Ground effects of the Ml 5.2, November 24, 2004, Salò earthquake, Northern Italy: a case study for the use of the INQUA scale

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On November 24, 2004, at midnight (23.59 PM, local time), a moderate earthquake (Ml 5.2, Mw 5.0; focal depth 8 km; source INGV, http://www.ingv.it/terremoti/bresciano2004/mecc-focale.html) hit the Lake Garda region, within the active fold and thrust belt of the Southern Alps (Figure 1). This earthquake was felt in the whole Northern Italy, from Venice to Milan and Genoa, and abroad, for instance in Switzerland; the epicentral area includes the town of Salò and its surroundings, where where significant damage occurred and more than 200 people were left homeless. Epicentral intensity of VII-VIII in the MCS scale has been assigned in a preliminary way based on severe damage at the villages of Clibbio and Pompegnino.

Figure 1: Digital elevation model of the study area including instrumental epicentre of the 24th November 2004 Salò earthquake (source INGV), focal mechanism (from the MEDNET Database) and the field stations where observations on coseismic ground effects have been collected. The inset box (a) shows a more detailed map of the epicentral area.

Field surveys have been conducted since the day after the earthquake in order to collect all the information on earthquake's ground effects. The analysis of its environmental effects is of some interest for two reasons, a) this is the first damaging seismic event in Italy after the release of the INQUA Scale (http://www.apat.gov.it/site/en-GB/Projects/INQUA_Scale/), and b) the same area was hit in 1901 by an earthquake of a similar size, which produced well-described rockfalls, effects on springs and lake water level, and liquefaction induced fissures along the lake shore. This makes it possible to compare the damage on buildings and the "damage" on the environment from both events. This will provide a significant test for the reliability of the INQUA scale within the assessed range of epicentral intensity.

Our preliminary data show that environmental effects are considerable in the area of Salò and along the Chiese River Valley ("Val Sabbia").

As of yet, we observed 5 sites with multiple rockfalls (max volume in the order of some 10^2 m^3), 3 sites with landslides (max volume ca 10^3 m^3), 5 sites showing fractures on the ground and on paved roads, 2 sites with fractures along the lake shore, 2 sites showing turbidity of the water (1 aqueduct and 1 small river).

In particular, the most significant effects occurred at the following sites:

- Clibbio: along the Chiese River large rockfalls with dolostone boulders up to ca. 75 m^3 detached from the mountain slope of Mt. Acuto; two houses were hit by the boulders, and the main road to Clibbio has been strongly damaged; new big rockfalls occurred also in the days following the mainshock;
- Pompegnino: several cracks on the ground and on the paved roads have been observed in the downtown area; these cracks show widening (from 1 cm to 2 cm) with time, especially after the strong rain occurred on Nov. 29 and 30, 2004;
- Salò: evidence of liquefaction and localized (over an area of ca. 500 m^2) lateral spreading and settlement, with fissuring up to 30 cm wide parallel to the waterfront area have been observed in the harbor (Figure 2); these effects replicated those occurred during the 1901 event.

Figure 2: Fissure parallel to the waterfront, affecting the concrete in the Salò harbor area. This feature is an evidence of liquefaction and localized lateral spreading.

In general, most severe environmental effects and damage to buildings occurred in the same areas, and intensity assessed from the MCS scale is in good agreement with intensity assessed with the INQUA scale. From our data, INQUA intensity of VIII should be assigned to Clibbio and Salò, and VII to Pompegnino.

More detailed analysis of the structural setting, of the distribution of ground effects out of the epicentral area, and of the chemical variations of springs and ground water are in progress, and will be presented during the meeting.

An earthquakes database linking epicentral Intensity and surface faulting parameters

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Empirical relationships between magnitude and surface faulting parameters for crustal earthquakes are found in literature (e.g., Wells and Coppersmith, 1994), based on available information from historical and recent earthquakes.

Likewise, in order to describe relationships between epicentral intensity and surface faulting parameters, an appropriate database has been developed within the framework of the INQUA Scale Project. The last update of this database provides, for 114 strong crustal earthquakes occurred worldwide, seismological data (magnitude Ms and epicentral intensity Ie in the MM scale; Wood and Neumann, 1931) and surface faulting parameters (surface rupture length SRL, maximum displacement MAX D). Common data sources are professional reports contemporaneous to the seismic event, scientific papers and databases from national agencies and research institutes.

