# AN INNOVATIVE APPROACH FOR ASSESSING EARTHQUAKE INTENSITIES: THE PROPOSED INQUA SCALE BASED ON SEISMICALLY-INDUCED GROUND EFFECTS IN THE ENVIRONMENT

**Working Group under the INQUA Subcommission on Paleoseismicity**

**PRESENTED AT THE XVI INQUA CONGRESS**

**RENO, USA**

**JULY 23 – 30, 2003**

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## ABSTRACT

The debate originated within the Workshop of the Subcommission on Paleoseismicity held during the XV INQUA Congress in Durban, August 1999, emphasized the importance of developing a multi-proxy empirical database on earthquake ground effects that can be used by, and incorporated into, seismic-hazard assessment practices. The Subcommission selected this task as the primary goal for the past inter-congress period. An interdisciplinary Working Group (WG) was established, including geologists, seismologists and engineers, in order to formalize the collected data into a new scale of macroseismic intensity based only on ground effects: the proposed INQUA scale.

This paper illustrates the results of the research conducted by the WG, introduces the proposed INQUA scale, and discusses major issues related to this innovative approach to the intensity assessment. The INQUA scale first draft is due to Leonello Serva, based on the compilation and comparison of the three most commonly used intensity scales, i.e., the Mercalli-Cancani-Sieberg (MCS), Medvedev-Sponhouer-Karnik (MSK) and Mercalli Modified (MM). Eutizio Vittori, Eliana Esposito, Sabina Porfido and Alessandro M. Michetti produced a revised version, after (a) integration with the revised MM

scale of Dengler and McPherson (1993) and (b) checking the scale against the description of coseismic ground effects and intensity assessments for several tens of historical and instrumental earthquakes in the world. This version of the INQUA scale, presented during the XVI INQUA Congress in Reno, July 23-30, 2003, is a joint contribution of the WG including new data, editing, comments and scientific discussion from Bagher and Jody Mohammadioun, Eugene Roghozin, Ruben Tatevossian, Aybars Gürpinar, Franck Audemard, Shmulik Marco, Jim McCalpin, Nils-Axel Mörner, and Valerio Comerci. At this stage, the newly revised MM scale for New Zealand (Hancox, Perrin and Dellow, 2002), kindly provided by Graeme Hancox, has been also taken into account.

The outstanding progress of paleoseismological and Quaternary geology research in the past decades makes available an entirely new knowledge for understanding the response of the physical environment to seismicity, thereby providing the basis for the proposed INQUA intensity scale. The INQUA scale allows to define the epicentral intensity starting from the VI – VII level, with increasing accuracy going towards the highest levels. In the intention of the WG, the INQUA scale should not be used alone, but in combination with the existing scales. In the intensity range up to IX – X the scale allows a comparison between environmental effects and damage indicators, emphasizing the role of primary tectonic effects, which are independent from the local economy and cultural setting. In the intensity range X to XII, the INQUA scale is arguably the only suitable tool for assessing the epicentral intensity. In summary, we regard the INQUA scale as an unreplaceable addition to all the existing scales up to the IX – X level, while it represent the substance of the epicentral intensity assessment for the highest degrees.

## INTRODUCTION

Exactly what is a major earthquake? And what type of tool can be used to effectively measure the size of such a catastrophic event? Though long addressed, this problem has yet to receive a really definitive answer despite the considerable effort expended. The effects produced by earthquakes at the surface have notably come under close scrutiny, recognizing the fact that they actually result from the cumulated effects of the source (vibrations generated during slip, finite deformations), of the propagation of seismic waves, and, lastly, of local site effects. Well before the introduction, in 1935 by Charles Richter, of the notion of “magnitude” based on measurements made on instrumentally-recorded motion, certain erudite seismologists (in the persons of Mercalli, Cancani, and Sieberg, among others), in the early years of the last century, devised the notion of the “intensity” of an earthquake at a given location, in the absence of any seismometer (e.g., Sieberg, 1930; Wood and Neumann, 1931). Here, it is indeed man himself, and the environment he has built for himself, that stand in lieu of seismic sensor: thus the manner in which earthquake vibrations affect human beings and objects, as well as damage incurred by man-made structures, are the main criteria upon which the scales of so-called “macroseismic” intensity repose. But, and “there’s the rub,” the drawback to these measurements is that they integrate, analogous to the response of a seismograph, the responses of the human apparatus, and the responses of buildings, both difficult to gauge, or “calibrate,” precisely.

Might it then be possible to assess the size of earthquakes at their source on the sole basis of natural effects, thereby disposing of intermediaries (bearing in mind that human judgments and the behavior of his built environment are strongly influenced by socio-cultural factors that effectively resist all attempts to adequately codifying them in the intensity scales)? The need for a different approach to constructing such scales is hence clearly delineated, if for no other reason than that it is essential for us to be capable of obtaining a reliable measurement of the size of earthquakes — not only those known to have occurred during historical times, prior to the advent of the instrumental era, but also, and perhaps more importantly yet, those that took place before history was written, or even before the regions concerned knew human occupation. This new intensity scale accordingly aims at evaluating earthquake size from the sole evidence inscribed in the environment itself (the Earth herself, recounting her past) and more particularly in the epicentral zone.

The debate originated within the Workshop of the Subcommission on Paleoseismicity held during the XV INQUA Congress in Durban, South Africa, in August 1999, led to the recognition that developing a multi-proxy empirical database on earthquake ground effects that can be used by, and incorporated into, seismic-hazard assessment practices represents one important research challenge for earth scientists and engineers. Therefore, the Subcommission selected this task as the primary goal for the past inter-congress period 1999-2003. In particular, an interdisciplinary Working Group has been established comprised of geologists, seismologists and engineers, in order to formalize the collected data into a new scale of intensity based solely on ground effects, which in the following will be referred to as the INQUA scale. This paper illustrates the results of the work done by the Working Group, introduces the INQUA scale, and discusses the major issues relating to this innovative approach to the intensity assessment.

There is one very important aspect in introducing a new intensity scale into the practice. A great deal of work in seismic hazard assessment is accomplished in the world, and intensity is a basic parameter in this. Any “new word” in this research field must not result in dramatic changes. Intensity VIII, for instance, has to mean more or less the same “strength” of the earthquake, regardless of which macroseismic phenomena (anthropic or geological) it is assessed from. Obviously the proposed INQUA intensity scale based on ground effects is not intended to replace the existing scales. We are simply affording a means to factor in the modifications induced by the earthquake on the physical environment, and then to compare them with the effects taken into account by other scales. There, indeed, the combined observations of widely varied effects is most likely to yield a more representative estimate of intensity—which in turn, using modern events as test cases, can then be collated with such instrumental measurements as magnitude and seismic moment.

## INTENSITY — WHY TODAY?

The intensity parameter is used in many parts of the world for seismic hazard analysis, and is destined to remain an important one in seismology, and earthquake geology and engineering. This is true for several reasons:

- Intensity studies enable the macroseismic field of historical and contemporary earthquakes to be reconstructed and, through this reconstruction, make it often possible to identify the seismogenic source. Figures 1 and 2 illustrate this point, by comparing the isoseismals from historical and contemporary earthquakes in the Southern Apennines of Italy.
- The isoseismal map of an earthquake makes possible the comparison between the attenuation derived using magnitude-distance relationships and the attenuation derived from the macroseismic field.
- The intensity values of an earthquake at various localities represent the combined effects of source-path and site conditions and could be very important in some cases from an engineering point of view.
- Original intensity scales are built on the observed consistency between severity (degree and extent) of ground effects and the local physical environment, which is also at the base of the concept of seismic landscape (Serva *et al.*, 1997; Michetti and Hancock, 1997; Serva *et al.*, 2002; see Figure 3). In paleoseismology, when geologists assess the magnitude of past earthquakes, a single category of paleoseismic evidence (such as fault surface displacement, size of liquefaction features, and uplifted shorelines) is generally used. However, it could be helpful to check the assessed magnitude against other phenomena (mainly on the ground, in the epicentral area: for instance, quality and quantity of landslides, changes in topography) that are described in the intensity scales at the intensity degree coherent with the assessed magnitude and focal depth.
- Most important, this parameter allows the comparison among recent earthquakes and historical ones, based on the effects described in the intensity scale. In using earthquake ground effects, this is particularly relevant for the highest degrees of the scale. In other words, the effects are compared rather than the calculated magnitudes of the earthquakes.

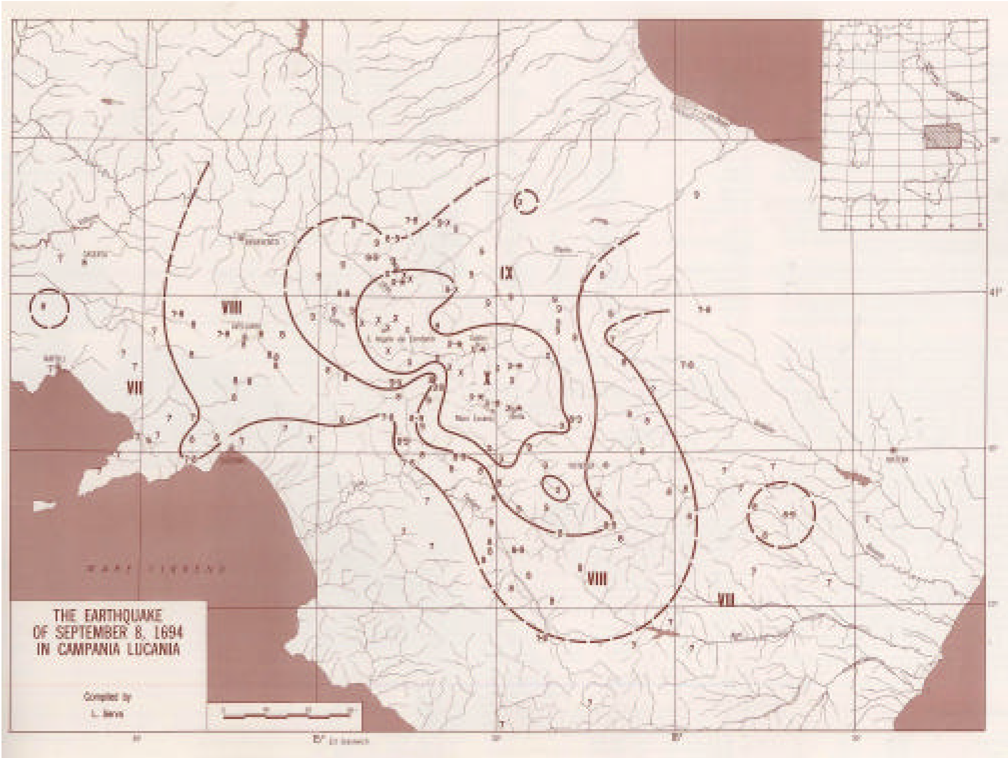



**Figure 1**: Isoseismal map for the 1694 Irpinia earthquake. After Postpischl, 1985a.

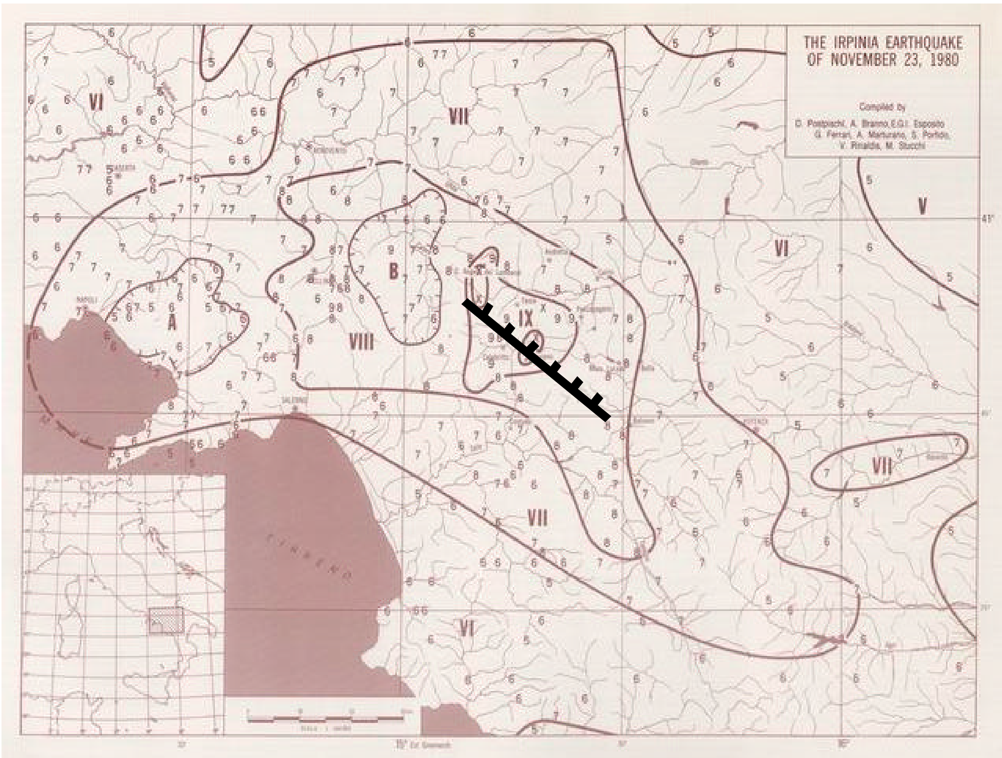



**Figure 2**: Isoseismal map and surface faulting for the 1980 Irpinia earthquake. After Postpischl, 1985a, modified.

## THE SHORTCOMINGS OF EARLIER SCALES — WHY INTENSITY SHOULD BE EVALUATED USING GROUND EFFECTS

Earthquakes have often been described in historical chronicles, with more or less precise details, depending on the culture of the time or place, or even because of specific practical interests (e.g., Postpischl, 1985a, Ambraseys *et al.*, 1994; Boschi *et al.*, 1995; 1997; 2000). Countries with a rich historical heritage therefore have available a long record of earthquakes whose size can only be evaluated on the basis of their effects on man-made structures and in the environment, as reported in these chronicles. For this reason, specific scales (macroseismic scales) have been developed defining degrees of intensity expressed in Roman numerals that generally range between I and XII. In the original scales, intensity degrees were based essentially on a hierarchical classification of effects. In a general way, the diagnostic effects for the lower degrees are essentially those on people and animals, for the intermediate degrees those on objects and buildings, for the highest degrees, when the sensors related to the human environment are obviously useless because the earthquake is so strong that everything has been destroyed, those on the natural surroundings. The effects on the ground reported in the scales include primary, tectonic features such as surface faulting, and secondary, mostly shaking-induced phenomena, such as ground cracks, slope instabilities, and liquefaction (Table 1; Serva, 1994; Esposito *et al.*, 1997). These effects are, in fact, often cited in historical and contemporary reports and have the advantage of not generally being influenced by human practices, many of them depending on source parameters and local geology alone (e.g., Koizumi, 1966; Youd and Hoose, 1978; Keefer, 1984; Xue-Cai and An-Ning, 1986; Youd and Perkins, 1987; Umeda *et al.*, 1987; Papadopoulos and Lefkopoulos, 1993; Ambraseys and Srbulov, 1995; Esposito *et al.*, 1997; Rodriguez *et al.*, 1999). It is proven that many natural effects occur only in the epicentral area (near field), and that they appear and start to become relevant at well-defined intensity levels. This means that a proper estimation of the intensity of an earthquake should take these effects into account.

