suggested a similar mechanism, but where the Sierra Nevada is obstructing the NW-movement of the only continental crustal blocks captured by the Pacific plate.

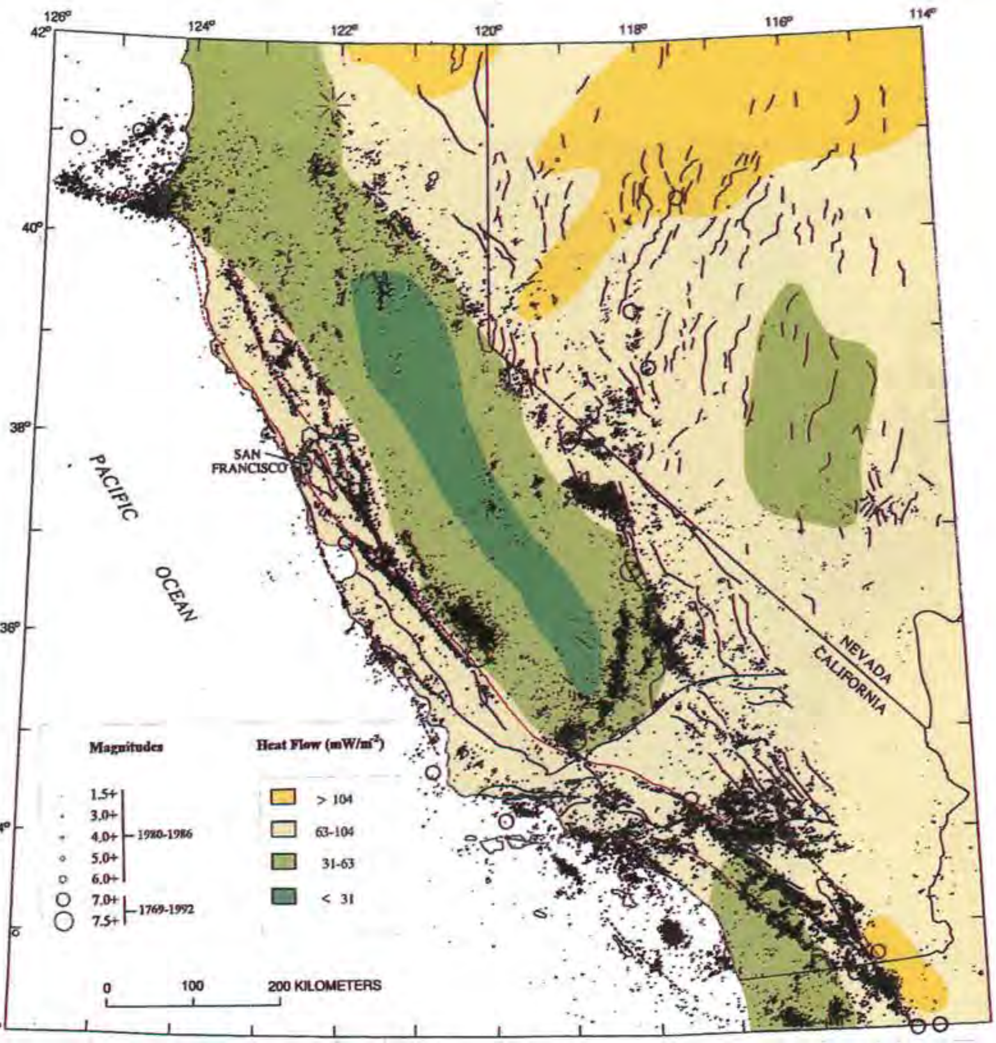

Fig. 8 - Heat flow density (after Lachenbruch and Sass, 1980), location of 64,000 $M \geqslant 1.5$ during 1980-86, and $M \geqslant 7.0$ during 1789-1992 earthquakes in California and western Nevada, and mapped Holocene faults (after Wallace, 1990). The presence of a deep-rooted cold body is evidenced by the low heat flow densities east of San Francisco; such a body is referenced in the test as DRCCB.

Of course this is only the first step and more would need to be done for a complete modelling of the area, as indicated by the methodological approach of this paper. However, this would require more geological and geophysical data and, primarily, a three dimensional investigation of the structural and rheological setting of the western U.S.A.. If this were done, a noteworthy improvement could be obtained in the definition of the seismic hazard of areas where a lot of people live under threat of destructive earthquakes. Besides the famous "Big One" expected in California, Wuetherich (1994) gives a dramatic seismic evaluation of a possibile $M=9$ or greater earthquake in the near future for the coastal portion of Oregon. A modelling as here suggested could reduce the uncertainties, and could probably explain why, for instance, Oregon has no known seismicity, and some portions of the San Andreas fault are seismically silent (such as the long-dormant segment B of W. L. Ellsworth, in Wallace, 1990).