In order to build a homogeneous database, it was necessary to convert the original intensity values (MSK, MCS) in the same scale (MM, Mercalli Modified), using published relationships among different scales (Shebalin et al., 1974; Krinitsky and Chang, 1988; Reiter, 1991). Similar conversions were necessary for magnitude values of pre-instrumental earthquakes, uniformed to Ms. It is clear that, after the cited conversions, an additional degree of uncertainty was introduced in the database.

Nevertheless, besides this inaccuracy, the analysis of collected data shows important implications in the meaning of epicentral intensity which, in our opinion, has lost the original link with the focal parameters of the earthquake and nowadays reflects basically the damage distribution. For example the Ms=6.0 26.09.1997 (Umbria-Marche, Italy), the Ms=6.8 06.07.1954 (Rainbow Mountain, Nevada, USA) and the Ms=8.0 18.11.1951 (Damxung, China) earthquakes have recorded similar values for Ie (**IX**), although the associated rupture zone was significantly different: in the first event SRL was about 10 km, while in the second and third events its length was respectively in the order of 18 km and 90 km.

This is even more evident for the most destructive earthquakes: for example, similar Ie (**XI**) were assessed for the Ms=7.0 13.01.1915 Fucino (Italy) and the Ms=7.9 10.07.1958 Lituya Bay (Alaska, USA) earthquakes, although surface faulting parameters were very different (SRL was about 20 km and 200 km, and MAX D was about 2m and 6.6 m, respectively).

As well, the comparison between the Ms=7.5, **Ie=IX**, SRL=235 km 04.02.1976 Motagua (Guatemala) and the Ms=5.7, **Ie=XI**, SRL=5.5 km 24.07.1969 Pariahuanca (Perù) earthquakes, make it evident the physical inconsistency of intensity values as currently accepted.

Thus, in order to re-establish the original significance of intensity, as a measure of the earthquake strength, the intensity assessment cannot disregard the distribution and size of coseismic effects (tectonic and non-tectonic) occurred on the physical environment, as recommended in the last updating of the INQUA Scale based on Earthquake Environmental Effects (Vittori and Comerci, eds., 2004).

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The INQUA Seismic Intensity Scale, its importance and problems

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It is no need to say that the macro-seismic intensity scale is the most common and useful scale to describe the strength of earthquake shaking. However, the criteria for each scale are mostly based on the effects on buildings and other artificial objects. Seismic responses of these objects are widely different each other due to different construction design, materials and time. For instance, strength of an old adobe house is not same as the strength of an engineered modern house. However, damages to these different structures are tend to be described as 'many houses are collapsed' and macro-seismic intensity is tend to be evaluated based on such a description.

Geological effects against a strong shaking are more universal across the cultural border and throughout human history. There is a hope that we can establish an international intensity scale to describe he strength of an earthquake shaking.

On the other hand, there are some issues we have to take into account for macro-seismic intensity scale based on geological effects. One of them is that the strength of geological materials widely varies from place to place. For instance, strength of geological strata overlaying stable cratonic basement is extremely different from that of the strata experienced intensive compaction at a mobile belt.

Other issue we have to take into account is that the seismic frequency spectra and geological effects. Although its extremely strong PGA and PGV characterize the 2004 Niigata-Cyuetsu earthquake, only limited and sporadic liquefactions are observed along the Shinano River Valley. To understand this evidence, we have to take into account for the frequency spectrum of the shaking, not only for the PGA and PGV.

Paleoseismology, seismic hazard, and the INQUA Scale Project

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The INQUA Subcommission on Paleoseismicity organized a workshop at the XV INQUA Congress in Durban in August 1999. Workshop participants emphasized the importance of developing a multi-proxy empirical database on earthquake ground effects that can be used in seismic hazard assessments. The Subcommission selected this task as the primary activity of the 1999-2003 inter-congress period. An interdisciplinary Working Group (WG) of geologists, seismologists, and engineers was established to develop a new scale of macroseismic intensity based only on ground effects. This scale came to be known as the INQUA scale.