**Table 1**: Ground effects in the MCS-1930, MM-1931, MSK-1964 and Japanese (JAP) intensity scales (after Esposito *et al.*, 1997).

| | |
|---|---|
| Cracks in saturated soil and/or loose alluvium: | |
| up to 1 cm: | MSK: VI |
| a few cm: | MSK: VIII: MM: VIII; MCS: VIII |
| up to lOcm: | MSK: IX; MM: IX |
| a few dm up to one meter | MSK: X; MCS: X |
| Cracks on road backfills and on natural terrigenous slopes over 10 cm | MSK: VII, VIII, IX; MM: VIII; MCS: VIII |
| Cracks on dry ground or on asphalted roads | MSK: VII, IX, XI: MCS: X, XI; JAP: VI |
| Faults cutting poorly consolidated Quaternary sediments | MSK: XI; MCS: XI |

| | |
|---|---|
| Faults cutting bedrock at the surface | MSK: XII; JAP: VII |
| Liquefaction and/or mud volcanoes and/or subsidence | MSK: IX, X; MM: IX, X; MCS: X, XI |
| Landslides in sand or gravel artificial dykes | MSK: VII, VIII, X; MM: VII; MCS: VII |
| Landslides in natural terrigenous slopes | MSK: VI, IX, X, XI; MM: X; MCS: X, XI; JAP: VI, VII |
| Rockfalls | MSK: IX, XI, XII; MM: XII; MCS: X, XI |
| Turbulence in the closed water bodies and formation of waves | MSK: VII, VIII, IX; MM: VII; MCS: VII, VIII |
| Formation of new water bodies | MSK: VIII, X, XII; MCS: XII |
| Change in the direction of flow in watercourses | MSK: XII; MCS: XII |
| Flooding | MSK: X, XII; MM: X; MCS: X |
| Variation in the water level of wells and/or the flow rate of springs | MSK: V, VI, VII, VIII, IX, X; MM: VIII; MCS: VII, X |
| Springs which dry out or are starting to flow | MSK: VII, VIII, IX |

However, over the past 40 years at least, proper attention has not been paid to these effects in estimating intensity because they were reputed to be too variable, and likewise because they were not properly weighted in the scales. For example, recent data indicate that some phenomena occur, or start to occur, at degrees other than the ones they are assigned to in the scales: liquefaction, for instance, starts at lower intensities (VI-VII, or even V; e.g., Keefer, 1984; Galli and Ferreli, 1995; Rodriguez *et al.*, 1999, Galli, 2000, Porfido *et al.*, 2002) and not at VII or IX as indicated in the scales. We argue that the existence of similar inconsistencies in the available macroseismic scales should not bring to the conclusion that ground effects are useless for assessing earthquake intensity. On the contrary, we believe that this is the result of several decades of research on earthquake engineering, Quaternary geology and paleoseismology, which brougth to the buildup of an entirely new knowledge in the study of coseismic environmental effects and their relations with a) the local tectonic and geomorphic setting, and b) the source parameters of the causative seismic event (e.g., Vittori *et al.*, 1991; McCalpin, 1996; Michetti and Hancock, 1997; Yeats *et al.*, 1997). The aim of our proposed scale is therefore to update the pre-existing scales by including this new knowledge into the earthquake intensity assessment. In fact, the problem of updating the intensity scales does also involve the effects on people and the manmade environment. For instance, a great deal of effort has been expended throughout the last century to increasing the robustness of the scales by improved definition and redistribution of the various typologies of damage to the different degrees of the scales. Along the same line, the new insights available today into the response of the physical environment to seismicity can lead to intensity evaluations which are better description of the real strength of the causative earthquake.

Also, the wide variability of some effects is not a good reason to exclude all seismically-generated natural phenomena from the scale. In most cases, this variability can be properly taken into account through a careful inspection of coseismic effects in the field, exactly in the same way as for the effects on humans and manmade environment. To improve the definition of the ground effects in the different degree of the scales, we checked our proposed scale against macroseismic data coming from the careful analysis of the earthquakes listed in Table 2. We carried out this comparison assuming the following notion. On the basis of our knowledge, we are convinced that the macroseismic degrees in the scales have mainly been defined by looking at the effects on humans and anthropic structures (especially buildings), whereas ground effects have been assigned mainly by looking at the isoseismal lines. Although not explicitly specified by the authors of the early scales, this is in our opinion the reasoning behind the assignment of a given effect to a given intensity degree. In any case, this is the criterion we have adopted in this paper in order to ensure the internal consistency of the new scale, and to allow a straightforward integration with the other scales.

The supposed uncertainties lead to an increasing lack in the confidence in using ground effects as diagnostics, and progressively the effects on human perception and the anthropic environment (mainly buildings) became the only sensors analyzed for intensity assessment. Exemplifying this logic, in the latest proposal by the European Seismological Commission to revise the MSK scale (Grunthal, 1998), these effects are not reported in the scale per se, only in a brief appendix. We believe, however, that if this orientation is pursued, intensity will come to reflect mainly the economic development of the area that experienced the earthquake instead of its “strength” (Serva, 1994). It is also our belief that by ignoring ground effects, it will not be possible to assess intensity accurately in sparsely populated areas and/or areas inhabited by people with different modes of existence, such as nomads. This point has been already very clearly made by Dengler and McPherson (1993); this proposal for a new scale is the logic extension of their approach. Furthermore the main problems arise for the highest degrees - XI and XII - where ground effects are the only ones that permit a reliable estimation of earthquake size. All the scales, in fact, show that in this range of intensity ground effects predominate.

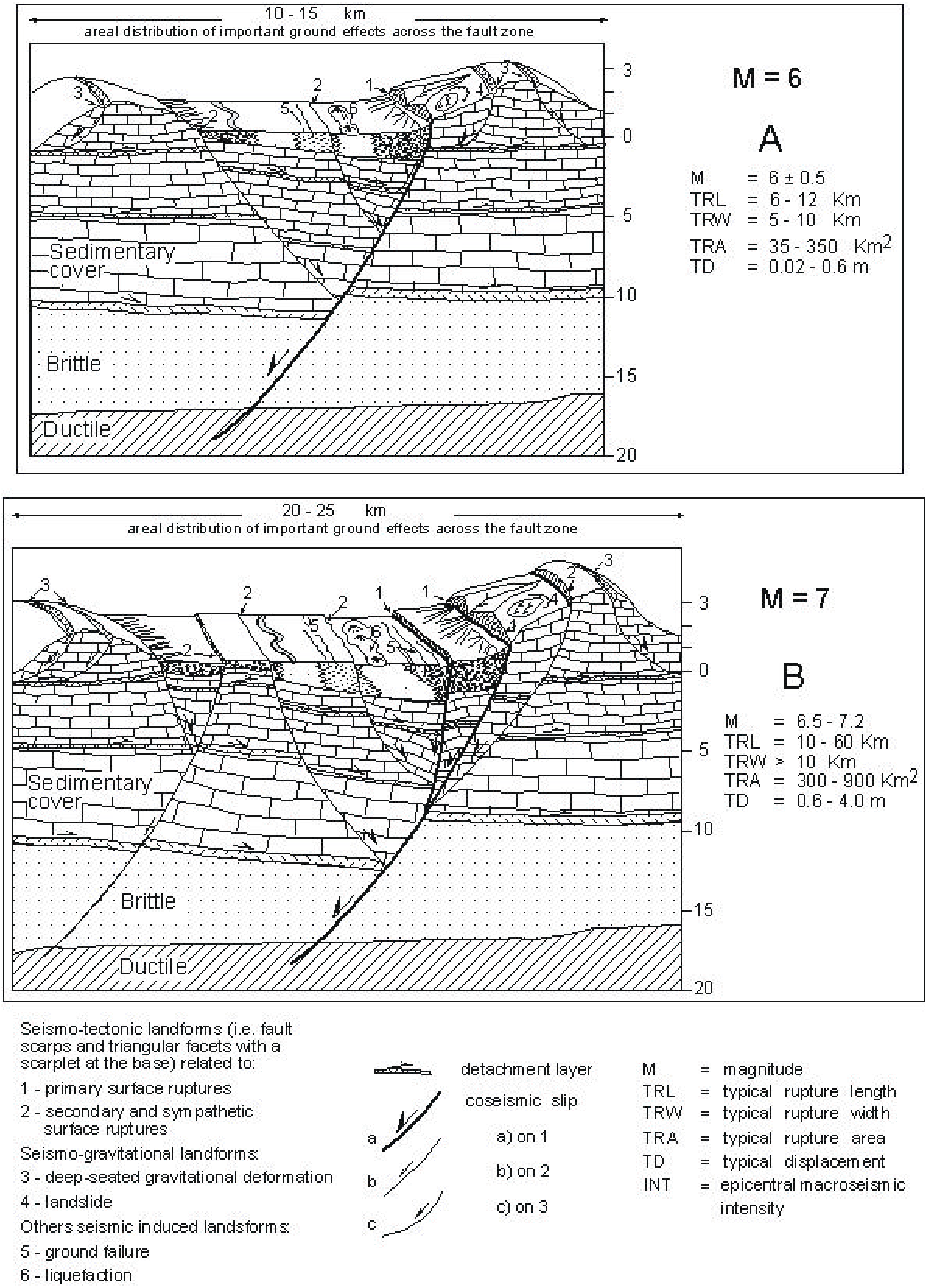



**Figure 3**: Seismic landscapes in the Apennines. Schematic block-diagram of two Quaternary intermountain basins associated with M ≅ 6 (A) and M ≅ 7 (B) normal faulting earthquakes; the picture illustrates the typical seismo-tectonic, sedimentary, and paleoseismological features due to the repetition of the coseismic ground effects over a geological time interval. Typical values of surface faulting parameters (rupture length, rupture width, rupture area, vertical displacement) are shown. After Serva *et al.*, 2002, modified.

Because of all this, we deem it necessary that the seismological community (in a broad sense — all people involved in seismic risk analysis) should continue to using scales that take into account all the natural phenomena pertaining to each degree. In line with this, we propose here a scale that reports only ground effects, based on the knowledge currently available in this matter.

The scale has been compiled based on the descriptions reported in: a) the three most common intensity scales, i.e., Mercalli-Cancani-Sieberg (MCS, Sieberg, 1930), Medvedev-Sponhouer-Karnik (MSK, 1964) and Modified Mercalli (MM, Wood and Neumann, 1931; Richter, 1958); b) the paper by Dengler and McPherson (1993); c) the newly revised MM scale for New Zealand (Hancox *et al.*, 2002) and d) a collection of pertinent papers, studies, and reports (as listed in Appendix 1). It should be noted that the description for any degree can be directly integrated into the corresponding degree of any of the above scales. Obviously, where they are not explicitly mentioned, a degree incorporates all the effects found in the lower degrees, although commonly more amply expressed and over a wider extent..

## GENERAL STATEMENTS

Serva (1994) and Esposito *et al.* (1997), among others, have already discussed some of the problems that must be dealt with when attempting to use natural effects for intensity assessment. However we think it would be useful to note the following considerations affecting the proper use of this scale.

In the following description of the proposed INQUA scale, text in italics refers to those effects directly usable to define an intensity degree (e.g., jumping stones, soil cracking, surface faulting). The size and the frequency of occurrence of many other natural effects, however, are not controlled by earthquake magnitude and hypocentral depth alone. Rather, they appear primarily to be governed by the duration and level of motion (acceleration, velocity, displacement), as well as by the frequency content of shaking, on the one hand, and by the local morphology and lithology of the terrain, on the other (so-called *land vocation* or likelihood or sensitivity to a specific phenomenon). For example, landslides depend on slope angles, the mechanical properties of the involved lithologies, water saturation, the nature and extent of vegetation, man-made changes and previous events. Hence, when the likelihood of an effect's occurring varies considerably depending on a number of controlling parameters, the intensity threshold can also vary significantly. So, landslides may occur for very low-intensity events (even IV; e.g., Keefer, 1984; Rodriguez *et al.*, 1999), but can be absent even for the strongest events (XII).

For such effects to be able to be used in assessing intensity, they will need to be painstakingly evaluated on a case-by-case basis. These therefore are not indicated in our scale as determinant for intensity assessment.

Notwithstanding the aforementioned limitations, we nevertheless believe that an accurate analysis, taking into proper account the land *vocation*, and therefore based on direct observations in the field, may allow intensity degree appraisal. For instance, in the Apennines of Italy, as well as in New Zealand, it is possible to determine well defined relationships between landslide distribution and earthquake magnitude, epicentre, isoseismals, faulting, geology, and topography (Porfido *et al.*, 2002; Hancox *et al.*, 2002). The analysis of the catalogues of Italian historical earthquakes (Postpischl, 1985a; 1985b; Boschi *et al.*, 1995; 1997; 2000) carried out by Romeo and Delfino (1997) shows that the triggering threshold for landslides, below which the number and size of the slides becomes negligible (< 5 %) is degree VI-VII, whereas for liquefaction it is ca. VII. During the recent, September – October 1997, Umbria-Marche earthquake swarm in Central Italy (maximum intensity VIII-IX), the size and frequency of rockfalls along road cuts, as well as that of fractures, sharply increase as one moves towards the inside of the epicentral area (Esposito *et al.*, 2000; Vittori *et al.*, 2000).