The use of accelerograms recorded under similar conditions

The last but not least important improvement given by the present methodology is the use

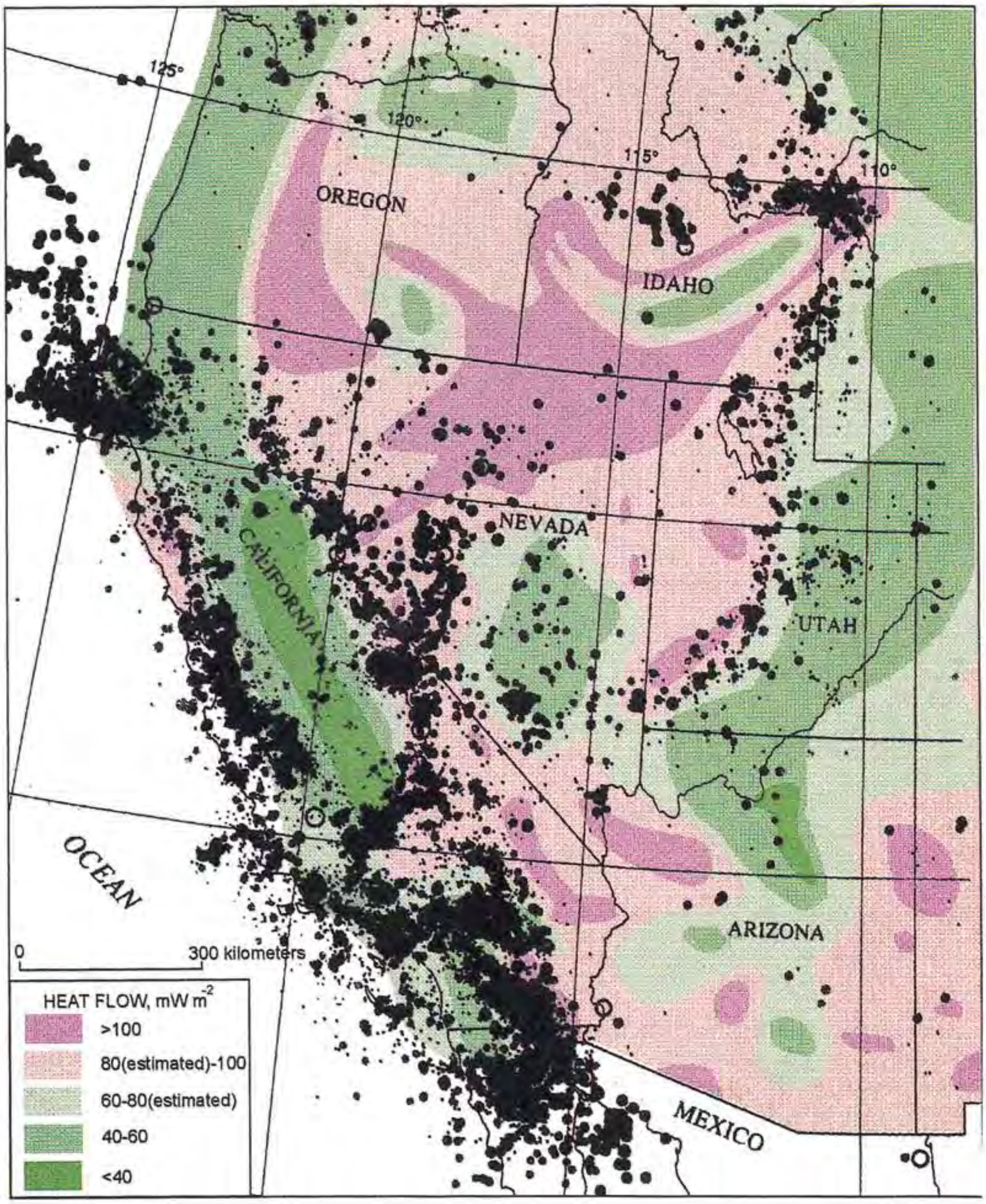

Fig. 9 - Relationship between seismicity (after Wallace, 1990) and heat flow density (after Sass et al., 1994) in the Western U.S.A.. See the location, just under the word CALIFORNIA, of the deep-rooted cold body of Fig. 8.

of real accelerograms recorded in situations similar to those individuated in the studied areas. Of course, the more similar the characteristics (from the geological, seismotectonic, morphological and geothecnical points of view) of the site where the accelerogram is recorded to those of the site under examination, the more reliable the accelerogram chosen to simulate the free-field seismic motion at the studied site. In this way better results are obtained than those from the rough approximations given by the current relationships between attenuation of the seismic energy and distance of the epicentral area from the site.

CONCLUSIONS

The described approach to estimating the seismic acceleration of the SSE (Safe Shutdown Earthquake) for the sites of important constructions, such as nuclear power plants, or other critical facilities subject to risk, overcomes both the difficulty of application in tectonically complex areas, and the main setback inherent in the fault/magnitude relationships extensively used the world over. Moreover it is a powerful tool in all cases where one can (or wishes) to apply statistical relationships to any seismic catalogue available for a studied area.

In the present methodology the survey of active faults at the ground surface is no longer regarded as a key element in the process of assessing the seismic potential of a tectonic structure, but only as part of it. On the other hand great importance is given to:

a) the definition in three dimensions (by means of deep exploration techniques) of all the seismogenic structures relevant to the seismic assessment of the site; these structures may not necessarily be formed by only a single fault, but also by the related tectonic features (secondary faults, fractures, deforming rocks, etc.);

b) the definition of a kinematic model for all the relevant area, delimited by reliable boundary conditions, and accounting for the behaviour of the active structures at least down to the maximum depth attained by known earthquakes in the region;

c) the evaluation of the shear strength of the rocks involved in recent/present tectonic processes;

d) the definition of an ***overall seismotectonic model*** of the relevant area in which all the geological, geophysical and seismological elements are correctly and completly explained;

e) the outline of the maximum potential (future) earthquake of the most important seismogenic structure for the site by comparison with similar tectonic structures worldwide;

f) the choice of the accelerograms most representative of the seismic motions that could be induced at the site should the potential earthquake be released from the most important seismogenic structure detected.