This paper summarizes the results of the research conducted by the WG, introduces the proposed INQUA scale, and discusses major issues arising from this innovative approach to the intensity assessment. Leonello Serva produced the first draft of the INQUA scale, based a comparison of the three most commonly used intensity scales – the Mercalli-Cancani-Sieberg scale (MCS), Medvedev-Sponhouer-Karnik scale (MSK), and Mercalli Modified scale (MM). Eutizio Vittori, Eliana Esposito, Sabina Porfido, and Alessandro M. Michetti revised Serva's draft scale, after considering the revised MM scale of Dengler and McPherson (1993), the new MM scale for New Zealand (Hancox et al., 2002), and descriptions of coseismic ground effects and intensity assessments for several tens of historical instrumented earthquakes. Bagher and Jody Mohammadioun, Eugene Roghozin, Ruben Tatevossian, Aybars Gürpinar, Franck Audemard, Shmulik Marco, Jim McCalpin, Nils-Axel Mörner, and Valerio Comerci provided helpful comments on this version of the INQUA scale prior to its release during the XVI INQUA Congress in Reno in July 2003.

The "INQUA Scale" is now the title of an INQUA funded project, aimed at applying this new approach to the study of earthquake environmental effects in the field, and in the revision of part strong seismic events, for a trial period of 4 years. After this trial period, an update version of the scale will be presented in Cairn, Australia, at the next INQUA Congress in 2007.

Paleoseismological and Quaternary geology research in recent decades has contributed significantly to the understanding we have today of the response of the physical environment to earthquakes, thereby providing the basis for the proposed INQUA intensity scale. The INQUA scale defines epicentral intensity, beginning at the VI – VII level, with increasing accuracy towards higher levels. In this higher intensity range, up to IX – X, the scale facilitates comparison of environmental effects and damage indicators, emphasizing the role of primary tectonic effects, which are independent of the local economy and cultural setting. In the intensity range below XI, the INQUA scale should not be used alone, but in conjunction with the other scales. In the intensity range XI to XII, the INQUA scale is arguably the only suitable tool for assessing epicentral intensity. Also, the INQUA scale is a vital tool for drawing isoseismals of IX, X, XI and XII degree in the epicentral areas of large earthquakes.

Indeed, comparison between recent large earthquakes shows serious inconsistency between epicentral intensity assessment and earthquake strength. For instance, MM scale epicentral intensity of IX, X, X, respectively, have been assigned to the Mw 7.9, Novembre 3, 2002, Denali fault, Alaska, the Mw 7.7, January 26, 2001, Bhuj, India, and the Mw 7.6, August 17, 1999, Izmit, Turkey, earthquakes.

This is clearly due to the lack of use of earthquake ground effects in the intensity assessment. For example, the low intensity assigned to the Denali Fault earthquake, which produced more than 300 km of surface faulting mostly across glaciated landscapes, is a result of the low density of population living in the epicentral area during this seismic event. We argue that if this approach is pursued, it will be impossible to compare large contemporary and future earthquakes with large historical earthquakes, and intensity of large earthquakes occurred in sparsely populated regions with intensity of large earthquakes occurred in densely populated regions. Intensity will reflect only the economy of the area, and not the physical parameters of the earthquake. In terms of seismic hazard assessment, this would be a dramatic loss of information. In fact, the original versions of the most important intensity scales (MM, MKS, MCS) in use worldwide do not allow this kind of assessment. Therefore, one of the main motivations for a new intensity scale based on ground effects is to reconcile the intensity assessment with the information on source parameters for large earthquakes.

Intensity is used in many parts of the world for seismic hazard analysis. It will remain an important parameter in seismology, earthquake geology, and engineering for many reasons:

· Intensity studies allow to reconstruct the macroseismic field of historical and contemporary earthquakes, and thus to identify seismogenic sources. Figure 1 illustrates this point by comparing isoseismal maps for historical and contemporary earthquakes in the Southern Apennines of Italy.

· An isoseismal map of an earthquake facilitates comparison of attenuation derived from magnitude-distance relationships and attenuation derived from the macroseismic field.

· The intensity values of an earthquake in specific localities represent the combined effects of source-path and site conditions and can be important from an engineering perspective.