Effects in the epicentral area (near field) depend essentially on the high-frequency vibration of ground motion (acceleration) and its duration, as well as on very low frequency seismic waves due to directivity and fling (slip on the fault), which give rise in the near field to long-period, so-called “killer” pulses (cf., the August, 17, 1999, Izmit/Kocaeli, Turkey and the 1999, Taiwan, earthquakes; e.g., EERI, 1999; USGS, 1999). In the far field, the effects are generally linked with long-period surface waves, more prominent on horizontal components of motion, and having long duration.

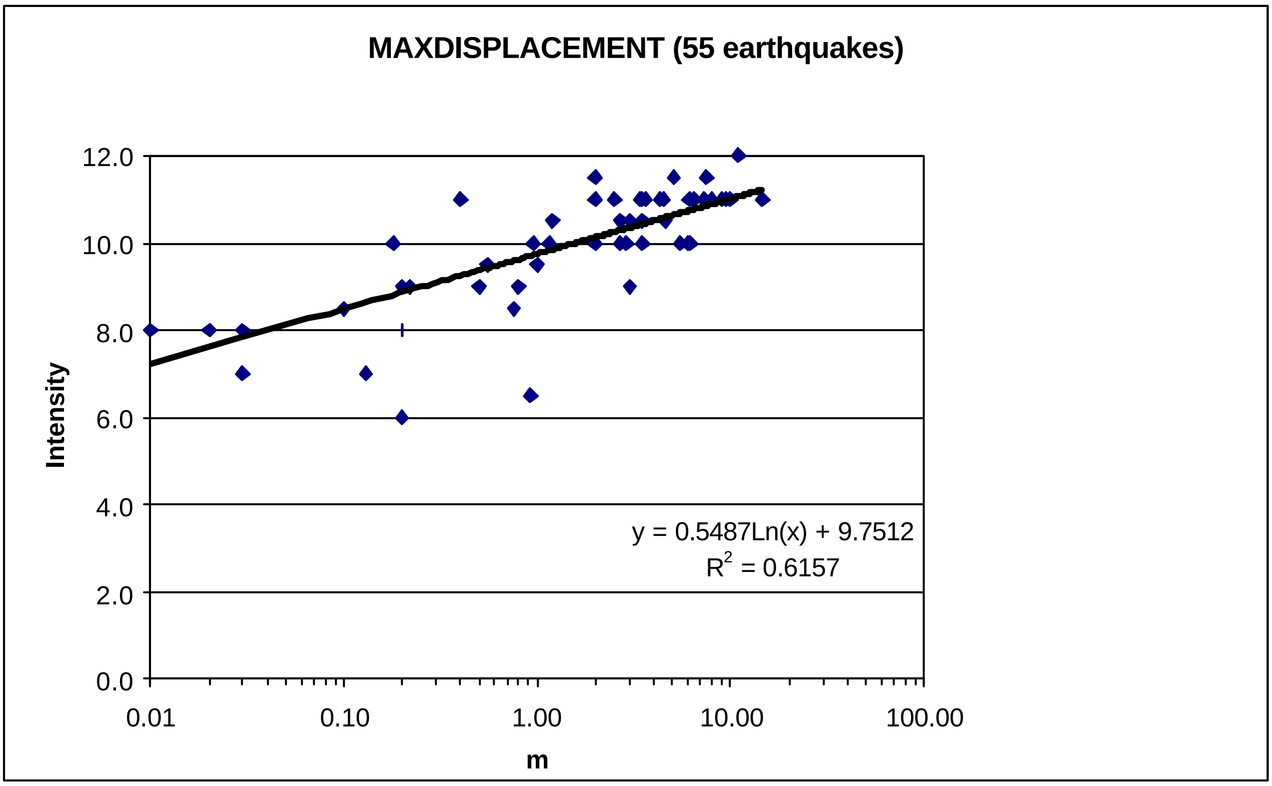
In summary, the environmental effects observed during earthquakes can be classified as follows:

A) Effects occurring under conditions of precarious equilibrium:
   1) They also can be induced by other natural events or human activities;
   2) They usually occur in mountainous or hilly areas, and in wet terrain;
   3) The highest concentration and amplitude of such effects can indicate the epicentral area, but, alternatively, also the area most prone to this phenomenon;
   4) Such effects, in the absence of independent evidence of seismicity (effects on man or man-made structures), do not allow the positive recognition of an earthquake and its intensity.

B) Effects occurring under conditions of relatively stable equilibrium:
   1) Earthquake markers: ascribable, due to their nature (frequency of occurrence, size, and areal distribution) only to an earthquake as causative event.
   2) Intensity gauges (mainly relevant for strong earthquakes):
      a) Undoubtedly connected to earthquakes because not producible by other processes, even of exceptional intensity:

b) In no way connected only to the environmental setting. Generally they occur in two cases:

- When the vertical component of acceleration is greater than gravity (in epicentral areas; e.g. Umeda *et al.*, 1987);
- When surface faulting takes place. It begins to show up for intensities around VIII, and, for the same tectonic environment, rupture length and offset are thereafter proportional to macroseismic intensity. An original relationship between surface faulting parameters and intensity for crustal earthquakes is here proposed (Figure 4 and Table 3).



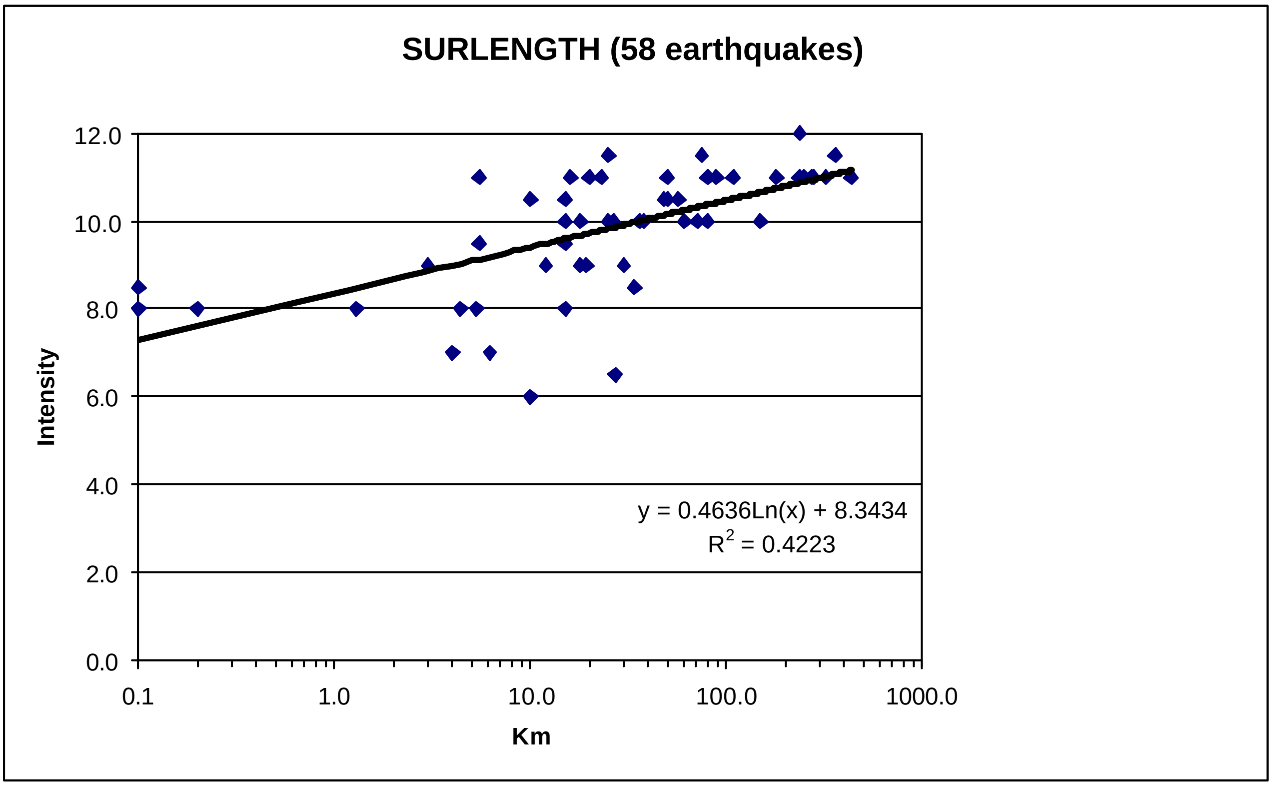



**Figure 4**: Diagram showing relations between epicentral intensity and surface faulting parameters for crustal earthquakes (4A, maximum displacement; 4B, rupture length); data from seismic events listed in Table 3.

## *THE INQUA SCALE*

As already mentioned, the assignment of each environmental effect to its proper intensity interval in the following INQUA scale has been based on a careful reading of the most widely applied scales, i.e., the MM, MCS and MSK scales, integrated with more recent work indicated in the references and Appendix 1.

In particular, the diagnostics used in the INQUA scale have been compared and found consistent with the macroseismic data available for a sample of historical and contemporary Italian earthquakes, as listed in Table 2. We have accurately reviewed the surface effects of 115 earthquakes occurred in Italy since the XII century, documented in available catalogs and historical sources directly analyzed. The effects have been categorized according to the scheme in Table 4. Each effect has been associated to the macroseismic intensity attributed in the historical catalogs (Caputo and Faita, 1984; Postpischl, 1985a; 1985b; Boschi *et al.*, 1995; Tinti and Maramai, 1996; Boschi *et al.*, 1997; Azzaro *et al.*, 2001; CPTI, 1999; Boschi *et al.*, 2000) on the basis of local damage patterns.

About the intensity threshold for the occurrence of landslides, we have also taken into account the data of 40 earthquakes worldwide given in Keefer (1984), updated with other 36 events word-wide by Rodriguez *et al.* (1999), and 22 earthquakes in New Zealand (Hancox *et al.*, 2002). For the onset of liquefaction we have also considered the data for Venezuela given in Rodriguez *et al.* (2002).

As for primary faulting, we have based our analysis on a first screening of the Wells and Coppersmith (1994) and Yeats *et al.* (1997) dataset of earthquakes associated to surface faulting, integrated with some recent Italian and Mediterranean region events. The screening has been based on the availability of epicentral intensity values and it is still a work in progress. We have plotted the maximum displacement and the surface rupture length versus epicentral intensity, obtaining the plots in Figure 4.

This database of macroseismic data is subject to expansion and revision in order to incorporate more case histories; however, we are convinced that the sample of seismic events studied is large enough for validating the proposed scale with a resolution consistent with the scope of the present paper. For instance, we found several crustal earthquakes associated with rupture lengths of tens of kilometers for which an epicentral intensity of VIII or even of VII (MM or MSK) has been reported. With the INQUA scale, an epicentral intensity of X or XI would have been assigned, which is unequivocally a better description of the size of these events, both in terms of magnitude and of ground shaking level.

The degrees of the INQUA scale can be directly compared with the corresponding degrees of most of the twelve-degree scales referred to above, in view of the fact that the differences among these scales are not substantial in terms of the level of accuracy they can provide (Appendix 2). The INQUA scale is an innovative proposal — or perhaps is simply the recognition that the work accomplished by earthquake scientists in the first decades of the XX century is worth pursuing along the lines of its original inspiration. It reflects the present viewpoint of its authors, which is necessarily subject to modification in its details, notwithstanding their effort to integrate the largest database possible. Contributions and criticism from other researchers are expected and will be welcomed. They will in all probability provide the basis for a revised version, where new effects may be incorporated and grade intervals of occurrence and size of effects better constrained.

## *DEFINITIONS OF INTENSITY DEGREES*

### I, II No perceptible environmental effects

a) Extremely rare occurrence of small effects detected only from instrumental observations, typically in the far field of strong earthquakes.

**III No perceptible environmental effects**

a) Primary effects are absent.

b) Extremely rare occurrence of small variations in water level in wells and/or the flow-rate of springs, typically in the far field of strong earthquakes.

**IV No perceptible environmental effects**

a) Primary effects are absent.

b) A very few cases of fine cracking at locations where lithology (e.g., loose alluvial deposits, saturated soils) and/or morphology (slopes or ridge crests) are most prone to this phenomenon.

c) Rare occurrence of small variations in water level in wells and/or the flow-rate of springs.

d) Extremely rare occurrence of small variations of chemical-physical properties of water and turbidity of water in lakes, springs and wells, especially within large karstic spring systems most prone to this phenomenon.

e) Exceptionally, rocks may fall and small landslides may be (re)activated, along slopes where equilibrium is already very unstable, e.g. steep slopes and cuts, with loose or saturated soil.

f) Extremely rare occurrence of karst vault collapses, which may result in the formation of sinkholes, where the water table is shallow within large karstic spring systems.

g) Very rare temporary sea level changes in the far field of strong earthquakes.

h) Tree limbs may shake.

**V Marginal effects on the environment**

a) Primary effects are absent.

b) A few cases of fine cracking at locations where lithology (e.g., loose alluvial deposits, saturated soils) and/or morphology (slopes or ridge crests) are most prone to this phenomenon.

c) Extremely rare occurrence of significant variations in water level in wells and/or the flow-rate of springs.

d) Rare occurrence of small variations of chemical-physical properties of water and turbidity of water in lakes, springs and wells.

e) Rare small rockfalls, rare rotational landslides and slump earth flows, along slopes where equilibrium is unstable, e.g. steep slopes, with loose or saturated soil.

f) Extremely rare cases of liquefaction (sand boil), small in size and in areas most prone to this phenomenon (hihgly susceptible, recent, alluvial and coastal deposits, shallow water table).

g) Extremely rare occurrence of karst vault collapses, which may result in the formation of sinkholes, where the water table is shallow within large karstic spring systems.

h) Occurrence of landslides under sea (lake) level in coastal areas.

i) Rare temporary sea level changes in the far field of strong earthquakes.

j) Tree limbs may shake.

## VI Modest effects on the environment

a) Primary effects are absent.

*b) Occasionally thin, millimetric, fractures are observed in loose alluvial deposits and/or saturated soils; along steep slopes or riverbanks they can be 1-2 cm wide. A few minor cracks develop in paved (asphalt / stone) roads.*

c) Rare occurrence of significant variations in water level in wells and/or the flow-rate of springs.

d) Rare occurrence of variations of chemical-physical properties of water and turbidity of water in lakes, springs and wells.

e) Rockfalls and landslides up to ca. 103 m3 can occur, especially where equilibrium is unstable, e.g. steep slopes and cuts, with loose / saturated soil, or weathered / fractured rocks. The area affected by them is usually less than 1 km2.

