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Simulation of macroseismic field in Central Greece

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Abstract
The distribution of seismic intensity is generally influenced by major geological and tectonic features and, on a smaller scale, by local geological conditions, such as the type of surface soil, the surface-to-bedrock soil structure in sedimentary basins and the depth of the saturated zone. The present paper attempted to determine the distribution of macroseismic intensities based on published attenuation laws in the area of Central Greece, using the epicentral intensity, magnitude, length and direction of fault and a considerable number of observation sites, for which the above mentioned information is available. The expected intensity values were then compared to those observed in the same sites, from four earthquakes in Volos, Central Greece, for which the fault plane solutions are also known. The deviations of the observed values from the theoretical model were then related to the local geological conditions and the corresponding correction factor determined for each site.

Key words *macroseismic intensity – peak ground acceleration – local geological conditions – Central Greece*

1. Introduction

The distribution of macroseismic intensities, when studied through isoseismals, usually reveals the main tectonic features of the felt area. Factors such as fault direction, depth of focus, local geological and topographical conditions, and, in general, small scale irregularities are not always «seen» in an isoseismal map. In order to avoid the generalisation that results from a smoothed isoseismal map, methods of analysis using independent intensity values which correspond to specific sites have been introduced (Evernden *et al.*, 1973; Evernden, 1975). Such procedures need a considerable number of macroseismic intensities and a database of the geographical co-ordinates of the corresponding sites.

Due to the high seismicity of Greece, ample macroseismic information is available for such studies. In particular, the area of Central Greece has experienced several major earthquakes in the 20th century (1957; $M_s = 6.8$, 1980; $M_s = 6.4$, etc.), from which, due to the well organised observer network throughout the country, the macroseismic intensity data set is large.

Greece, following the instructions proposed for all countries during the UNESCO financed «study of the seismicity of the Balkan region» (Shebalin *et al.*, 1974), adopted the MSK-64 intensity scale and it is assumed that from 1970 the intensities of earthquakes in the area of Greece have been – more or less – homogeneously assessed.

The attenuation of intensities using the isoseismal maps of Greek earthquakes was stud-

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ied by several authors (*e.g.*, Drakopoulos, 1978; Drakopoulos and Stamelou, 1987; etc.). For Central Greece earthquakes, local attenuation laws were derived using individual intensity data points (Kouskouna, 1991). In that study all the sites and intensity values were digitised for an area of 24 square degrees, and their dominating surface geological conditions were categorised into three general groups (soft, medium and hard soils).

The present study adopted a different approach for the analysis of the above data. Taking into consideration the intensity distribution of a specific earthquake with a specific magnitude, associated to a specific fault length and direction, the distribution of the expected intensities of a future earthquake with the same parameters at the same sites was simulated. In this procedure the influence of local geological conditions was taken into account through dense girding of the geological maps of the studied area.