· Intensity scales are built on the observed consistency between the severity of ground effects and the local physical environment, which also underpins the concept of seismic landscape. Geologists commonly assess the magnitude of a past earthquake from a single type of paleoseismic evidence, for example fault surface displacement, size of liquefaction features, or uplifted shorelines. However, a variety of natural features, considered together by the INQUA scale, can be used to refine estimates of earthquake strength and focal depth.

· Most importantly, the INQUA scale facilitates comparison of prehistoric and historic earthquakes. In other words, earthquake effects are compared rather than hypothetical calculated magnitudes.

The results of ongoing activity within the INQUA Scale Project will be presented during the meeting.

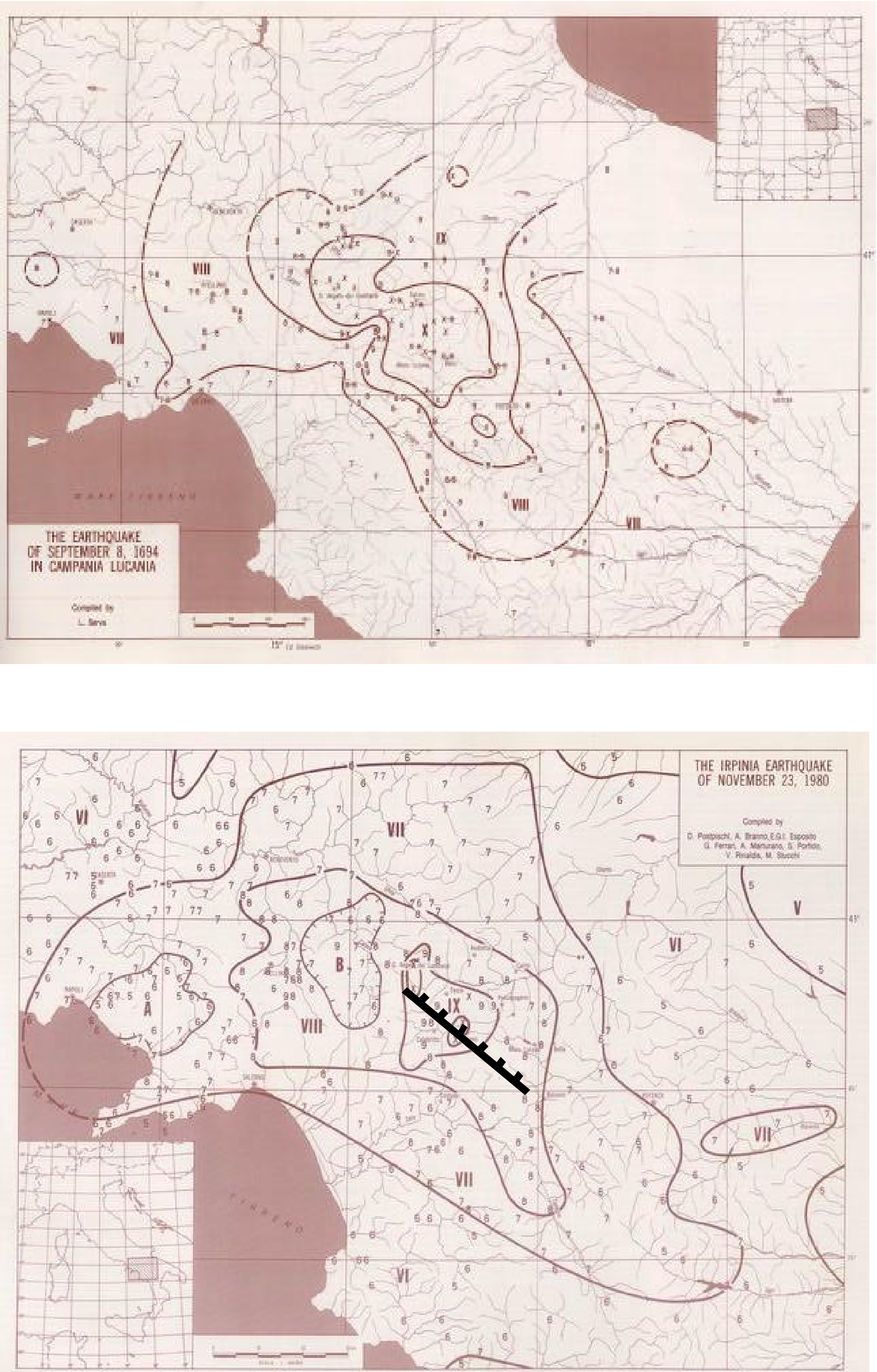

Figure 1. Isoseismal maps for the September 8, 1694, and November, 23, 1980, Irpinia, earthquakes in Southern Italy; surface faulting for the 1980 Irpinia earthquake is also shown. After Postpischl, 1985a, modified.