*f) Rare cases of liquefaction (sand boil), small in size and in areas most prone to this phenomenon (hihgly susceptible, recent, alluvial and coastal deposits, shallow water table).*

g) Extremely rare occurrence of karst vault collapses, which may result in the formation of sinkholes.

h) Occurrence of landslides under sea level in coastal areas.

i) Occasionally significant waves are generated in still waters.

*j) In wooded areas, trees shake; a very few unstable limbs may break and fall, also depending on species and state of health.*

## VII Appreciable effects on the environment

a) Primary effects observed very rarely. Limited surface faulting, with length of tens of meters and centimetric offset, may occur associated with volcano-tectonic earthquakes.

*b) Fractures up to 5-10 cm wide are observed commonly in loose alluvial deposits and/or saturated soils; rarely in dry sand, sand-clay, and clay soil fractures up to 1 cm wide. Centimetric cracks common in paved (asphalt or stone) roads.*

c) Rare occurrence of significant variations in water level in wells and/or the flow rate of springs. Very rarely, small springs may temporarily run dry or be activated.

d) Quite common occurrence of variations of chemical-physical properties of water and turbidity of water in lakes, springs and wells.

e) Scattered landslides occur in prone areas; where equilibrium is unstable (steep slopes of loose / saturated soils; rock falls on steep gorges, coastal cliffs) their size is sometimes significant ($10^3$ - $10^5$ $m^3$); in dry sand, sand-clay, and clay soil, the volumes are usually up to 100 $m^3$. Ruptures, slides and falls may affect riverbanks and artificial embankments and excavations (e.g., road cuts, quarries) in loose sediment or weathered / fractured rock. The affected area is usually less than 10 $km^2$.

f) *Rare cases of liquefaction, with sand boils up to 50 cm in diameter, in areas most prone to this phenomenon (hihgly susceptible, recent, alluvial and coastal deposits, shallow water table).*

g) Possible collapse of karst vaults with the formation of sinkholes, even where the water table is deep.

h) Occurrence of significant landslides under sea level in coastal areas.

i) Waves may develop in still and running waters.

j) In wooded areas, trees shake; several unstable branches may break and fall, also depending on species and state of health.

## VIII Considerable effects on the environement

a) *Primary effects observed rarely. Ground ruptures (surface faulting) may develop, up to several hundred meters long, with offsets generally smaller than 5 cm, particularly for very shallow focus earthquakes, such as volcano-tectonic events. Tectonic subsidence or uplift of the ground surface with maximum values on the order of a few centimeters may occur.*

b) *Fractures up to 25 - 50 cm wide are commonly observed in loose alluvial deposits and/or saturated soils; in rare cases fractures up to 1 cm can be observed in competent dry rocks. Decimetric cracks common in paved (asphalt or stone) roads, as well as small pressure undulations.*

c) *Springs can change, generally temporarily, their flow-rate and/or elevation of outcrop. Some small springs may even run dry. Variations in water level are observed in wells.*

d) *Water temperature often change in springs and/or wells. Water in lakes and rivers frequently become muddy.*

e) Small to moderate ($10^3$ - $10^5$ $m^3$) landslides widespread in prone areas; rarely they can occur also on gentle slopes; where equilibrium is unstable (steep slopes of loose / saturated soils; rock falls on steep gorges, coastal cliffs) their size is sometimes large ($10^5$ - $10^6$ $m^3$). Landslides can occasionally dam narrow valleys causing temporary or even permanent lakes. Ruptures, slides and falls affect riverbanks and artificial embankments and excavations (e.g., road cuts, quarries) in loose sediment or weathered / fractured rock. The affected area is usually less than 100 km$^2$.

f) *Liquefaction may be frequent in the epicentral area, depending on local conditions; sand boils up to ca. 1 m in diameter; apparent water fountains in still waters; localised lateral spreading and settlements (subsidence up to ca. 30 cm), with fissuring parallel to waterfront areas (river banks, lakes, canals, seashores).*

g) Karst vaults may collapse, forming sinkholes.

h) Frequent occurrence of landslides under the sea level in coastal areas.

i) Significant waves develop in still and running waters.

j) *Trees shake vigorously; some branches or rarely even tree-trunks in very unstable equilibrium may break and fall.*

k) *In dry areas, dust clouds may rise from the ground in the epicentral area.*

**IX Natural effects leave significant and permanent traces in the environment.**

a) *Primary effects observed commonly. Ground ruptures (surface faulting) develop, up to a few km long, with offsets generally smaller than 10 - 20 cm. Tectonic subsidence or uplift of the ground surface with maximum values in the order of a few decimeters may occur.*

b) *Fractures up to 50 - 100 cm wide are commonly observed in loose alluvial deposits and/or saturated soils; in competent rocks they can reach up to 10 cm. Significant cracks common in paved (asphalt or stone) roads, as well as small pressure undulations.*

c) Springs can change their flow-rate and/or elevation of outcrop to a considerable extent. Some small springs may even run dry. Variations in water level are observed in wells.

d) Water temperature often change in springs and/or wells. Water in lakes and rivers frequently become muddy.

e) *Landsliding widespread in prone areas, also on gentle slopes; where equilibrium is unstable (steep slopes of loose / saturated soils; rock falls on steep gorges, coastal cliffs) their size is frequently large (10$^5$ m$^3$), sometimes very large (10$^6$ m$^3$). Landslides can dam narrow valleys causing temporary or even permanent lakes. Riverbanks, artificial embankments and excavations (e.g., road cuts, quarries) frequently collapse. The affected area is usually less than 1000 km$^2$.*

f) *Liquefaction and water upsurge are frequent; sand boils up to 3 m in diameter; apparent water fountains in still waters; frequent lateral spreading and settlements (subsidence of more than ca. 30 cm), with fissuring parallel to waterfront areas (river banks, lakes, canals, seashores).*

g) Karst vaults of relevant size collapse, forming sinkholes.

h) Frequent large landslides under the sea level in coastal areas.

*i) Large waves develop in still and running waters. Small tsunamis may reach the coastal areas with tidal waves up to 50 - 100 cm high.*

j) Trees shake vigorously; branches or even tree-trunks in unstable equilibrium frequently break and fall.

k) In dry areas dust clouds may rise from the ground.

l) In the epicentral area, small stones may jump out of the ground, leaving typical imprints in soft soil.

**X Environmental effects become dominant.**

*a) Primary ruptures become leading. Ground ruptures (surface faulting) can extend for several tens of km, with offsets reaching 50 - 100 cm and more (up to ca. 1-2 m in case of reverse faulting and 3-4 m for normal faulting). Gravity grabens and elongated depressions develop; for very shallow focus earthquakes, such as volcano-tectonic events, rupture lengths might be much lower. Tectonic subsidence or uplift of the ground surface with maximum values in the order of few meters may occur.*

*b) Large landslides and rock-falls (> $10^5$ - $10^6$ $m^3$) are frequent, practically regardless to equilibrium state of the slopes, causing temporary or permanent barrier lakes. River banks, artificial embankments, and sides of excavations typically collapse. Levees and earth dams may even incur serious damage. The affected area is usually up to 5000 $km^2$.*

c) Many springs significantly change their flow-rate and/or elevation of outcrop. Some may run dry or disappear, generally temporarily. Variations in water level are observed in wells.

d) Water temperature often change in springs and/or wells. Water in lakes and rivers frequently become muddy.

*e) Open ground cracks up to more than 1 m wide are frequent, mainly in loose alluvial deposits and/or saturated soils; in competent rocks opening reach several decimeters. Wide cracks develop in paved (asphalt or stone) roads, as well as pressure undulations.*

f) *Liquefaction, with water upsurge and soil compaction, may change the aspect of wide zones; sand volcanoes even more than 6 m in diameter; vertical subsidence even > 1m; large and long fissures due to lateral spreading are common.*

g) Large karst vaults collapse, forming great sinkholes.

h) Frequent large landslides under the sea level in coastal areas.

*i) Large waves develop in still and running waters, and crash violently into the shores. Running (rivers, canals) and still (lakes) waters may overflow from their beds. Tsunamis reach the coastal areas, with tidal waves up to a few meters high.*

j) Trees shake vigorously; branches or even tree-trunks very frequently break and fall, if already in unstable equilibrium.

k) In dry areas, dust clouds may rise from the ground.

*l) Stones, even if well anchored in the soil, may jump out of the ground, leaving typical imprints in soft soil.*

**XI Environmental effects become essential for intensity assessment.**

*a) Primary surface faulting can extend for several tens of km up to more than 100 km, accompanied by offsets reaching several meters. Gravity graben, elongated depressions and pressure ridges develop. Drainage lines can be seriously offset. Tectonic subsidence or uplift of the ground surface with maximum values in the order of numerous meters may occur.*

*b) Large landslides and rock-falls (> $10^5$ - $10^6$ $m^3$) are frequent, practically regardless to equilibrium state of the slopes, causing many temporary or permanent barrier lakes. River banks, artificial embankments, and sides of excavations typically collapse. Levees and earth dams incur serious damage. Significant landslides can occur at 200 – 300 km distance from the epicenter. Primary and secondary environmental effects can be observed over territory as large as 10000 $km^2$.*

c) Many springs significantly change their flow-rate and/or elevation of outcrop. Frequently, they may run dry or disappear altogether. Variations in water level are observed in wells.

d) Water temperature often change in springs and/or wells. Water in lakes and rivers frequently becomes muddy.

*e) Open ground cracks up to several meters wide are very frequent, mainly in loose alluvial deposits and/or saturated soils. In competent rocks they can reach 1 m. Very wide cracks develop in paved (asphalt or stone) roads, as well as large pressure undulations.*

*f) Liquefaction changes the aspect of extensive zones of lowland, determining vertical subsidence possibly exceeding several meters, numerous large sand volcanoes, and severe lateral spreading features.*

g) Very large karst vaults collapse, forming sinkholes.

h) Frequent large landslides under the sea level in coastal areas.

i) *Large waves develop in still and running water, and crash violently into the shores. Running (rivers, canals) and still (lakes) waters may overflow from their beds. Tsunamis reach the coastal areas with tidal waves up to many meters high.*

*j) Trees shake vigorously; many tree branches break and several whole trees are uprooted and fall.*

k) In dry areas dust clouds may arise from the ground.

*l) Stones and small boulders, even if well anchored in the soil, may jump out of the ground leaving typical imprints in soft soil.*

**XII Environmental effects are now the only tool enabling intensity to be assessed.**

a) *Primary surface faulting can extend for several hundreds of km up to 1000 km, accompanied by offsets reaching several tens of meters. Gravity graben, elongated depressions and pressure ridges develop. Drainage lines can be seriously offset. Landscape and geomorphological changes induced by primary effects can attain extraordinary extent and size (typical examples are the uplift or subsidence of coastlines by several meters, appearance or disappearance from sight of significant landscape elements, rivers changing course, origination of waterfalls, formation or disappearance of lakes).*

b) *Large landslides and rock-falls (> $10^5$ - $10^6$ $m^3$) are frequent, practically regardless to equilibrium state of the slopes, causing many temporary or permanent barrier lakes. River banks, artificial embankments, and sides of excavations typically collapse. Levees and earth dams incur serious damage. Significant landslides can occur at more than 200 – 300 km distance from the epicenter. Primary and secondary environmental effects can be observed over territory larger than 50000 $km^2$.*

c) Many springs significantly change their flow-rate and/or elevation of outcrop. Frequently, they may run dry or disappear altogether. Variations in water level are observed in wells.

d) Water temperature often changes in springs and/or wells. Water in lakes and rivers frequently becomes muddy.

e) *Ground open cracks are very frequent, up to one meter or more wide in the bedrock, up to more than 10 m wide in loose alluvial deposits and/or saturated soils. These may extend up to several kilometers in length.*

f) *Liquefaction occurs over large areas and changes the morphology of extensive flat zones, determining vertical subsidence exceeding several meters, widespread large sand volcanoes, and extensive severe lateral spreading features.*

g) Very large karst vaults collapse, forming sinkholes.

h) Frequent very large landslides under the sea level in coastal areas.

i) *Large waves develop in still and running water, and crash violently into the shores. Running (rivers, canals) and still (lakes) waters overflow from their beds; watercourses change the direction of flow. Tsunamis reach the coastal areas with tidal waves up to tens of meters high.*

j) Trees shake vigorously; many tree branches break and many whole trees are uprooted and fall.

k) In dry areas dust clouds may arise from the ground.

l) *Even large boulders may jump out of the ground leaving typical imprints in soft soil.*

## INTENSITY-FAULT PARAMETER RELATIONSHIPS: DISCUSSION AND CONCLUSIONS

Published empirical relationships between surface faulting parameters (i.e. rupture length, rupture area, rupture width, displacements) versus magnitude (e.g., Bonilla, 1978; Wells and Coppersmith, 1994), do not take into account dynamic parameters, notably stress drop, which varies versus fault length and slip type (cf. Mohammadioun and Serva, 2001). For instance, the systematic use, in the Wells and Coppersmith (1994) relation, of moment magnitude M (wherein stress drop is arbitrarily set at 30 bars) is liable to cause magnitudes to be either over- or underestimated. Accordingly, in order to assess the magnitudes of historical seismic events on the strength of paleoseismicity data, it is indispensable that rupture dynamics and the stress environment be taken into account. Recent paleoseismicity studies in the region of the San Andreas fault (Runnerstrom *et al.*, 2002) indicates that maximum displacement increases versus the depth of the seismogenic zone: displacement measured at the surface accordingly represents the lower limit of this parameters, and using it will unavoidably lead to an underestimation of magnitude.

The other primary effects of earthquakes (uplift and/or subsidence) are accounted for to a certain extent by relationships between magnitude and slip-rate (e.g., Slemmons and dePolo, 1986; Petersen and Wesnousky, 1995; Anderson *et al.*, 1996).

To date, there are no relationships linking primary ground effects and intensity. However, this connection is well evidenced in the description of the macroseismic scales for IX, X, XI, XII intensity degrees (see Table 1). We compiled new relationships using the data reported in Table 3 from a selected sample of crustal earthquakes. The data are plotted in Figure 4. We derived regression curves from the obtained values. This is a preliminary attempt that will be revised and updated by adding more detailed information on the earthquakes in Table 3, and including data from other surface faulting events.