Application of the methodology could become even more sophisticated and reliable were it to meet widespread approval by researchers in seismotectonics: data banks could then be set up for recording and classifying the seismogenic structures on the basis of the parameters outlined before.

An ever increasing series of cases would facilitate obtaining solutions and, more importantly, obtaining them with the help of increasingly better and more reliable data. Thus it would be helpful if the experts, who endorse the approach herein described and are in a position to conclusively characterize the seismically active structures present in the areas where they operate, would contact the author of this paper in order to assess the possibility of creating a common data bank for the most relevant seismogenic structures worldwide.

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REFERENCES AND BIBLIOGRAPHY

Aki K.; 1982: *Three-dimensional seismic inhomogeneities in the lithosphere and asthenosphere: evidence for decoupling in the lithosphere and flow in the asthenosphere.* Rev. of Geoph. and Space Phys., **20**, 161-170.

Allen C.R., 1975: *Geological criteria for evaluating seismicity.* Geol. Soc. Am. Bull., **86**, 1041-1057.

Anders M.H.; 1994: *Constraints on North American plate velocity from the Yellowstone hotspot deformation field.* Nature, **369**, 53-55.

Anderson D.L.; 1972: *La faglia di San Andreas.* Le Scienze, **42**, 139-155.

Anderson E.M.; 1951: *The dynamics of faulting and dyke formation with application to Britain.* 2nd edition, Oliver and Boyd. Edinburg, Scotland.

Anderson S.R.; 1994: *Evolution of the Santa Cruz mountains, California through tectonic growth and geomorphic decay.* Journ. of Geoph. Res., **99**, 20161-20179.

Artyuschov E.V.; 1983: *Geodynamics. Development in geotectonics.* Elsevier, Amsterdam, 312 pp.

Atwater B.F.; 1987: *Evidence for great Holocene earthquakes along the outer coast of Washington State.* Science, **236**, 942-944.

Auboin J., Debelmas J. and Latreille M.; 1980: *Geology of the Alpine chains born of the Tethys.* Mem. du BRGM, **115**, Fricotel Ets, Paris, 355 pp.

Baker D.M., Lillie R.J., Yeats R.S., Johnson G.D., Yousuf M. and Zamin A.S.H.; 1988: *Development of the Himalayan frontal thrust zone: Salt Range, Pakistan.* Geology, **16**, 3-7.

Bally A.W., Catalano R. e Oldow J.; 1985: *Elementi di tettonica regionale.* Pitagora Editrice, Bologna, 276 p.

Billings M.P.; 1972: *Structural geology.* 3rd ed., Prentice-Hall, Inc., Englewood Cliffs, New Jersey, 606 p.

Bloch R.B., Von Huene R., Hart P.E. and Wentworth C.M.; 1993: *Style and magnitude of tectonic shortening normal to the San Andreas fault across Pyramid Hills and Kettleman Hills South Dome, California.* Geol. Soc. Am. Bull., **105**, 464-478.

Boccaletti M., Coli M., Ferrari G., Giglia G., Lazzarotto A., Merlanti F., Nicolich R., Rapani G. and Postpischl D.; 1985: *Considerations on the seismotectonics of Northern Apennines.* Tectonophysics, **117**, 7-38.

Bonilla M.G., Mark R.K. and Lienkaemper J.J.; 1984: *Statistical relations among earthquake magnitude, surface rupture length and surface fault displacement.* Bull. Seism. Soc. Am., **74**, 2379-2411.

Boriani A., Bonafede M., Piccardo G.B. and Vai G.B. (eds.); 1989: *The lithoshpere in Italy.* Accademia Nazionale dei Lincei, Roma, 540 pp.

Borisoff B.A., Reisner G.I and Sholpo V.N.; 1976: *Tectonics and maximum magnitudes of earthquakes.* Tectonophysics, **33**, 167-185.

Boschi E., Pantosti D. and Valensise G.; 1994: *L'identificazione geologica delle faglie sismogenetiche.* Le Scienze n. 310.

Bott M.H.P.; 1982: *The interior of the earth.* 2th ed., Edward Arnold; London, 402 p.

Brocher T.M., Carr M.D., Fox K.F. Jr. and Hart P.E.; 1993: *Seismic reflection profiling across Tertiary extensional structures in the eastern Amargosa Desert, southern Nevada, Basin and Range province.* Geol. Soc. Am. Bull., **105**, 30-46.

Bürgman R., Arrowsmith R., Dumiand McLaughlin R.; 1994: *Rise and fall of the Santa Cruz mountains, California, from fission tracks, geomorphology, and geodesy.* Journ. of Geoph. Res., **99**, 20181-20202.

Byerlee J.; 1978: *Friction of rocks.* Pageoph., **116**, 615-626.

Carlslaw H.S. and Jaeger J.C.; 1971: *Conduction of heat in solids. 2th ed.*, Oxford University Press, London, 510 pp.

Carter N.L. and Tsenn M.C.; 1987: *Flow properties of continental lithosphere.* Tectonophysics, **136**, 27-63.

Carter N.L., Hansen F. and Senseny P.E.; 1982: *Stress magnitudes in natural rock salt.* Journ. of Geoph. Res., **87**, 9289-9300.

Castle R.O. and Gilmore T.D.; 1992: *A revised configuration of the southern California uplift.* Geol. Soc. Am. Bull., **104**, 1577-1591.