The INQUA Scale Project: Analysis and distribution of ground effects by type for Italian earthquakes.

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By means of a comprehensive review of over one hundred earthquakes with intensity ranging between III≤I≤XII MCS distributed in the Italian territory (Porfido et al., 2004; Vittori & Comerci, 2004), we have identified and classified by type a large number of earthquake-induced ground effects, occurred since XII century.

The ground effects have been categorized in primary, which include essentially surface faulting features, and secondary, which include four principal classes of features. The 5 resulting classes include the following information:

- **Surface faulting:** Normal/Reverse/Oblique/Strike slip dextral-sinistral.
- **Hydrological anomalies:** Hydrological discharge rate/water level change/Hydrological-chemical-physical changes and turbidity/New springs /River overflows and lake seiches/Temporary sea level changes/Tsunamis.
- **Liquefaction and vertical movements:** Liquefaction and lateral spreading/Soil and backfilling compaction/Tectonic subsidence/Uplift.
- **Landslides:** Landslides in rock: rockfalls, rock slides, rock avalanches, rock slumps, rock block slides. 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. Karst vault collapses and sinkholes (terminology according to Varnes 1978, and Keefer, 1984 classifications).
- **Ground cracks:** Paved roads/Stiff ground/Loose sediments/Wet soil.

Thanks to the large availability of historical and present-day information (Esposito et al.,1997; Esposito et al., 2000; Esposito et al., 2001; Michetti et al., 2000; Porfido et al., 2002), the obtained data have been compiled in a database, which is enlarged and updated on a regular basis.

The main parameters in the database are: type of ground effect, locality of occurrence and estimated intensity. The latter, given in MCS degrees, represents the local macroseismic intensity, assigned mainly based on the structural damage to buildings.

Moreover, the database includes specific parameters describing the single ground effects, such as: dimensions (length, width, volume, etc..), lithology (rock/loose sediment, etc..) and frequency of observed feature per km^2.

The already available data allow a preliminary assessment of the triggering threshold, size and density for most of the main geological effects of earthquakes, as a function of intensity (Vittori & Comerci, 2004).

Such a database represents the basic tool to test and calibrate the new INQUA EEE Scale. Clearly, to this end, and especially for a reliable application of the scale everywhere, it is now essential to implement data of geological effects for earthquakes occurred all over the world.

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Intensity – fault parameter relationships: implications for seismic hazard assessment

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Empirical relationships between surface faulting parameters (i.e. rupture length, rupture area, rupture width, displacement) versus magnitude (Bonilla, 1978; Wells & Coppersmith, 1994), also taking into account correctly the regional and local tectonic setting, are commonly used for seismic hazard assessment. 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 & de Polo, 1986; Petersen & Wesnousky, 1995; Anderson et al., 1996). As well, it is reasonable to expect that a similar direct correlation should exist between Intensity and primary effects of earthquakes.

To verify this assumption, a search for intensity values of earthquakes for which surface rupture parameters are available (e.g., those listed in Wells & Coppersmith, 1993) has permitted to build a first example of relationships linking primary ground effects and intensity, as illustrated in Figure 1. The diagrams show epicentral intensity (MM) versus maximum displacement (MAX D) and surface rupture length (SRL), for 114 earthquakes occurred worldwide.

The obtained relationships need be improved, being based on a still limited set of data; however it is clear that the size of primary ground effects is directly correlated with intensity, in the same way of magnitude.