We know that everybody can bring forward well-justified criticism concerning this approach, which we are willing to take into consideration. However, it is a fact that, within a given tectonic environment, intensity should increase if magnitude increases. It is entirely implausible that an earthquake of M = 6.5–7.0 should produce the same intensity as a M = 7.5–8 one. It is not physically correct, and macroseismic scales, if properly used, do not allow these values. Of course intensity XII, by definition, is where the scales saturate and therefore calls for professional judgment. In view of the preceding, the regressions in Figure 4 represent a very early stage of this endeavor. In fact, the purpose of publishing it is to provide a gentle provocation for the scientific community. We hope therefore that it will easily be proven false—but in the sense of Popper, 1934.

The use of ground effects for macroseismic intensity assessment is obviously affected by several uncertainties, as widely discussed in this paper. Most of the physical phenomena included in the proposed INQUA scale are relatively poor indicators of level, and should be considered carefully when used for intensity measurement. For the intensity levels lower than IX, the attempt of the INQUA scale is to bring environmental effects in line with the damage indicators. In this range, the INQUA scale should be used along with the other scales. For this reason, we have included as Appendix 2 a set of comparative tables to allow a direct integration between most commonly used scales and the INQUA proposed scale. However, in the intensity range between X and XII the distribution and size of primary tectonic effects is arguably the most useful diagnostic of the intensity level. As suggested in the proposed INQUA scale, field observations on fault rupture length and surface displacement should be therefore consistently implemented in the macroseismic study of past and future earthquakes.

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**Table 2**: Set of Italian earthquakes considered for testing and calibrating the proposed INQUA scale. For each earthquake we compared the distribution of ground effects and the macroseismic intensity assessed from persons and surroundings, and manmade structures of all kinds. Mm is macroseismically derived magnitude, except for most recent earthquakes where instrumental data are available. Numbers refers to sources listed in Appendix 1.

| Earthquakes | Epicentral zone | Magnitude (Mm) | Reference |
|---|---|---|---|
| 1169.02.04 | East Sicily | 6.6 | 15, 16, 17, 22, 27, 126, 146 |
| 1456.12.05 | Central -Southern Italy | 7.3 | 15, 16, 17, 27, 53, 107, 126 |
| 1511.03.26 | Slovenia | 7.2 | 15, 16, 17, 22, 27, 126, 146 |
| 1542.12.10 | Siracusano | 6.9 | 11,15, 16, 17, 27, 126, 146 |
| 1561.08.19 | Vallo di Diano | 6.4 | 15, 16, 17, 27 |
| 1570.11.17 | Ferrara | 5.3 | 15, 16, 17, 27, 126 |
| 1613.08.25 | Naso | 5.9 | 15, 16, 17, 27 |
| 1624.03.18 | Argenta | 5.4 | 15, 16, 17, 27, 126 |
| 1627.07.30 | Gargano | 7.0 | 11, 15, 16, 17, 22, 27, 126, 146 |
| 1638.03.27 | Calabria | 7.1 | 15, 16, 17, 22, 27, 146 |
| 1638.06.08 | Crotonese | 7.0 | 15, 16, 17, 27 |
| 1661.03.22 | Romagna Apennines | 5.6 | 15, 16, 17, 27, 126 |
| 1661.12.03 | Montecchio | 5.0 | 15, 16, 17, 27 |
| 1688.06.05 | Sannio | 6.4 | 15, 16, 17, 27 , 42, 126, 133 |
| 1690.12.23 | Anconetano | 5.3 | 15, 16, 17, 27 |
| 1693.01.09 | Val di Noto | 6.0 | 11, 15, 16, 17, 22, 27 , 126, 146 |
| 1694.09. 08 | Irpinia-Basilicata | 6.9 | 15, 16, 17, 27, 42, 126, 133 |
| 1703.01.14 | Umbria-Lazio Apennines | 6.7 | 15, 16, 17, 27, 126 |
| 1706.11.03 | Maiella | 6.7 | 15, 16, 17, 27 |
| 1726.09. 01 | Palermo | 5.7 | 15, 16, 17, 27 , 146 |
| 1731.03. 20 | Foggiano | 6.5 | 15, 16, 17, 22, 27 , 126, 146 |
| 1739.05. 10 | Naso | 5.5 | 15, 16, 17, 27 |
| 1743.02. 20 | Basso Ionio | 7.0 | 15, 16, 17, 22, 27, 126, 146 |
| 1751.07. 27 | Umbria Apennines | 6.2 | 15, 16, 17, 27 |
| 1755.12. 09 | Vallese | 6.0 | 15, 16, 17, 27 |
| 1781.04. 04 | Romagna | 5.9 | 15, 16, 17, 27, 126 |
| 1781.06. 03 | Umbria-Marche Apennines | 6.3 | 15, 16, 17, 27 |
| 1781.07. 17 | Romagna | 5.5 | 15, 16, 17, 27, 126 |
| 1783.02. 05 | Calabria | 6.8 | 15, 16, 17, 22, 27, 22, 59, 146 |
| 1786.12. 25 | Riminese | 5.7 | 15, 16, 17, 27, 126 |
| 1799.07. 28 | Marche Apennines | 5.9 | 15, 16, 17, 27, 126 |
| 1802.05. 12 | Valle dell'Oglio | 5.7 | 15, 16, 17, 27, 126 |
| 1805.07. 26 | Molise | 6.7 | 15,16, 17, 22, 27, 39, 42, 43, 44, 45, 52, 109, 125, 126 , 146 |
| 1808.04. 02 | Valle del Pellice | 5.7 | 15, 16, 17, 27, 126 |
| 1818.02. 20 | Catanese | 6.2 | 15, 16, 17, 22, 27, 126, 146 |
| 1818.09. 08 | Madonie | 5.3 | 15, 16, 17, 27 |
| 1819.02. 24 | Madonie | 5.4 | 15, 16, 17, 27 |
| 1823.03. 05 | Northern Sicily | 5.9 | 15, 16, 17, 22, 27, 126, 146 |
| 1826.02. 01 | Basilicata | 5.8 | 15, 16, 17, 27, 124 |
| 1828.02. 02 | Casamicciola terme | 4.5 | 15, 16, 17, 27 |
| 1828.10. 09 | Valle dello Staffora | 5.7 | |
| 1831.01.02 | Lagonegro | 5.4 | 27, 124, 27 |
| 1831.05. 26 | Liguria occidentale | 5.5 | 15, 16, 17, 27 |
| 1832.01. 13 | Valle del Topino | 6.1 | 15, 16, 17, 27 |
| 1832.03. 08 | Crotonese | 6.5 | 15, 16, 17, 22, 27, 146 |
| 1834.02. 14 | Alta lunigiana | 5.8 | 15, 16, 17, 27 |

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|---|---|---|---|
| 1836.04. 25 | Calabria settentrionale | 6.2 | 15, 16, 17, 22, 27, 146 |
| 1846.08. 14 | Toscana settentrionale | 5.8 | 15, 16, 17, 22, 27,146 |
| 1851.08. 14 | Melfi | 5.6 | 15, 16, 17, 27, 124, 126 |
| 1853.04. 09 | Caposele | 5.9 | 15, 16, 17, 27 ,124, 126 |
| 1854.02. 12. | Casentino | 6.1 | 15, 16, 17, 27 |
| 1855.07. 25 | Vallese | 5.8 | 15, 16, 17, 27 |
| 1857.12. 16 | Basilicata | 6.9 | 15, 16, 17, 27, 42, 123, 124, 125, 126 |
| 1859.01. 20 | Trevigiano | 5.2 | 15, 16, 17, 27 |
| 1865.07. 19 | Mt. Etna area | 5.1 | 10, 15, 16, 17, 27 |
| 1870.10. 04 | Casentino | 6.1 | 15, 16, 17, 27, 126 |
| 1873.03. 12 | Southern Marche | 6.0 | 15, 16, 17, 27 |
| 1873.06. 29 | Bellunese | 6.3 | 15, 16, 17, 27, 126 |
| 1875.03. 17 | Romagna sud-orientale | 5.8 | 15, 16, 17, 27, 126 |
| 1883.07. 28 | Casamicciola terme | 5.7 | 15, 16, 17, 27, 28, 63, 105 |
| 1887.02. 23 | W Liguria | 5.4 | 15, 16, 17, 22, 27, 126, 146 |
| 1887.12. 03 | N Calabria | 5.5 | 15, 16, 17, 27, 126 |
| 1894.08. 08 | Mt. Etna area | 5.3 | 15, 16, 17, 27 |
| 1894.11. 16 | S Calabria | 6.1 | 15, 16, 17, 22, 27, 146 |
| 1895.05. 18 | Impruneta | 4.8 | 15, 16, 17, 27 |
| 1897.12. 18 | Umbria-Marche Apennines | 4.8 | 15, 16, 17, 27 |
| 1898.06.27 | Rieti | 5.1 | 26, 27, 126 |
| 1899.06. 26 | Valle del Bisenzio | 4.8 | 15, 16, 17, 27 |
| 1899.07. 19 | Albani Hills | 4.8 | 15, 16, 17, 27 |
| 1904.02. 24 | Marsica | 5.8 | 10, 15, 16, 17, 27, 126 |
| 1905.04. 29 | Alta Savoia | 5.1 | 15, 16, 17, 27, |
| 1905.09. 08 | Calabria | 7.1 | 15, 16, 17, 22, 27, 146 |
| 1908.07. 10 | Carnia | 5.1 | 15, 16, 17 27 |
| 1908.12.28. | S Calabria | 7.1 | 15, 16, 17, 22, 27, 146 |
| 1909.08. 25 | S. Toscana | 5.1 | 15, 16, 17, 27 |
| 1910.06. 07 | Irpinia –Basilicata | 5.8 | 15, 16, 17, 27, 121 |
| 1911.10. 15 | Mt. Etna area | 5.2 | 10,15, 16, 17, 27, 126 |
| 1913.06. 28 | N Calabria | 5.4 | 15, 16, 17, 27 |
| 1914.05. 08 | Mt. Etna area | 4.9 | 10,15, 16, 17, 27 , 126 |
| 1915.01. 13 | Avezzano | 7.1 | 15, 16, 17, 27, 58, 110, 113, 126 |
| 1916.05. 17 | N Adriatic Sea | 5.4 | 15, 16, 17, 27 |
| 1916.06. 16 | N Adriatic Sea | 4.8 | 15, 16, 17, 27 |
| 1916.08. 16 | N Adriatic Sea | 5.4 | 15, 16, 17, 27 |
| 1919.06. 29 | Mugello | 6.0 | 15, 16, 17, 27 |
| 1919.09.10 | S Toscana | 5.4 | 15, 16, 17, 27, 126 |
| 1920.09. 07 | Garfagnana | 6.3 | 15, 16, 17, 27, 118, 126 |
| 1927.12. 26 | Colli albani | 4.8 | 15, 16, 17, 27 |
| 1928.03. 27 | Carnia | 5.8 | 15, 16, 17, 27 |
| 1930.07. 23 | Irpinia | 6.6 | 3,15, 16, 17, 27,114, 27, 44, 47, 125, 126 |
| 1933.09. 26 | Maiella | 5.8 | 15, 16, 17, 27, 126 |
| 1936.10. 18 | Cansiglio | 6.0 | 15, 16, 17, 27 |
| 1938.07. 18 | Alpi Cozie | 4.8 | 15, 16, 17, 27 |
| 1940.01. 15 | Golfo di Palermo | 5.3 | 15, 16, 17, 27 |
| 1945.06. 29 | Valle dello Staffora | 5.1 | 15, 16, 17, 27 |
| 1947.05. 11 | Central Calabria | 5.4 | 15, 16, 17, 27 , 126 |
| 1948.08. 18 | Northern Puglia | 5.1 | 15, 16, 17, 27 |
| 1956.05. 26 | Santa Sofia | 4.3 | 15, 16, 17, 27 |
| 1959.04. 05 | Valle dell'Ubaye | 4.8 | 15, 16, 17, 27 |
| 1961.10. 31 | Antrodoco | 5.1 | 15, 16, 17, 27 |
| 1962.08. 21 | Irpinia | 6.0 | 15, 16, 17, 27, 126 |
| 1968.01. 15 | Valle del Belice | 6.6 | 15, 16, 17, 27, 29, 126 |

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|---|---|---|---|
| 1976.05. 06 | Friuli | 6.3 | 24, 27, 29, 60, 116 |
| 1976.09. 11 | Friuli | 5.8 | 15, 16, 17, 27 |
| 1976.09. 15 | Friuli | 6.2 | 15, 16, 17 ,27 |
| 1978.04. 15 | Golfo di Patti | 6.0 | 15, 16, 17, 27 |
| 1979.09. 19 | Valnerina | 5.8 | 15, 16, 17, 27 |
| 1980.11. 23 | Irpinia-Basilicata | 6.9 | 13, 15, 27 ,41, 42, 45, 46, 48, 108, 125, 126, 127, 128, 129 |
| 1982.03. 21 | Golfo di Policastro | 5.1 | 15, 16, 17, 27 |
| 1983.11. 09 | Parmense | 4.6 | 15, 16, 17, 19,27, 27 |
| 1984. 05.07 | Abruzzi Apennines | 5.4 | 15, 16, 17, 19, 27, 45 |
| 1990.12. 13 | SE Sicily | 5.1 | 15, 16, 17, 27, 40 |
| 1997.09. 20. | Umbria-Marche Apennines | 6.0 | 1, 37, 38, 50, 51, 152 |
| 1998.09. 09 | Lauria | 5.6 | 108 |
| 2002.09. 06 | Southern Tyrrhenian Sea | 5.6 | 23, 31 |
| 2002.10. 31 | San Giuliano | 5.8 | 151 |

**Table 3**: Earthquakes considered for the analysis of relations between epicentral intensity and surface faulting parameters. Selected events for which best constrained data are available have been used for the diagrams in Figure 4. Where not available, we converted intensity values in the MM scale (for a comparison between the different scales see Shebalin *et al.*, 1974; Krinitsky and Chang, 1988; Reiter, 1991), and magnitude values to Ms (magnitude values for pre-instrumental earthquakes are derived from macroseismic data).