Chen W.P. and Molnar P.; 1983: *Focal depths of intracontinental and intraplate earthquakes and their implications for the thermal and mechanical properties of the lithosphere.* Journ. of Geoph. Res., **88**, 4183-4214.

Chiaruttini C. and Siro L.; 1981: *The correlation of peak ground horizontal acceleration with magnitude, distance and seismic intensity for Friuli and Ancona, Italy, and the Alpide Belt.* Bull. Seism. Soc. Am., **71**, 1993-2009.

Cocco M. and Rovelli A.; 1989: *Evidence for the variation of stress drop between normal and thrust faulting earthquakes in Italy.* Journ. Geoph. Res., **94**, 9399-9416.

Cornell C.A.; 1968: *Engineering seismic risk analysis.* Bull. Seism. Soc. Am., **58**, 1583-1606.

Coward M.P., Dewey J.F. and Hancock P.L. (eds); 1987: *Continental extensional tectonics.* Geological Society Special Publication, **28**.

Coward M.P., Dietrich D. and Park R.G. (eds); 1989: *Alpine tectonics.* Blackwell Scientific Publication, Oxford, 450 p.

Crone A.J.; 1991: *Earthquake in aseismic zones.* Nature, **352**.

Davis D.M. and Lillie R.J; 1994: *Changing mechanical response during continental collision: active examples from foreland thrust belts of Pakistan.* Journal of Structural Geology, **16**, 21-34.

Davis T.L. and Namson J.S.; 1994: *A balanced cross-section of the 1994 Northridge earthquake, southern California.* Nature, **372**, 167-169.

Davy P., Sornette A. and Sornette D.; 1990: *Some consequences of a proposed fractal nature of continental faulting.* Nature, **348**, 56-58.

De Jonge M.R., Wortel M.J.R. and Spakman W.; 1993: *From tectonic reconstruction to upper mantle model: an application to Alpine-Mediterranean region.* Tectonophysics, **223**, 53-65.

de Polo C.M., Peppin W. and Johnson P.A.; 1993: *Contemporary tectonics, seismicity, and potential earthquake sources in the White Mountains seismic gap, west-central Nevada and east-central California, U.S.A.*. Tectonophysics, **225**, 271-299.

De Rito R.F, Cozzarelli F.A. and Hodge D.S.; 1986: *A forward approach to the problem of non linear viscoelasticity and the thickness mechanical lithosphere.* Journ. of Geoph. Res., **91**, 8295-8313.

D'Offizi S.; 1986: *Aspetti geologici nei problemi di localizzazione, progettazione e costruzione degli impianti di produzione di energia elettrica in Italia: una breve casistica ragionata.* Soc. Geol. It., **35**, 495-506.

D'Offizi S.; 1988: *Ricerca ed esplorazione nell'area geotermica di Torre Alfina (Lazio-Umbria).* Boll. Soc. Geol. It., **107**, 265-337.

D'Offizi S., Magri L. and Muzzi F.; 1991: *Seismic Assessment for NPP according to Italian practice.* Workshop on "Special Issues of Level 1 PSA". Cologne (FRG).

D'Offizi S., Minelli G. and Pialli G.; 1994: *Foredeeps and thrust systems in Northern Apennines.* Present Volume.

Ellsworth W.L.; 1991: *Putting pieces together.* Nature, **349**, 371-372.

ENEL; 1993: *Valutazione della sismicità del sito di Montalto di Castro.* Internal report for the Ministry of Environment of Italy, 123 pp., 42 figs.

EPRI (Electric Power Researche Institute); 1987: *Seismic Hazard Methodology for the Central and Eastern United - Volume 1 Methodology.* Report NP 4726 prepared for Seismicity Owners Group and EPRI under Research Projects P101-38, -45, -46, 2256-14.

Faccioli E.; 1979: *Engineering seismic risk analysis of the Friuli Region.* Boll. di Geof. Teor. ed Appl., **21**, 173-190.

Fadaye K. and Ranalli G.; 1990: *Rheology of the lithosphere in the East African Rift System.* Geophys. J. Int., **102**, 445-453.

Fischer G.J. and Paterson M.S.; 1989: *Dilatancy during rock deformation at high temperatures and pressures.* Journ. of Geoph. Res., **94**, no. B12, 17607-17617.

Frohlich C.; 1989: *I terremoti profondi.* Le Scienze, **XLII** no. 247, 15-23.

Furlong K.P.; 1993: *Thermal-rheologic evolution of the upper mantle and the development of the San Andreas fault system.* Tectonophysics, **223**, 149-164.

Furlong K.P. and Atkinson S.M.; 1993: *Seismicity and thermal structure along the northern Andreas fault system, California, U.S.A.*. Tectonophysics, **217**, 23-30.

Handy M.R.; 1989: *Deformation regimes and the rheological evolution of fault zones in the lithosphere: the effects of pressure, temperature, grainsize and time.* Tectonophysics. **163**, 119-152.

Harms T.A., Jayko A.S. and Blake M.C. Jr.; 1992: *Kinematic evidence for extensional unroofing of the Franciscan Complex along the Coast Range fault, northern Diablo Range, California.* Tectonics, **11**, 228-241.

Harris R.A. and Simpson R.W.; 1992: *Changes in static stress on southern California faults after the 1992 Landers earthquake.* Nature, **360**, 251-254.

Helffrich G.; 1991: *Relationship of deep seismicity to the thermal structure of subducted lithosphere.* Nature, **353**, 252-255.