It is noteworthy that in several cases earthquakes in a wide range of SRL and MAX D have attributed similar intensities. Moreover, it is remarkable that earthquakes with similar SRL and MAX D values display important differences in intensity values. These discrepancies confirm that the commonly assessed intensity values, strictly linked to damages to building, are more influenced by the distribution of settlements and technical development than the energy of earthquakes. This is a fact in particular in the intensity range between X and XII where, while the level of damage to buildings tend to saturate, the distribution and size of primary tectonic effects still display significant differences from a degree to the next one, thus resulting as a potentially highly diagnostic tool to assess the intensity level. Therefore, although useful for nearly all the intensity degrees, the use of a scale based essentially on environmental effects, such as the newly conceived INQUA EEE (Earthquake Environmental Effects) scale (Vittori & Comerci, 2004), should be recommended in the intensity range IX to XII.

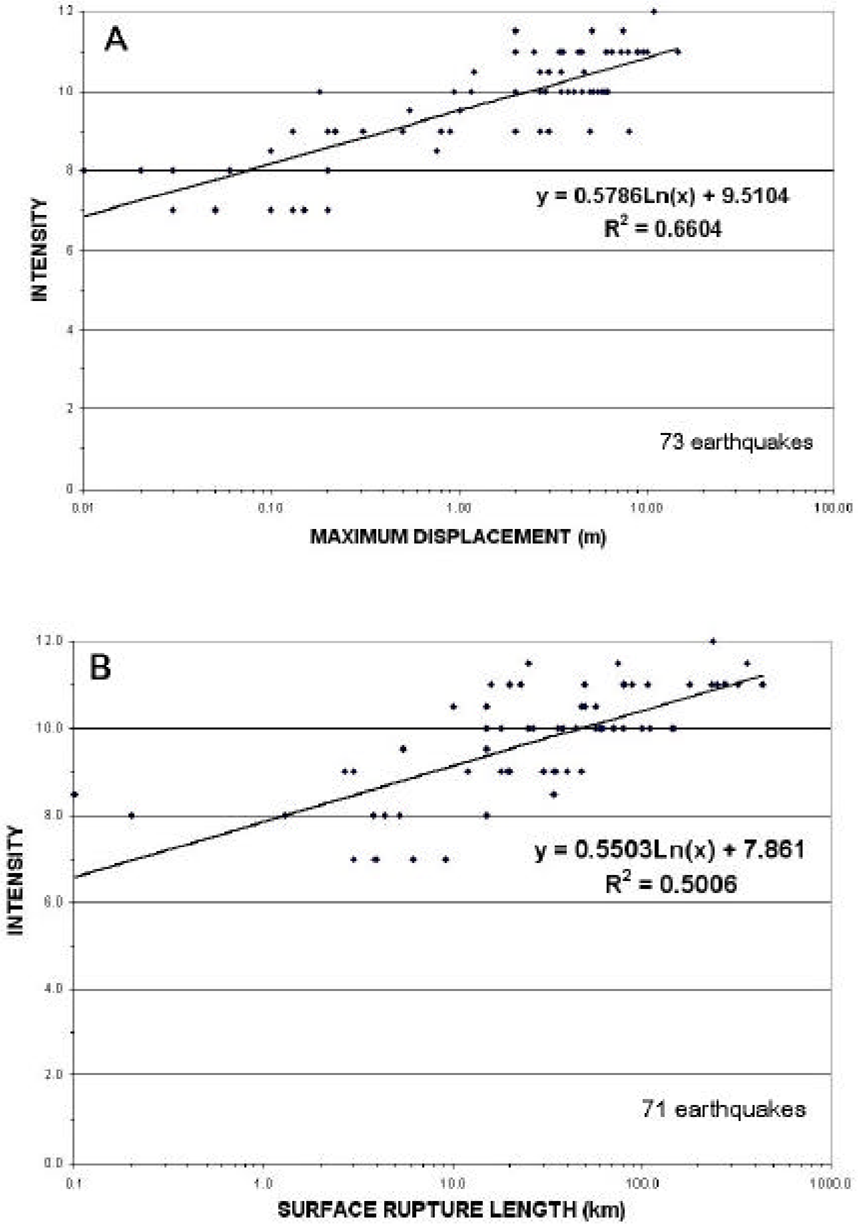

Figure 1: Diagram showing relations between epicentral intensity and surface faulting parameters for 114 crustal earthquakes

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