| EQ NUM | LOCATION | EQ NAME | EQ DATE | EPIC INTENSITY | REFERENCES | MS | SUR LEN | MAX DISP |
|---|---|---|---|---|---|---|---|---|
| 1. | USA, Calif | Fort Tejon | 09/01/1857 | 11,0 | http://www.msu.edu/~fujita/earthquake/intensity.html<br>Sieh, K., 1978. Slip along the San Andreas Fault associated with the great 1857 earthquake. Bulletin of the Seismological Society of America, 68, 1421-1428.<br>Grant L. and Sieh, K, 1993. Stratigraphic evidence for 7 meters of dextral slip on the San Andreas Fault during the 1857 earthquake in the Carrizo Plain. Bulletin of the Seismological Society of America, 83, 619-635.<br>C.F. Richter, 1958, Elementary Seismology, San Francisco, California, W.H. Freeman, p. 768. | 8,3 | 322,0 | 9,50 |

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|---|---|---|---|---|---|---|---|---|
| 2. | USA, Calif | Owens Valley | 26/03/1872 | 11,0 | http://www.msu.edu/~fujita/earthquake/intensity.html Vittori, E., Michetti, A.M., Slemmons, D.B., & Carver, G.A., (1993) - Style of recent surface deformation at the south end of the Owens Valley fault zone, eastern California, Geological Society of America, Abstracts with Program Volume 25, Number 5, April 1993, p. 159. C.F. Richter, 1958, Elementary Seismology, San Francisco, California, W.H. Freeman, p. 768. | 7,6 | 108,0 | 10,00 |
| 3. | Mexico | Pitaycachi | 03/05/1887 | 11,5 | Bull, W.B. and P.A: Pearthree, 1988. Frequency and size of Quateranry surface ruptures of the Pitaycachi Fault, Northeastern Sonora, Mexico, Bulletin of the Seismological Society of America, 78, 956-978. http://www.geo.arizona.edu/K-12/azpepp/education/history/pitay.html | 7,4 | 75,0 | 5,10 |
| 4. | Japan | Nobi | 27/10/1891 | 11,0 | http://www.hp1039.jishin.go.jp/eqchreng/6-2-2.htm Matsuda, T., 1974. Surface faults associated with Nobi (Mino-Owari) earthquake of 1891, Japan. Earthquake Research Inst., Univ. Tokyo, Spec. Bull. 13, 85-126. | 8,0 | 80,0 | 8,00 |
| 5. | Japan | Rikuu | 31/08/1896 | 10,0 | http://www.hp1039.jishin.go.jp/eqchreng/4-2-5.htm Matsuda, T., Yamazaky, H., Nakata, T. and Imaizumi T., 1980. The surface faults associated with the Rikuu earthquake of 1896. Earthquake Research Inst., Univ. Tokyo, Bull., 55, 795-855. | 7,2 | 36,0 | 3,50 |
| 6. | Turkey | Büyük Menderes Basin | 20/09/1899 | 9,0 | Ergin, K., Guclu, U and Uz, Z., 1967. A Catalog of Earthquakes for Turkey and Surrounding Area (11 A.D. to 1964 A.D.). ITU publications, No:24, Istanbul. Altunel, E., 1999. Geologic and geomorphologic observations in relation to 20 th september 1899 Menderes earthquake, western Turkey. Journal of the Geological Society, London, 156, 241-246. | | 40,0 | 2,0 |
| 7. | USA, Calif | San Francisco | 18/04/1906 | 11,0 | http://neic.usgs.gov/neis/eqlists/USA/1906_04_18.html http://www.msu.edu/~fujita/earthquake/intensity.html Lawson, A.C., Chairman, 1908. The California earthquake of April 18, 1906 – Report of the State Earthquake Investigation Committee. Carnegie Institute, Washington, Pub. 87, v.1. C.F. Richter, 1958, Elementary Seismology, San Francisco, California, W.H. Freeman, p. 768. | 7,9 | 432,0 | 6,10 |

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|---|---|---|---|---|---|---|---|---|
| 8. | Turkey | Mürefte ªarköy | 09/08/1912 | 10,0 | Ergin, K., Guclu, U and Uz, Z., 1967. A Catalog of Earthquakes for Turkey and Surrounding Area (11 A.D. to 1964 A.D.). ITU publications, No:24, Istanbul. Ambraseys, N.N. and Finkel, C.F. (1987). The Saros-Marmara Earthquake of 9 August 1912, Earthquake Eng. and Struct. Dyn. 15: 189-211. Altunel, E., Barka, A.A., akir, Z., Kozaci, Ö., Hitchcock, C., Helms, J., Bachuber, J. & Lettis, W. 2000. What goes on at the eastern termination of the November 12, 1999 Düzce earthquake, M=7.2, North Anatolian Fault, Turkey. American Geophysical Fall Meeting, California, USA, Abstracts, p. F816. | 7,0 | 110,0 | 5,0 |
| 9. | Italy | Avezzano | 13/01/1915 | 11,0 | http://www.msu.edu/~fujita/earthquake/intensity.html Boschi E., G. Ferrari, P. Gasperini, E. Guidoboni, G. Smriglio and G. Valensise (Eds.), 1995, Catalogo dei forti terremoti in Italia dal 461 a. C. al 1980, 2. ING-SGA, Bologna, 973 p. Michetti A.M., Brunamonte F., Serva L. and Vittori E. (1996) - Trench investigations along the 1915 Fucino earthquake fault scarps (Abruzzo, Central Italy): geological evidence of large historical events. Journal of Geophysical Research, 101, 5921-5936. | 7,0 | 23,0 | 2,00 |
| 10. | China | Kansu | 16/12/1920 | 12,0 | Editorial Board for the Lithospheric Dynamics Atlas of China, State Seismological Bureau, 1989, Lithospheric Dynamics Atlas of China. Tav 24. Deng Q., Chen S., Song F.M., Zhu S., Whang Y., Zhang W., Burchfiel B.C., Molnar P., Royden L., and Zhang P., 1986. Variations in the geometry and amount of slip on the Haiyuan Fault Zone, China, and the surface rupture of the 1920 Haiyuan earthquake. Earthquake Source Mechanics, Geophysical Monograph 37, 169-182. | 8,5 | 237,0 | 11,00 |
| 11. | Japan | Tango | 07/03/1927 | 9,0 | http://www.hp1039.jishin.go.jp/eqchreng/7-2-3.htm Yamasaki N. and Tada F., 1928. The Oku-Tango earthquake of 1927. Earthquake Research Institute, 4, 159-177. | 7,7 | 18,0 | 3,00 |

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|---|---|---|---|---|---|---|---|---|
| 12. | Bulgaria | Papazili | 18/04/1928 | 10,5 | Bonchev S. and Bakalov P., 1928. Les tremblements de terre dans la Bulgarie du Sud les 14 et 18 avril 1928. Rev. Soc. Géol. Bulgare. Special Catalogue of Earthquakes of the Northern Eurasia (SECNE) Editors N.V.Kondorskaya and V.I.Ulomov. C.F. Richter, 1958, Elementary Seismology, San Francisco, California, W.H. Freeman, p. 768. Shebalin,N.V., Leydecker,G., Mokrushina,N.G., Tatevossian,R.E., Erteleva,O.O. & V.Yu.Vassiliev (1997): Earthquake Catalogue for Central and Southeastern Europe 342 BC - 1990 AD. -- Final Report to Contract ETNU - CT 93 - 0087 | 6,9 | 50,0 | 3,50 |
| 13. | New Zealand | Hawkes Bay | 02/02/1931 | 10,5 | http://www.pnbhs.school.nz/Intranet/Art%20History/Art%20Deco%20Napier/earthquake.htm | 7,8 | 15,0 | 4,60 |
| 14. | China | Kehetuohai-E | 10/08/1931 | 11,0 | http://iisee.kenken.go.jp/net/hara/china.htm | 7,9 | 180,0 | 14,60 |
| 15. | Japan | Saitama | 21/09/1931 | 7,0 | http://www.hp1039.jishin.go.jp/eqchreng/5-2-5.htm | 6,8 | 0,0 | 0,00 |
| 16. | USA, Nevada | Cedar Mountain | 21/12/1932 | 10,0 | http://www.msu.edu/~fujita/earthquake/intensity.html C.F. Richter, 1958, Elementary Seismology, San Francisco, California, W.H. Freeman, p. 768. Slemmons, D.B., Jones, Austin E., and Gimlett, James I., 1965, Catalog of Nevada earthquakes, 1852 - 1960: Bulletin of the Seismological Society of America, v. 55, no. 2, p. 537 - 583. | 7,2 | 61,0 | 2,70 |
| 17. | China | Changma | 25/12/1932 | 10,0 | Peltzer, G., P. Tapponnier, Y. Gaudemer, et al., Offsets of late Quaternary morphology, rate of slip, and recurrence of large earthquakes on the Chang Ma fault, Gansu, China, J. Geophys. Res., 93, 7793-7812, 1988. Shih, Chen-liang, Wen-lin Huan, Kuo-Kan Yao, and Yuan-ding Hsie (1978). On the fracture zones of the Changmaearthquake of 1932 and their causes, Chinese Geophysics, 1(1), 17-46. Fu, Z., and Liu, G. (2001) Dynamic analysis on interaction between the Haiyuan-Gulang-Changma great earthquakein the north bounbady of the Tibetan plateau, Seismology and Geology, 23, 35-42 (in Chinese). http://iisee.kenken.go.jp/net/hara/china.htm | 7,7 | 148,5 | 6,20 |

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|---|---|---|---|---|---|---|---|---|
| 18. | Turkey | Kirsehir | 19/04/1938 | 9,5 | Special Catalogue of earthquakes of the northern Eurasia (SECNE) Editors N.V. Kondorskaya and V.I. Ulomov, http://seismo.ethz.ch/gshap/neurasia/nordasiacat.txt Ergin, K., Guclu, U and Uz, Z., 1967. A Catalog of Earthquakes for Turkey and Surrounding Area (11 A.D. to 1964 A.D.). ITU publications, No:24, Istanbul. Ambraseys, 70 | 6,8 | 15,0 | 1,00 |
| 19. | Turkey | Erzincan | 26/12/1939 | 11,0 | Ergin, K., Guclu, U and Uz, Z., 1967. A Catalog of Earthquakes for Turkey and Surrounding Area (11 A.D. to 1964 A.D.). ITU publications, No:24, Istanbul. Barka, A. 1996. Slip distribution along the North Anatolian fault associated with the large earthquakes of the period 1939 to 1967. BSSA, 86, 1238-1254. http://www.msu.edu/~fujita/earthquake/intensity.html Erhan Altunel, 2003, personal communication | 8,0 | 360,0 | 7,50 |
| 20. | Turkey | Erbaa | 20/12/1942 | 10,0 | Ergin, K., Guclu, U and Uz, Z., 1967. A Catalog of Earthquakes for Turkey and Surrounding Area (11 A.D. to 1964 A.D.). ITU publications, No:24, Istanbul. Erhan Altunel, 2003, personal communication. | 7,3 | 45,0 | 3,5 |
| 21. | Turkey | Ladik (Tosya) | 26/11/1943 | 11,0 | http://www.msu.edu/~fujita/earthquake/intensity.html Ergin, K., Guclu, U and Uz, Z., 1967. A Catalog of Earthquakes for Turkey and Surrounding Area (11 A.D. to 1964 A.D.). ITU publications, No:24, Istanbul. Ambraseys, N.N., 1970. Some characteristics features of the Anatolian fault zone. Tectonophysics, 9, 143-165. Erhan Altunel, 2003, personal communication | 7,5 | 270,0 | 4,50 |
| 22. | Turkey | Çerkeº, Gerede, Bolu | 01/02/1944 | 10,0 | Ergin, K., Guclu, U and Uz, Z., 1967. A Catalog of Earthquakes for Turkey and Surrounding Area (11 A.D. to 1964 A.D.). ITU publications, No:24, Istanbul. Erhan Altunel, 2003, personal communication | 7,4 | 100,0 | 4,5 |
| 23. | Peru | Ancash | 10/11/1946 | 11,0 | http://www.msu.edu/~fujita/earthquake/intensity.html Sebrier,M., J. L. Mercier,J.Machare, D. Bonnet, J. Cabrera, and J. L. Blanc, 1988. State of stress in an overriding plate situated above a flat slab: the Andes of central Peru, Tectonics, 7, 895-928, 1988. | 7,3 | 20,0 | 3,50 |

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|---|---|---|---|---|---|---|---|---|
| 24. | Japan | Fukui | 28/06/1948 | 11,5 | http://www.msu.edu/~fujita/earthquake/intensity.html Tsuya, H., ed. 1950. The Fukui earthquake of June 28, 1948. Tokyo, Special Committee for the Study of the Fukui earthquake, 197 p., 2 pl. Kanamori, H. 1973. Mode of strain release associated with major earthquakes in Japan. Earth Planet. Sci. Ann. Rev. 1, 213-239. | 7,3 | 25,0 | 2,00 |
| 25. | China | Danxiong | 18/11/1951 | 11,0 | http://iisee.kenken.go.jp/net/hara/china.htm Tapponnier, P., Mercier, J.,L., Armij Han T., and Zhou, J., 1981. evidence for active normal faultir Tibet:. Nature 294, 410-414. Armijo, R., Tapponier, P., and Han, T.L. 1989. Late Cenozoic right-lateral strike-slip faulting in Southern Tibet. Journ. Geopphys. Res., 94, 2787-2838. | 8,0 | 81,0 | 7,30 |
| 26. | USA, Calif | Kern County | 21/07/1952 | 10,5 | http://www.msu.edu/~fujita/earthquake/intensity.html Buwalda, J. & St. Amand, P. 1955. Geological effects of the Arvin-Tehachapy earthquake. In: G. Oakeshott, Earthquakes in Kern County California during 1952. San Francisco, Calif. Dept. of Natural Resources, Division of Mines, Bulletin, 171, 41-56. Stein, R.S., & Thatcher, W. 1981. Seismic and aseismic deformation associated with the 1952 Kern County, California, earthquake and relationship to the Quaternary history of the White Wolf Fault. Journ. Geophys. res. 86, 4913-4928. | 7,7 | 57,0 | 1,20 |
| 27. | Turkey | Canakkale | 18/03/1953 | 11,0 | http://www.msu.edu/~fujita/earthquake/intensity.html Ergin, K., Guclu, U and Uz, Z., 19 Catalog of Earthquakes for Turkey Surrounding Area (11 A.D. to A.D.). ITU publications, No:24, Istan Ketin, I., & Roesli, F. 1954. Makroseismische Untersuchungen über das nordwestanatolesche Beben Wom 18 März 1953. Eclogae Geol. Helvetiae, 46, 187-208. | 7,2 | 50,0 | 4,35 |
| 28. | USA, Nevada | Stillwater | 24/08/1954 | 8,5 | http://www.msu.edu/~fujita/earthquake/intensity.html Coffman, Jerry L., and von Hake, Carl A., 1970. Earthquake History of the United States, U.S. Department of Commerce, Publication 41-1, 208 p. | 6,9 | 34,0 | 0,76 |