Hiraga H. and Shimamoto T.; 1987: *Textures of sheared halite and their implications for the seismogenic slip of deep faults.* Tectonophysics. **144**, 69-86.

Holmes A.; 1984: *Principles of physical geology*. 3rd ed. by D.L. Holmes, Van Nostrand Reinhold, (UK) 730 p.

Holzer T.L.; 1994: *Predicting earthquake effects-learning from Northridge and Loma Prieta.* Science, **265**, 1182-1183.

Hooke R.; 1668: *Discourse on earthquake.* De Potentia Restitutiva, London, England.

Hueckel T.A., Peano A., Pellegrini R. and D'Offizi S.; 1993: *Thermoplasticity model for subducting lithospheric rocks.* Annales Geophysicae, **11** suppl. 1, part I - C19.

Humphreys E.D. and Clayton R.W.; 1990: *Tomographic image of the southern California mantle.* Journ. of Geoph. Res., **95**, 19725-19746.

Humphreys E.D. and Dueker K.G.; 1994: *Physical state of the Western U.S. upper mantle.* Journ. of Geoph. Res., **99**, 9635-9650.

Humphreys E.D. and Hager B.H.; 1990: *A kinematic model for the late Cenozoic development of southern California crust and upper mantle.* Journ. of Geoph. Res., **95**, 19747-19762.

Humphreys E.D. and Weldon II R.J.; 1994: *Deformation across the western United States: a local estimate of the Pacific-North America transform deformation.* Journ. of Geoph. Res., **99**, 19995-20010.

IAEG; 1986: *Proceedings of the International Symposium on Engineering Problems in Seismic Areas.* Geol. Appl. ed Idrog., Bari.

ISMES; 1987: *Definition of the seismogenetic zones of interest and assessment of the design basis earthquake for Chashma site (Pakistan).* Internal report for the Pakistan Atomic Energy Commission.

ISMES; 1987: *Review of the geological and seismological reports prepared between 1975 and 1982 for the proposed Chasma nuclear power plant site (Pakistan).* Internal report for the Pakistan Atomic Energy Commission.

ISMES; 1992: *Evaluation of operating and design earthquakes for the Crimea nuclear power plant site: seismogenic zonation.* 368 pp., 98 ff., 35 pl.. Internal report for the Atomenergoexport (Moscow).

Ito E. and Sato H.; 1991: *Aseismicity in the lower mantle by superplasticity of the descending slab.* Nature, **351**, 140-141.

Jackson J. and McKenzie; 1988: *The relationship between plate motions and seismic moment tensors, and the rates of active deformation in the Mediterranean and Middle East.* Geoph. Journ., **93**, 45-73.

Jaeger J.G. and Cook N.G.W.; 1979: *Fundamental of rocks mechanics.* 3rd edition. Chapman and Hall, London.

John B.E. and Foster D.A.; 1993: *Structural and thermal constraints on the initiation angle of detachment faulting in the southern Basin and Range: the Chemehuevi Mountains case study.* Geol. Soc. Am. Bull., **105**, 1091-1108.

Jones L., Aki K., Boore D., Celebi M., Donnellan A., Hall J., Harris R., Hauksson E., Heaton T., Hough S., Hudnut K., Hutton K., Johnston M., Joyner W., Kanamori H., Marshall G., Michael A., Mori J., Murray M., Ponti D., Reasenberg P., Schwartz D., Seeber L., Shakal A., Simpson R., Thio H., Tinsley J., Todorovska M., Trifunac M., Wald D. and Zoback M.L.; 1994: *The Magnitude 6.7 Northridge, Califonia, Earthquake of 17 January 1994.* Science, **266**, 389-397.

Jones C.H., Wernicke B.P., Farmer G.L., Walker G.D., Coleman D.S., McKenna L.W. and Perry F.V.; 1992: *Variation across and along a major continental rift: an interdisciplinary study of the Basin and Range Province, western USA.* Tectonophysics, **213**, 57-96.

Karato S. and Wu P.; 1993: *Rheology of the upper mantle: a synthesis.* Science, **260**, 771-778.

Kerr R.A.; 1990: *Making deep earthquakes in laboratory?.* Science, **247**, 30-31.

King G.C.P., Stein R.S. and Lin J.; 1994: *Static stress change and triggering earthquake.* Bull. Seism. Soc. Am., **84**, 935-953.

Kirby S.H.; 1980: *Tectonic stresses in the lithosphere: constraints provided by the experimental deformation of rocks.* Journ. of Geoph. Res., **85**, 6353-6363.

Kirby S.H.; 1985: *Rock mechanics observations pertinent to the rheology of the continental lithosphere and the localization of strain along shear zones.* Tectonophysics, **119**, 1-27.

Kirby S.H., Durham W.B. and Stern L.A.; 1991: *Mantle phase changes and deep earthquake faulting in subducting lithosphere.* Science, **252**, 216-225.

Kirby S.H. and Kronenberg A.K.; 1991: *Rheology of the lithosphere: selected topics.* Review of Geophysics, **25**, 1219-1244.

Kiureghian A.D. and Ang A.H.S.; 1977: *A fault-rupture model for seismic risk analysis.* Bull. Seism. Soc. Am., **67**, 1173-1194.

Knipe R.J. and Rutter E.H. (eds.); 1990: *Deformation mechanisms, rheology and tectonics.* Geol. Society Special Publ., London, Alden Press, Oxford, 535 p.