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|---|---|---|---|---|---|---|---|---|
| 29. | Mongolia | Gobi-Altai | 04/12/57 | 11,0 | http://www.msu.edu/~fujita/earthquake/intensity.html Florensov, N.A., and Solonenko, V.P. 1965. The Gobi-Altai earthquake. Moscow, Nauka, 1963. | 7,9 | 250,0 | 9,00 |
| 30. | USA, Alaska | Lituya Bay | 10/07/58 | 11,0 | http://www.msu.edu/~fujita/earthquake/intensity.html Plafker, G., Hudson, T., Bruns, T., and Rubin, M. 1978. Late Quaternary offsets along the Fairweather Fault and crustal plate interaction in southern Alaska. Canadian Journ. Earth Sciences 15, 805-816. | 7,9 | 280,0 | 6,50 |
| 31. | USA, Montana | Hebgen Lake | 18/08/59 | 10,0 | http://www.msu.edu/~fujita/earthquake/intensity.html Coffman, Jerry L., and von Hake, Carl A., 1970. Earthquake History of the United States, U.S. Department of Commerce, Publication 41-1, 208 p. Myers, W.B. and Hamilton, W. 1964. Deformation accompanying the Hebgen Lake earthquake of August 17, 1959. U.S.G.S. Prof. Paper 435-I, 55-98. | 7,3 | 26,5 | 5,50 |
| 32. | Greece | Agios-Efstratios | 19/02/68 | 9,0 | Van Gils, J.M. & G. Leydecker (1991): Catalogue of European earthquakes with intensities higher than 4. -- Commission of the European Communities - nuclear science and technology. 353 pp - ISBN 92-826-2506-0, Catal. No.: CD-NA-13406-EN-C. Brussels - Luxembourg. Pavlides, S.B., and Tranos, M.D. 1991. Structural characteristics of two strong earthquakes in the North Aegean: Ierissos, 1932, and Agios Efstratios, 1968. Jour. Structural Geology 13, 205-214. Shebalin,N.V., Leydecker,G., Mokrushina,N.G., Tatevossian,R.E., Erteleva,O.O. & V.Yu.Vassiliev (1997): Earthquake Catalogue for Central and Southeastern Europe 342 BC - 1990 AD. -- Final Report to Contract ETNU - CT 93 - 0087 | 7,2 | 3,0 | 0,50 |
| 33. | Peru | Pariahuanca | 24/07/69 | 11,0 | http://www.msu.edu/~fujita/earthqu ntensity.html | 5,7 | 5,5 | 0,40 |
| 34. | China | Tonghai | 04/01/70 | 10,5 | http://iisee.kenken.go.jp/net/hara/ch m | 7,5 | 48,0 | 2,70 |
| 35. | USA, Calif | San Fernando | 09/02/71 | 11,0 | http://www.msu.edu/~fujita/earthquake/intensity.html Coffman, J L., von Hake, Carl A., and Stover, Carl W., 1982, Earthquake history of the United States: Publication 41-1, Rev. Ed. (with supplement through 1980), | 6,5 | 16,0 | 2,50 |

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|---|---|---|---|---|---|---|---|---|
| | | | | | National Oceanic and Atmospheric Administration and U.S. Geological Survey, Boulder, Colo., 258p. | | | |
| 36. | China | Luhuo | 06/02/73 | 11,0 | http://iisee.kenken.go.jp/net/hara/china.htm | 7,3 | 89,0 | 3,60 |
| 37. | Russia | Tadzhikestan | 11/08/74 | 7,0 | V.I. Ulomov, R.P. Fadina, A.P. Katok, et al. (1977). Earthquakes in Middle Asia. In: I.V. Gorbunova, N.V. Kondorskaya, N.V. Shebalin (eds.), Earthquakes in the USSR in 1974, 1977, 49-98. | 7,3 | 0,0 | 0,00 |
| 38. | China | Haicheng | 04/02/75 | 9,5 | http://iisee.kenken.go.jp/net/hara/china.htm http://www.msu.edu/~fujita/earthquake/intensity.html | 7,4 | 5,5 | 0,55 |
| 39. | Guatemala | Motagua | 04/02/76 | 11,0 | http://www.msu.edu/~fujita/earthquake/intensity.html | 7,5 | 235,0 | 3,40 |
| 40. | Russia | Gazli, Uzbekistan | 08/04/76 | 8,0 | Ulomov, V.I., M.G. Flenova, A.P. Katok, et al. (1980). Earthquakes in Middle Asia and Kazakhstan. In: I.V. Gorbunova, N.V. Kondorskaya, N.V. Shebalin (eds.), Earthquakes in the USSR in 1976, 1980, 27-39. | 7,0 | 0,0 | 0,00 |
| 41. | Russia | Gazli, Uzbekistan | 17/05/76 | 9,0 | Ulomov, V.I., M.G. Flenova, A.P. Katok, et al. (1980). Earthquakes in Middle Asia and Kazakhstan. In: I.V. Gorbunova, N.V. Kondorskaya, N.V. Shebalin (eds.), Earthquakes in the USSR in 1976, 1980, 27-39. | 7,3 | 0,0 | 0,00 |
| 42. | China | Tangshan | 27/07/76 | 10,5 | http://iisee.kenken.go.jp/net/hara/china.htm http://www.msu.edu/~fujita/earthquake/intensity.html | 7,9 | 10,0 | 3,00 |
| 43. | Greece | Thessaloniki | 20/06/78 | 9,0 | Van Gils, J.M. & G. Leydecker (1991): Catalogue of European earthquakes with intensities higher than 4. -- Commission of the European Communities - nuclear science and technology. 353 pp - ISBN 92-826-2506-0, Catal. No.: CD-NA-13406-EN-C. Brussels - Luxembourg. Shebalin,N.V., Leydecker,G., Mokrushina,N.G., Tatevossian,R.E., Erteleva,O.O. & V.Yu.Vassiliev (1997): Earthquake Catalogue for Central and Southeastern Europe 342 BC - 1990 AD. -- Final Report to Contract ETNU - CT 93 - 0087 | 6,4 | 19,4 | 0,22 |
| 44. | Germany | Swabian Jura | 03/09/78 | 7,5 | Van Gils, J.M. & G. Leydecker (1991): Catalogue of European earthquakes with intensities higher than 4. -- Commission of the European Communities - nuclear science and technology. 353 pp - ISBN 92-826-2506-0, Catal. No.: CD-NA-13406-EN-C. Brussels - Luxembourg. | 5,3 | 0,0 | 0,00 |

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|---|---|---|---|---|---|---|---|---|
| 45. | Italy | Umbria (Norcia) | 19/09/79 | 8,5 | Boschi E., E. Guidoboni, G. Ferrari, G. Valensise, and P. Gasperini (Eds.), 1997, Catalogo dei forti terremoti in Italia dal 461 a. C. al 1990, 2. ING-SGA, Bologna, 644 p. Blumetti A.M., Dramis F., Gentili B. & Pambianchi G. (1991) La struttura di Monte Alvagnano-Castel Santa Maria nell'area nursina: aspetti geomorfologici e sismicità storica. Rend. Soc. Geol. It., 13, 71-76, 5 fig. | 5,9 | 0,1 | 0,10 |
| 46. | USA, Calif | Greenville | 24/01/80 | 7,0 | http://neic.usgs.gov/neis/eqlists/sig_1980.html | 5,9 | 6,2 | 0,03 |
| 47. | France | Arudy | 29/02/80 | 7,5 | J.M. Van Gils, G. Leydecker, 1991, Catalogue of European earthquakes with intensities higher than 4<br>J. Fréchet,A. Rigo, A. Souriau, F. Thouvenot, Comparison of two damaging earthquake in France in 1996: Saint Paul de Fenoullet (Pyrenees) and Epagny (Alps)<br>Gagnepain-Beyneix, J., H. Haessler et T. Modiano, The Pyrenean earthquake of February 29, 1980: an example of complex faulting, Tectonophysics, 85, 273-290, 1982<br>Lambert J., Levret-Albaret A. (dir), Cushing M. et Durouchoux C. 1996. Mille ans de séismes en France. Catalogue d'épicentres : paramètres et références. Ouest Editions, Presses Académiques, Nantes, 80p.<br>Lambert J. (dir), Bernard P., Czitrom G., Dubié J.Y.,Godefroy P. et Levret-Albaret A. 1997 Les tremblements de terre en France : Hier, Aujourd'hui, Demain. Editions BRGM, Orléans, 196p | 5,0 | 0,0 | 0,00 |
| 48. | USA, Calif | Mammoth Lakes | 27/05/80 | 6,0 | http://neic.usgs.gov/neis/eqlists/sig_1980.html | 6,1 | 20,0 | 0,00 |
| 49. | Mexico | Mexicali Valley | 09/06/80 | 7,0 | http://neic.usgs.gov/neis/eqlists/sig_1980.html<br>W. Ortega, J. Frez y F. Suárez, (1997) "The Victoria México, earthquake of June 9, 1980", Geof. Int., vol. 36-3, pp. 139-159. | 6,4 | 0,0 | 0,00 |
| 50. | Japan | Izu-Hanto-Toho | 29/06/80 | 7,0 | http://neic.usgs.gov/neis/eqlists/sig_1980.html | 6,2 | 0,0 | 0,00 |
| 51. | Greece | Almyros | 09/07/80 | 8,0 | Van Gils, J.M. & G. Leydecker (1 Catalogue of European earthq with intensities higher than Commission of the Eur Communities - nuclear science | 6,4 | 5,3 | 0,20 |

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|---|---|---|---|---|---|---|---|---|
| | | | | technology. 353 pp - ISBN 92-826-<br>0, Catal. No.: CD-NA-13406-<br>Brussels - Luxembourg.<br>Shebalin,N.V., Leydecker,G., Mokrushina,N.G., Tatevossian,R.E., Erteleva,O.O. & V.Yu.Vassiliev (1997): Earthquake Catalogue for Central and Southeastern Europe 342 BC - 1990 AD. -- Final Report to Contract ETNU - CT 93 - 0087 | | | |
| 52. USA, Kentuc | Sharp-sburg | 27/07/80 | 7,0 | http://neic.usgs.gov/neis/eqlists/sig_1980.html | 4,7 | 0,0 | 0,00 |
| 53. Italy | South Apennines | 23/11/80 | 10,0 | Van Gils, J.M. & G. Leydecker (1<br>Catalogue of European earthq<br>with intensities higher than<br>Commission of the Eur<br>Communities - nuclear science<br>technology. 353 pp - ISBN 92-826-<br>0, Catal. No.: CD-NA-13406-<br>Brussels - Luxembourg.<br>Boschi E., G. Ferrari, P. Gasperini, E. Guidoboni, G. Smriglio, and G. Valensise (Eds.), 1995, Catalogo dei forti terremoti in Italia dal 461 a. C. al 1980, ING-SGA, Bologna, 973 p. | 6,9 | 38,0 | 1,15 |
| 54. North Yemen | Dhamer | 13/12/82 | 8,0 | http://neic.usgs.gov/neis/eqlists/sig_1982.html | 6,0 | 15,0 | 0,03 |
| 55. Russia | Kum-Dagh, Turkmenia | 14/03/83 | 8-9 | S.S. Arefiev, V.M. Graizer, D.N. Zargarian, et al. (1985). Rupture in the source and aftershocks of the Kum-Dagh earthquake of March 14, 1983. In: N.V. Shebalin (ed.) Macroseismic and instrumental studies of strong earthquakes. Problems of engineering seismology, n.26, 1985, 27 | 5,7 | 20,0 | 0,13 |
| 56. Columbia | Popayan | 31/03/83 | 8,0 | http://neic.usgs.gov/neis/eqlists/sig_1983.html | 4,9 | 1,3 | 0,01 |
| 57. USA, Calif | Coalinga | 02/05/83 | 8,0 | http://neic.usgs.gov/neis/eqlists/sig_1983.html | 6,5 | 0,0 | 0,00 |
| 58. Belgium | Liege | 08/11/83 | 4,5 | Van Gils, J.M. & G. Leydecker (1991): Catalogue of European earthquakes with intensities higher than 4. -- Commission of the European Communities - nuclear science and technology. | 4,3 | 0,0 | 0,00 |

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|---|---|---|---|---|---|---|---|---|
| | | | | | 353 pp - ISBN 92-826-2506-0, Catal. No.: CD-NA-13406-EN-C. Brussels - Luxembourg. | | | |
| 59. | Russia | Gazli, Uzbekistan | 19/03/84 | 9-10 | A.A. Abdukadyrov, G.Yu. Azizov, A.G. Aronov, et al. The Gazli earthquake of March 19, 1984 In: N.V. Kondorskaya (ed.), Earthquakes in the USSR in 1984, 1987, 67-85. | 7,2 | 0,0 | 0,0 |
| 60. | USA, Calif | Morgan Hill | 24/04/84 | 7,0 | http://neic.usgs.gov/neis/eqlists/sig_1984.html | 6,1 | 0,0 | 0,00 |
| 61. | Italy | Perugia | 29/04/84 | 8,0 | Boschi E., E. Guidoboni, G. Ferrari, G. Valensise, and P. Gasperini (Eds.), 1997, Catalogo dei forti terremoti in Italia dal 461 a. C. al 1990, 2. ING-SGA, Bologna, 644 p. | 5,3 | 0 | 0 |
| 62. | Italy | Lazio-Abruzzo | 07/05/84 | 8,0 | Boschi E., E. Guidoboni, G. Ferrari, G. Valensise, and P. Gasperini (Eds.), 1997, Catalogo dei forti terremoti in Italia dal 461 a. C. al 1990, 2. ING-SGA, Bologna, 644 p. | 5,8 | 0 | 0 |
| 63. | England | North Wales | 19/07/84 | 6,0 | http://neic.usgs.gov/neis/eqlists/sig_1984.html | 4,7 | 0,0 | 0,00 |
| 64. | Japan | Naganoken-Seibu | 13/09/84 | 5,0 | http://neic.usgs.gov/neis/eqlists/sig_1984.html | 6,1 | 0,0 | 0,00 |
| 65. | Argentina | Mendoza | 26/01/85 | 7,0 | http://neic.usgs.gov/neis/eqlists/sig_1985.html | 5,9 | 0,0 | 0,00 |
| 66. | New Guinea | New Britain | 10/05/85 | 8,0 | http://neic.usgs.gov/neis/eqlists/sig_1985.html | 7,1 | 0,0 | 0,00 |
| 67. | New Guinea | New Ireland | 03/07/85 | 7,0 | http://neic.usgs.gov/neis/eqlists/sig_1985.html | 7,2 | 0,0 | 0,00 |
| 68. | USA, Calif | Kettleman Hills | 04/08/85 | 6,0 | http://neic.usgs.gov/neis/eqlists/sig_1985.html | 5,9 | 0,0 | 0,00 |
| 69. | Canada | Nahanni | 05/10/85 | 6,0 | http://neic.usgs.gov/neis/eqlists/sig_1985.html | 6,6 | 0,0 | 0,00 |
| 70. | USA, Calif | N. Palm Springs | 08/07/86 | 7,0 | http://neic.usgs.gov/neis/eqlists/sig_1986.html | 6,0 | 9,0 | 0,01 |
| 71. | Greece | Kalamata | 13/09/86 | 10,0 | http://neic.usgs.gov/neis/eqlists/sig_1986.html | 5,8 | 15,0 | 0,18 |
| 72. | Taiwan | Hualien | 14/11/86 | 7,0 | http://neic.usgs.gov/neis/eqlists/sig_1986.html | 7,8 | 0,0 | 0,00 |
| 73. | New Zealand | Edge-cumbe | 02/03/87 | 10,0 | http://neic.usgs.gov/neis/eqlists/sig_1987.html | 6,6 | 18,0 | 2,90 |

| | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| 74. | USA, Calif | Whittier Narrows | 01/10/87 | 8,0 | http://neic.usgs.gov/neis/eqlists/sig_1987.html | 5,7 | 0,0 | 0,00 |
| 75. | USA, Calif | Elmore Ranch | 24/11/87 | 6,0 | http://neic.usgs.gov/neis/eqlists/sig_1987.html | 6,2 | 10,0 | 0,20 |
| 76. | USA, Calif | Supersti-tion Hills | 24/11/87 | 6,5 | http://neic.usgs.gov/neis/eqlists/sig_1987.html | 6,6 | 27,0 | 0,92 |
| 77. | USA, Calif | Pasadena | 03/12/88 | 6,0 | http://neic.usgs.gov/neis/eqlists/sig_1988.html | 4,2 | 0,0 | 0,00 |
| 78. | Russia | Armenia | 07/12/88 | 10,0 | Dorbath, L., C. Dorbath, L. Rivera, et al. (1992). Geometry, segmentation and stress regime of the Spitak (Armenia) earthquake from the analysis of the aftershock sequence. // Geophys. Journal Inter. 108, 1992, 309-328. | 6,8 | 25,0 | 2,00 |
| 79. | USA, Calif | Loma Prieta | 18/10/89 | 9,0 | http://www.msu.edu/~fujita/earthquake/intensity.html http://neic.usgs.gov/neis/eqlists/sig_1989.html | 7,1 | 2,7 | 0,2 |
| 80. | Algeria | Chenoua | 29/10/89 | 7,0 | http://neic.usgs.gov/neis/eqlists/sig_1989.html | 5,7 | 4,0 | 0,13 |
| 81. | USA, Calif | Upland | 28/02/90 | 7,0 | http://neic.usgs.gov/neis/eqlists/sig_1990.html | 5,5 | 0,0 | 0,00 |
| 82. | Iran | Rudbar-Tarom | 20/06/90 | 10,0 | http://www.msu.edu/~fujita/earthquake/intensity.html | 7,7 | 80,0 | 0,95 |
| 83. | Russia | Racha, Georgia | 29/04/91 | 8-9 | Papalashvili, V.G., O.Sh. Varazanashvili, S.A. Gogmachadze et al. (1997). The Racha-Java earthquake of April 29, 1991. In: *Earthquakes in the USSR in 1991*, 1997, 18-25. | 6,9 | 0 | 0 |
| 84. | USA, Calif | Sierra Madre | 28/06/91 | 7,0 | http://neic.usgs.gov/neis/eqlists/sig_1991.html | 5,1 | 0,0 | 0,00 |
| 85. | Turkey | Erzincan | 13/03/92 | 9,0 | http://www.yapiworld.com/editor/erzincan.htm Erdik, Mustafa and Beyen, Kemal, ' Intensity Assessments ' March 13, 1992 (MS:6.8) Erzincan Earthquake; A preliminary Reconnaissance Report, Bogazici University, May 1992 | 6,8 | 30,0 | 0,20 |
| 86. | USA, Calif | Joshua Tree | 23/04/92 | 7,0 | http://neic.usgs.gov/neis/eqlists/sig_1992.html | 6,3 | 0,0 | 0,00 |

| | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| 87. | USA, Calif | Landers | 28/06/92 | 10,0 | http://www.msu.edu/~fujita/earthquake/intensity.html http://www.eqe.com/publications/bigbear/bigbear.htm Assessed in the field by the Authors | 7,6 | 85,0 | 6,00 |
| 88. | USA, Calif | Big Bear | 28/06/92 | 8,0 | http://www.eqe.com/publications/bigbear/bigbear.htm<br><br>http://neic.usgs.gov/neis/eqlists/sig_1992.html | 6,7 | 0,0 | 0,00 |
| 89. | USA, Nevada | Little Skull Mtn | 29/06/92 | 8,0 | http://pubs.usgs.gov/dds/2000/dds-058/Ch_J.pdf Smith, Kenneth D., Brune, James N., de Polo, Diane, Savage, Martha K., Anooshehpoor, Rasool, Sheeham, Anne F., (2001), The 1992 Little Skull Mountain earthquake sequence, southern Nevada Test Site. Bulletin of the Seismological Society of America, vol. 91, no. 6, pp.1595-1606. | 5,4 | 0,0 | 0,00 |
| 90. | USA, Oregon | Scotts Mills | 25/03/93 | 7,0 | http://neic.usgs.gov/neis/eqlists/sig_1993.html Madin, I.P., G.P. Priest, M.A. Mabey, S.D. Malone, T.S. Yelin, D. Meier, March 25, 1993, Scotts Mills Earthquake- western Oregon's wake-up call, *Oregon Geology* 55, 51-57, 1993. | 5,4 | 0,0 | 0,00 |
| 91. | USA, Calif | Eureka Valley | 17/05/93 | 8,0 | http://pubs.usgs.gov/dds/2000/dds-058/Ch_J.pdf Assessed in the field by the Authors | 5,8 | 4,4 | 0,02 |
| 92. | Russia | Neftegprsk | 29/05/95 | 9,0 | Arefiev, S.S., E.A. Rogozhin, Tatevossian R.E., Rivera L., Cisternas A. (2000). The Neftegorsk (Sakhalin Island) 1995 earthquake: A rare interplate event. Geophys. J. Int., v. 143, 2000, 595-607. | 7,6 | 35,0 | 8,1 |
| 93. | Italy | Colfiorito Umbria-Marche | 26/09/1997 | 9,0 | Vittori E., G. Deiana, E. Esposito, L. Ferreli, L. Marchegiani, G. Mastrolorenzo, A.M. Michetti, S. Porfido, L. Serva, A.L. Simonelli & E. Tondi, 2000, Ground effects and surface faulting in the September-October 1997 Umbria-Marche (Central Italy) seismic sequence, Journal of Geodynamics, 29, 535-564. | 6,0 | 12,0 | 0,80 |
| 94. | Italy | Lauria S. Apennines | 09/09/1998 | 8,0 | Michetti A.M., L. Ferreli, E. Esposito, S. Porfido, A.M. Blumetti, E. Vittori, L. Serva & G.P. Roberts, 2000, Ground effects during the September 9, 1998, Mw = 5.6, Lauria earthquake and the seismic potential of the aseismic Pollino region in Southern Italy, Seismological Research Letters, 71, 31-46. | 5,6 | 0,2 | 0,02 |

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|---|---|---|---|---|---|---|---|---|
| 95. | Turkey | Izmit | 17/08/1999 | 10 | http://www.ngdc.noaa.gov/seg/hazard/sig_srch.shtml Barka, Aykut A; Akyuz, H Serdar; Altunel, Erhan; Sunal, G; Cakir, Ziya; Dikbas, Aynur; Yerli, Baris; Armijo, R; Meyer, B; de Chabalier, J B; Rockwell, Thomas K; Dolan, J R; Hartleb, Ross D; Dawson, Timothy E; Christofferson, S A; Tucker, A; Fumal, T E; Langridge, Robert M; Stenner, H D; Lettis, William; Bachhuber, J; Page, W D, 2002, The surface rupture and slip distribution of the 17 August 1999 Izmit earthquake (M 7.4), North Anatolian Fault, Bulletin of the Seismological Society of America, vol.92, no.1, pp.43-60. Youd, T.L., Jean-Pierre Bardet and Jonathan D. Bray, Technical Editors, 2000, Kocaeli, Turkey Earthquake of August 17, 1999: Reconnaissance Report, Earthquake Spectra, Supplement A to Volume 16, EERI Publication Number 2000-03, Cd. | 7.4 | 145,0 | 5,2 |
| 96. | Turkey | Düzce | 12/11/1999 | 9 | http://www.ngdc.noaa.gov/seg/hazard/sig_srch.shtml Hitchcock C., Erhan Altunel, Aykut Barka, Jeffrey Bachhuber, William Lettis, John Helms, Scott Lindvall, 2003. Timing of Late Holocene Earthquakes on the Eastern Düzce Fault and Implications for Slip Transfer between the Southern and Northern Strands of the North Anatolian Fault System, Bolu, Turkey, Turkish J. Earth Sci., 12, (2003), 119-136. Youd, T.L., Jean-Pierre Bardet and Jonathan D. Bray, Technical Editors, 2000, Kocaeli, Turkey Earthquake of August 17, 1999: Reconnaissance Report, Earthquake Spectra, Supplement A to Volume 16, EERI Publication Number 2000-03, Cd. | 7.2 | 40,0 | 5,0 |

**Table 4**: Categories used for the analysis of secondary earthquake ground effects.

| *Class of effect* | *subset* |
|---|---|
| **Hydrological anomalies** | • Hydrological discharge rate/water level change<br>• Hydrological-chemical-physical changes and turbidity<br>• New springs<br>• River overflows and lake seiches<br>• Temporary sea level changes - tsunamis |
| **Liquefaction and vertical movements** | • Liquefaction and lateral spreading<br>• Soil and backfilling compaction<br>• Tectonic subsidence/uplift |
| **Landslides**<br>(based on Table II in Keefer, 1984) | • Landslides in rock: rockfalls, rock slides, rock avalanches, rock slumps, rock block slides<br>• Landslides in soil: soil falls, soil slides, soil avalanches, soil slumps, soil block slides, slow earth flows, soil lateral spreads, rapid soil flows, subaqueous landslides<br>• karst vault collapses and sinkholes |
| **Ground cracks** | • Paved roads<br>• Stiff ground<br>• Loose sediments – wet soil |

**Appendix 1**: References for the earthquakes listed in Table 2 and 3.



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|---|---|
| 1. | AA.VV.- Sottoprogetto 5B2 del GNDT – 1997, Effetti di superficie indotti dal sisma del 26/09/1997 e successive repliche (Umbria-Marche)- Aggiornamento rapporto preliminare al19.10.1997. Atti 16° Conv. Naz. Gruppo Nazionale Geofisica Terra Solida, Roma, pp. 17. |
| 2. | Abdukadyrov, A.A., G.Yu. Azizov, A.G. Aronov, et al. (1987). The Gazli earthquake of March 19, 1984 In: N.V. Kondorskaya (ed.), *Earthquakes in the USSR in 1984*, 1987, 67-85. |
| 3. | Alfano G. B., 1931, Il terremoto Irpino del 23 luglio 1930. Osservatorio di Pompei 1931. |
| 4. | Altunel, E., 1999. Geologic and geomorphologic observations in relation to 20 th september 1899 Menderes earthquake, western Turkey. Journal of the Geological Society, London, 156, 241-246. |
| 5. | Altunel, E., Barka, A.A., Cakir, Z., Kozaci, Ö., Hitchcock, C., Helms, J., Bachuber, J. & Lettis, W. 2000. What goes on at the eastern termination of the November 12, 1999 Düzce earthquake, M=7.2, North Anatolian Fault, Turkey. American Geophysical Fall Meeting, California, USA, Abstracts, p. F816. |
| 6. | Ambraseys, N.N. and Finkel, C.F. (1987). The Saros-Marmara Earthquake of 9 August 1912, Earthquake Eng. and Struct. Dyn. 15: 189-211. |
| 7. | Arefiev, S.S., E.A. Rogozhin, Tatevossian R.E., Rivera L., Cisternas A. (2000). The Neftegorsk (Sakhalin Island) 1995 earthquake: A rare interplate event. Geophys. J. Int., v. 143, 2000, 595-607. |
| 8. | Arefiev, S.S., V.M. Graizer, D.N. Zargarian, et al. (1985). Rupture in the source and aftershocks of the Kum-Dagh earthquake of March 14, 1983. In: N.V. Shebalin (ed.) Macroseismic and instrumental studies of strong earthquakes. Problems of engineering seismology, n.26, 1985, 27 |
| 9. | Armijo, R., Tapponier, P., and Han, T.L. 1989. Late Cenozoic right-lateral strike-slip faulting in Southern Tibet. Journ. Geopphys. Res., 94, 2787-2838. |
| 10. | Azzaro R., Barbano M.S., Antichi B., Rigano R., 2001, Macroseismic catalogue of Mt. Etna earthquakes from 1832 to 1998. Acta Vulcanologia, 12 (1-2). |
| 11. | Barbano M. S., Rigano R., Azzaro R., 2000, Analisi storico-sismologiche sugli eventi sismici principali che hanno interessato le città di Augusta, Noto e Siracusa. In L. Decanini e G. F. Panza “Scenari di pericolosità sismica ad Augusta, Siracusa e Noto”, CNR-GNDT - pp.14-31 |
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