Kondorskaya N.V. and Kireyev I.A.; 1985: *On the estimation of the earthquake maximum magnitude based on a joint analysis of seismological and geothermal parameters.* Tectonophysics, **121**, 79-85.

Krinitzsky E.L.; 1993: *Earthquake probability in engineering - Part 1: The use and misuse of the expert opinion. The third Richard H. Jahns distinguished lecture in engineering geology.* Engineering Geology, **33**, 257-288.

Krinitzsky E.L.; 1993: *Earthquake probability in engineering - Part 2: Earthquake recurrence and limitations of Gutenberg-Richter b-values for the engineering of structures. The third Richard H. Jahns distinguished lecture in engineering geology.* Engineering Geology, **36**, 1-52.

Lachenbruch A.H. and Sass J.H.; 1980: *Heat flow and energetics of the San Andreas fault system.* Journ. Geoph.

Res., **85**, 6185-6222.

Lachenbruch A.H. and Sass J.H.; 1988: *The stress heat-flow paradox and thermal results from Cajon pass.* Geoph. Res. Lett., **15**, 981-984.

Lachenbruch A.H., Sass J.H. and Galanis S.P. jr.; 1985: *Heat flow in southernmost California and the origin of the Salton trough.* Journ. of Geoph. Res., **90**, 6709-6736.

Lallemand S.E., Scnürle P. and Malavieille J.; 1994: *Coulomb theory applied to accretionary and non accretionary wedges: possible causes for tectonic erosion and/or frontal accretion.* Journ. of Geoph. Res., **99**, 12033-12055.

Lees J.M. and Nicholson C.; 1993: *Three-dimensional tomography of the 1992 southern California sequence: constraints on dynamic earthquake rupture?.* Geology, **21**, 387-390.

Louie J.N., Clayton R.W. and Le Bras R.J.; 1988: *Three-dimensional imaging of steeply dipping structure near San Andreas fault, Parkfield, California.* Geophysics, **53**, 176-185.

Luyendyk B.P.; 1990: *Neogene-age fault slip in the continental transform zone in southern California.* Annales Tectonicae, **IV**, 24-34.

Luyendyk B.P.; 1991: *A model for Neogene crustal rotations, transtension, and transpression in southern California.* Geol. Soc. Am. Bull., **103**, 1528-1536.

Machette M.N., Personius S.F., A.R., Schwartz D.P. and Lund W.R.; 1991: *The Wasatach fault zone, Utah - segmentation and history of Holocene earthquakes.* Journ of Struct. Geol., **13**, 137-149.

Maluski H. and Matte P.; 1984: *Ages of alpine tectonometamorphic events in Northwestern Himalaya: Northern Pakistan: by ^{39} Ar/^{40} Ar method.* Tectonics, **3**, 1-18.

Mandl G.; 1988: *Mechanics of tectonic and faulting.* Elsevier, Amsterdam, 407 pp.

McBride J.H. and Brown L.D.; 1986: *Reanalysis of the COCORP deep seismic reflection profile across the San Andreas fault, Parkfield, California.* Bull. Seism. Soc. Am., **76**, 1668-1686.

McGarr A.; 1982: *Analysis of states of stress between provinces of constant stress.* Journ. of Geoph. Res., **87**, 9279-9288.

McGuire R.K.; 1977: *Effects of uncertainty in seismicity on estimates of seismic hazard for the East Coast of the United States.* Bull. Seism. Soc. Am., **67**, 827-848.

McGuire R.K. (edr.); 1993: *The practice of earthquake hazard assessment.* IASPEI and ESC.

Mongelli F.; 1981: *Evolution of geotemperatures from oil wells in Italy.* Geothermics, **10**, 29-38.

Montgomery D.R.; 1993: *Compressional uplift in the central California coast ranges.* Geology, **21**, 543-546.

Moos D. and Zoback M.D.; 1993: *State of stress in the Long Valley caldera, California.* Geology, **21**, 837-840.

Morgan P. and Baker B.H. eds.; 1983: *Processes of continental rifting.* Elsevier, Amsterdam, 680 p.

Nur A., Ron H. and Beroza G.C.; 1993: *The nature of the Landers-Mojave earthquake line.* Science, **261**, 201-202.

Nye J.F.; 1953: *The flow law of ice from measurements in glacier tunnels, laboratory experiments and the Jungfraufirn borehole experiment.* Proc. Real Soc. London, Ser. A, **219**, 477-489.

Oppenheimer D., Beroza G., Carver G., Dengler L., Eaton J., Gee L., Gonzalez F., Jayko A., Li W.H., Lisowski M., Magee M., Marshall G., Murray M., McPherson R., Romanowicz B., Satake K., Simpson R., Somerville P., Stein R. and Valentine D.; 1993: *The Cape Mendocino, California, Earthquakes of April 1992: Subduction at the Triple Junction.* Science, **261**, 433-437.

Ord A. and Hobbs B.E.; 1989: *The strength of the continental crust, detachment zones and the development of plastic instabilities.* Tectonophysics, **158**, 269-289.

Page B.M. and Brocher T.M.; 1993: *Thrusting of the central California margin over the edge of the Pacific Plate during transform regime.* Geology, **21**, 635-638.

Pasquale V., Verdoya M., Chiozzi P. and Augliera P.; 1993: *Dependence of the seismotectonic regime on the thermal state Northern Apennines.* Tectonophysics, **217**, 31-41.

Patacca E. and Scandone P.; 1986: *Seismical hazard: seismotectonic approach.* IAEG 1986 - Engineering geology problems in seismic areas. Bari, **5**, 103-115.

Pavlis T.L., Serpa L.F. and Keener C.; 1993: *Role of seismogenic process in fault-rock development: an example from Death Valley, California.* Geology, **21**, 267-270.

Pezzopane S.K. and Weldon II R.J.; 1993: *Tectonic role of active faulting in central Oregon.* Tectonics, **12**, 1140-1169.

Ranalli G.; 1987: *Rheology of the earth.* Allen and Unwin, Boston, 366 p.

Ranalli G. and Murphy D.C.; 1987: *Rheological stratification of the lithosphere.* Tectonophysics, **132**, 281-295.

Reches Z., Schubert G. and Anderson C.; 1994: *Modeling of periodic great earthquakes on the San Andrea fault: effects of nonlinear crustal rheology.* Journ. of Geoph. Res., **99**, 21983-22000.

Reid H.F.; 1911: *The elastic rebound theory of earthquakes.* Bull. Dept. Geol. Univ. California, **6**, 413.

Reiter L.; 1990: *Earthquake Hazard Analysis.* Columbia University Press, New York, 254 pp.

Rossmanith H.P. ed.; 1990: *Mechanics of jointed and faulted rocks.* A.A. Balkema, Rotterdam, 994 pp.

Roure F., Heitzmann P. and Polino R. eds.; 1990: *Deep structure of the Alps.* Soc. Geol. Ital., Vol. Spec. no. 1, Louis Jean Imprimerie, France, 367 p.

Rutter E.H. and Brodie; 1991: *Lithosphere rheology-a note of caution.* Journ. of Struct. Geol., **13**, 363-367.

Rybicki K.R.; 1994: *Shear stress on a vertical strike-slip fault in a layered medium due to tectonic loading: San Andreas fault system.* Journ. of Geoph. Res., **99**, 20011-20021.

Salisbury M.H. and Fountain D.M.; 1990: *Exposed cross-sections of the continental crust.* Kluwer Academic Publishers, Dordrecht, 662 pp.

Sanders C.O.; 1993: *Interaction of the San Jacinto and San Andreas fault zones, southern California: triggered earthquake migration and coupled recurrence interval.* Science, **260**, 973-975.

Sass J.H., Lachenbruch A.H., Galanis S.P. Jr., Morgan P., Priest S.S., Moses T.H. Jr. and Munroe R.J.; 1994: *Thermal regime of the Southern Basin and Range Province: 1. Heat flow data from Arizona and Mojave Desert of California and Nevada.* Journ. of Geoph. Res., **99**, 22093-22119.

Scheidegger A.E.; 1963: *Principles of geodynamics.* Springer-Verlag, Berlin, 362 pp.

Scholz C.H.; 1990: *Earthquakes as chaos.* Nature, **348**, 197-198.

Scholz C.H.; 1990: *The mechanics of earthquakes and faulting.* Cambridge University Press, 439 pp.

Schwartz D.P. and Coppersmith K.J.; 1984: *Fault behaviour and characteristic earthquakes: examples from the Wasatch and San Andreas fault zones.* Journ. of Geoph. Res., **89**, 5681-5698.

Seeber L. and Armbruster J.G.; 1983: *Continental subduction along the Northwestern and Central portions of the Himalayan arc.* Boll. Geof. Teor. Appl., **25**, 409-425.

Serva L.; 1990: *Il ruolo delle scienze della terra nelle analisi di sicurezza di un sito.* Boll. Soc. Geol. It., **109**, 375-411.

Serva L.; 1993: *An analysis of the world major regulatory guides for NPP seismic design - A guideline for high risk facilities.* ENEA, Direzione Relazioni, Roma.

Seyfert C.K. (edr.); 1987: *The encyclopedia of structural geology and plate tectonics.* Van Nostrand Rheinold Company Inc., New York, 876 pp.

Sibson R.H.; 1974: *Frictional constraints on thrust, wrench and normal faults.* Nat. Phys. Sci., **249**, 542-544.

Sibson R.H.; 1982: *Fault zone models, heat flow, and the depth distribution of earthquakes in the continental crust of the United States.* Bull. Seism. Soc. Am., **72**, 151-163.

Sibson R.H.; 1990: *Conditions for fault-valve behaviour.* From Knipe R.J. and Rutter E.H. (eds), 1990: *Deformation mechanisms, rheology and tectonics.* Geol. Society Special Publ., London, Alden Press, Oxford, no 54, 15-28.

Sibson R.H.; 1990: *Rupture nucleation on unfavourably oriented fault.* Bull. Seism. Soc. Am., **80**, 1580-1604.

Sibson R.H.; 1991: *Loading of faults to failure.* Bull. Seism. Soc. Am., **81**, 2493-2497.

Slejko D. and Kijko A.; 1990: *Seismic hazard assessment for the main seismogenic zones in the Eastern Alps.* Tectonophysics, **191**, 165-183.

Slejko D., Carulli G.B., Nicolich R., Rebez A., Zanferrari A., Cavallin A., Doglioni C., Carraro F., Castaldini D., Iliceto V., Semenza E. and Zanolla C.; 1989: *Seismotectonic of the Eastern Southern Alps: a review.* Boll. Geof. Teor. Appl., **31**, 109-136.

Slemmons D.B. and de Polo C.M.; 1986: *Evaluation of active faulting and associated hazards.* In:Wallace R.E. (ed.), Active Tectonics, Geophysics Study Committee, National Academic Press, Washington D.C., 45-62.

Spetzler H., Sondergeld C., Sobolev G. and Salov B.; 1987: *Seismic and strain studies on large laboratory rock samples being stressed to failure.* Tectonophysics, **144**, 55-68.

Stein R.S. and King G.C.P.; 1984: *Seismic Potential Revealed by Surface Folding: 1983 Coalinga, California, earthquake.* Science, **224**, 869-872.

Stein R.S. and Yeats R.S.; 1989: *Hidden earthquakes.* Sci. Am., **260**, 48-57.

Stein R.S. and Ekström G.; 1992: *Seismicity and geometry of a 110-km-long blind thrust fault, 2. Synthesis of the 1982-1985 California earthquake sequence.* Journ. of Geoph. Res., **97**, 4865-4883.

Stevenson D.J.; 1994: *Weakening under stress.* Nature, **372**, 129-130.

Strehlau J. and Meissner R.; 1987: *Estimation of crustal viscosities and shear stresses from an extrapolation of experimental steady state flow data.* Fuchs and C. Froidevaux (eds.) Composition, Structure and Dynamics of the Lithosphere-Astenosphere System. Am. Geophys. Union, Geodyn. Ser., **16**, 69-87.

Sykes L.R. and Jaumé S.C.; 1990: *Seismic activity on neighbouring faults as a long-term precursor to large earthquakes in the San Francisco bay area.* Nature, **348**, 595-599.

Toksöz, Uyeda S. and Francheteau J.; 1980: *Volcanics ridges and arc.* Elsevier, Amsterdam, 538 p.

Trehu A.M., Asudeh I., Brocher T.M., Luetgert J.H., Mooney W.D., Nabelek J.L. and Nakamura Y.; 1994: *Crustal architecture of the Cascadia forearc.* Science, **266**, 237-243.

Turcotte D.L. and Schubert G.; 1982: *Geodynamics: Applications of continuum physics to geological problems.* John Wiley and Sons, New York, 347 p.

Unruh J.R., Lettis W.R. and Sowers J.M.; 1994: *Kinematic interpretation of the 1992 Landers earthquake.* Bull. Seism. Soc. Am., **84**, 537-546.

Upp R.R.; 1989: *Holocene activity and tectonic setting of the Macama fault zone, Mendocino County, California.* Eng. Geol., **27**, 375-412.

USNRC; 1978: *Appendix A of 10 CFR 100: Seismic and geologic siting criteria for nuclear power plants.* NRC, Washington DC.

USNRC; 1992: *Appendix B of 10 CFR 100: Seismic and geologic siting criteria for nuclear power plants.* NRC, Washington DC.

Viskocil Wassef A.M. and Green R.; 1983: *Recent crustal movements, 1982.* Elsevier, Amsterdam, 351 p.

Walcott D.; 1993: *Neogene tectonics and kinematics of western North America.* Tectonics, **12**, 326-333.

Wallace R. (ed); 1990: *The San Andreas fault system, California.* USGS Professional paper 1515.

Walter A.W. and Mooney W.D.; 1982: *Crustal structure of the Diablo and Gabilan ranges, Central California: a reinterpretation of existing data.* Bull. Seism. Soc. Am., **72**, 1567-1590.

Ward S.N.; 1994: *A multisciplinar approach to seismic hazard in southern California.* Bull. Seism. Soc. Am., **84**, 1293-1309.

Wdowinski S. and Axen G.J; 1992: *Isostatic rebound due to tectonic denudation: a viscous flow model of a layered lithosphere.* Tectonics, **11**, 303-315.

Weertman J. and Weertman J.R.; 1975: *High temperature creep of rock and mantle viscosity.* Ann. Rev. Earth Planet. Sci., **3**, 293-315.

Weldon R. and Humphreys E.; 1986: *A kinematic model of southern California.* Tectonics, **5**, 33-48.

Wells D.L. and Coppersmith K.J; 1994: *New Empirical Relationships among Magnitude, Rupture Length, Rupture Width, Rupture Area, and Surface Displacement.* Bull. Seism. Soc. Am., **84**, 974-1002.

Wesnousky S.G., Prentice C.S. and Sieh K.E.; 1991: *An offset Holocene stream channel and the rate of slip along the northern reach of the San Jacinto fault zone, San Bernardino Valley, California.* Geol. Soc. Am. Bull., **103**, 700-709.

Wezel F.C.; 1986: *The origin of arcs.* Elsevier, Amsterdam, 567 p.

Wezel F.C. ed.; 1981: *Sedimentary basins of Mediterranean margins.* Tecnoprint, Bologna, 520 p.

Wuethrich B.; 1994; *It's official: Quake danger in Northwest rivals the California's.* Science, **265**, 1802-1803.

Yeats R.S. and Lillie R.J.; 1991: *Contemporary tectonics of the Himalayan frontal fault system: folds, blind thrusts and the 1905 Kangra earthquake.* Journ. of Struct. Geol., **13**, 215-225.

Zandt G. and Carrigan C.R.; 1993: *Small scale convective instability and upper mantle viscosity under California.* Science, **261**, 460-463.

Zoback M.D. and Beroza G.C.; 1993: *Evidence for near-frictionless faulting in the 1989 (M 6.9) Loma Prieta, California, earthquake and its aftershocks.* Geology, **21**, 181-185.