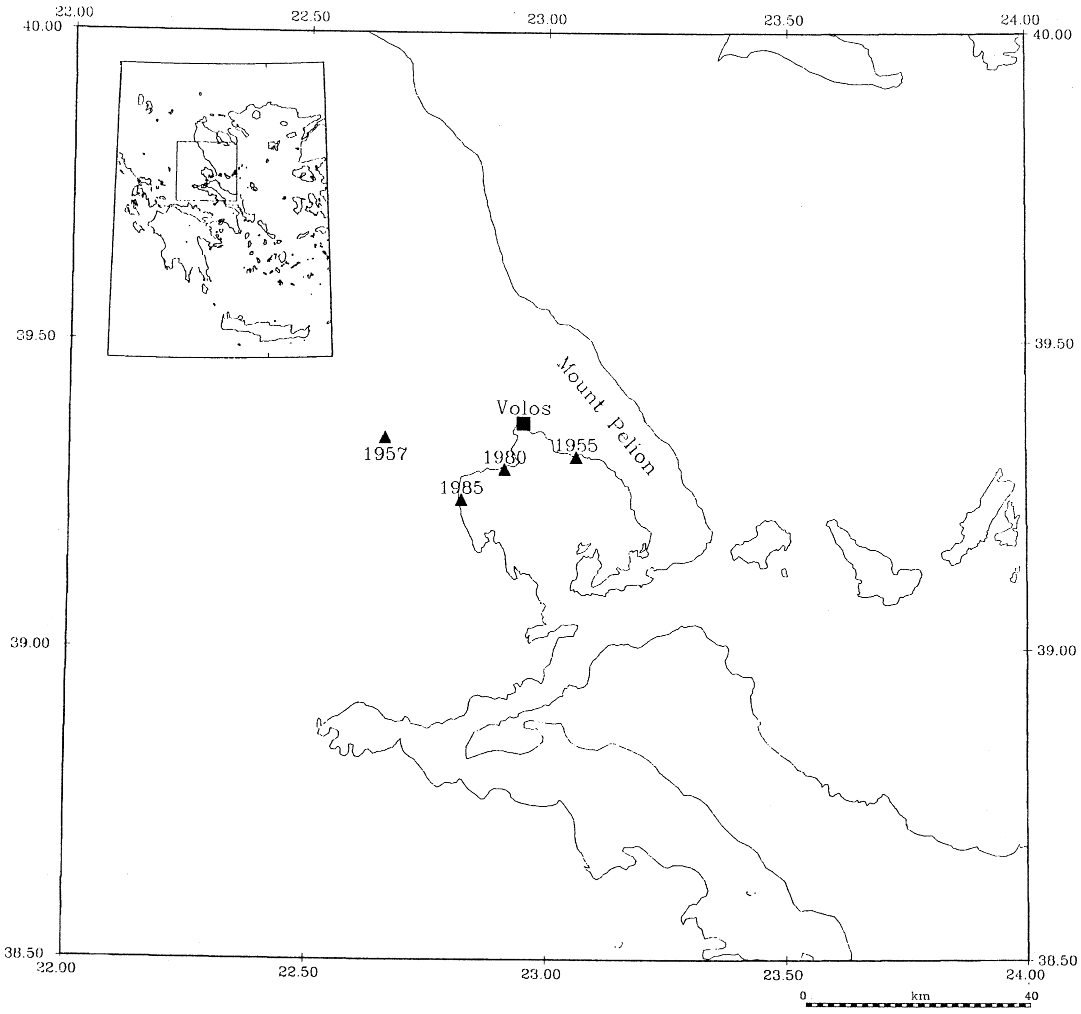

Fig. 1. The studied area of Central Greece. Triangles represent the studied earthquake epicentres.

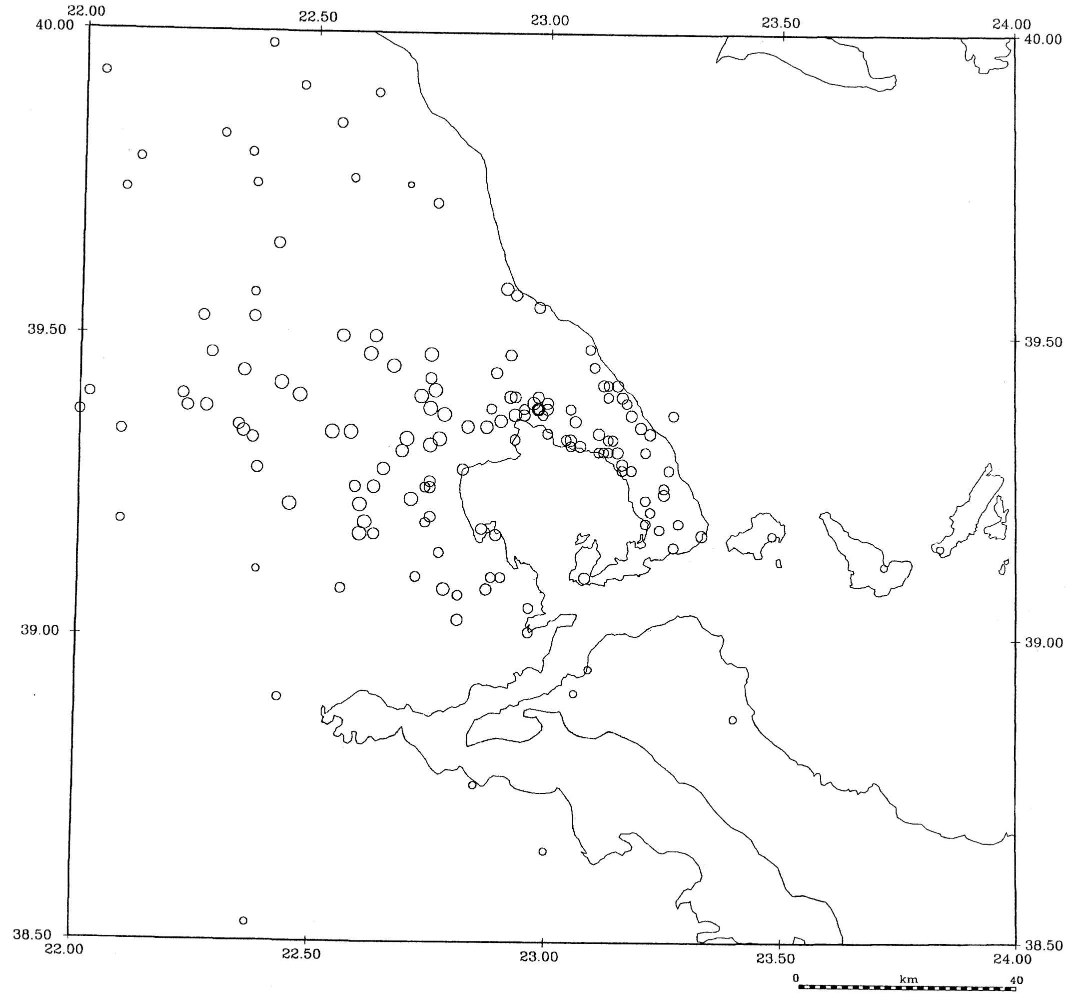

Fig. 2. Spatial distribution of intensities observed corresponding to the 1957 earthquake. Maximum intensity reached IX-X degrees.

2. Data

The data used in the present study concern four earthquakes with the parameters shown in table I (see also fig. 1).

From these earthquakes the macroseismic intensities as well as the corresponding sites were taken into account for the analysis. The distribution of the observed intensities from two of them are shown in figs. 2 and 3. One of

Table I. Parameters of the earthquakes used in the present study.

Date	M_s	Lat.	Long.	$I_{\max}$
1955 April 19	6.2	39.31	23.06	8-9
1957 March 8	6.8	39.34	22.66	9-10
1980 July 9	6.4	39.29	22.91	8-9
1985 April 30	5.8	39.24	22.82	6-0

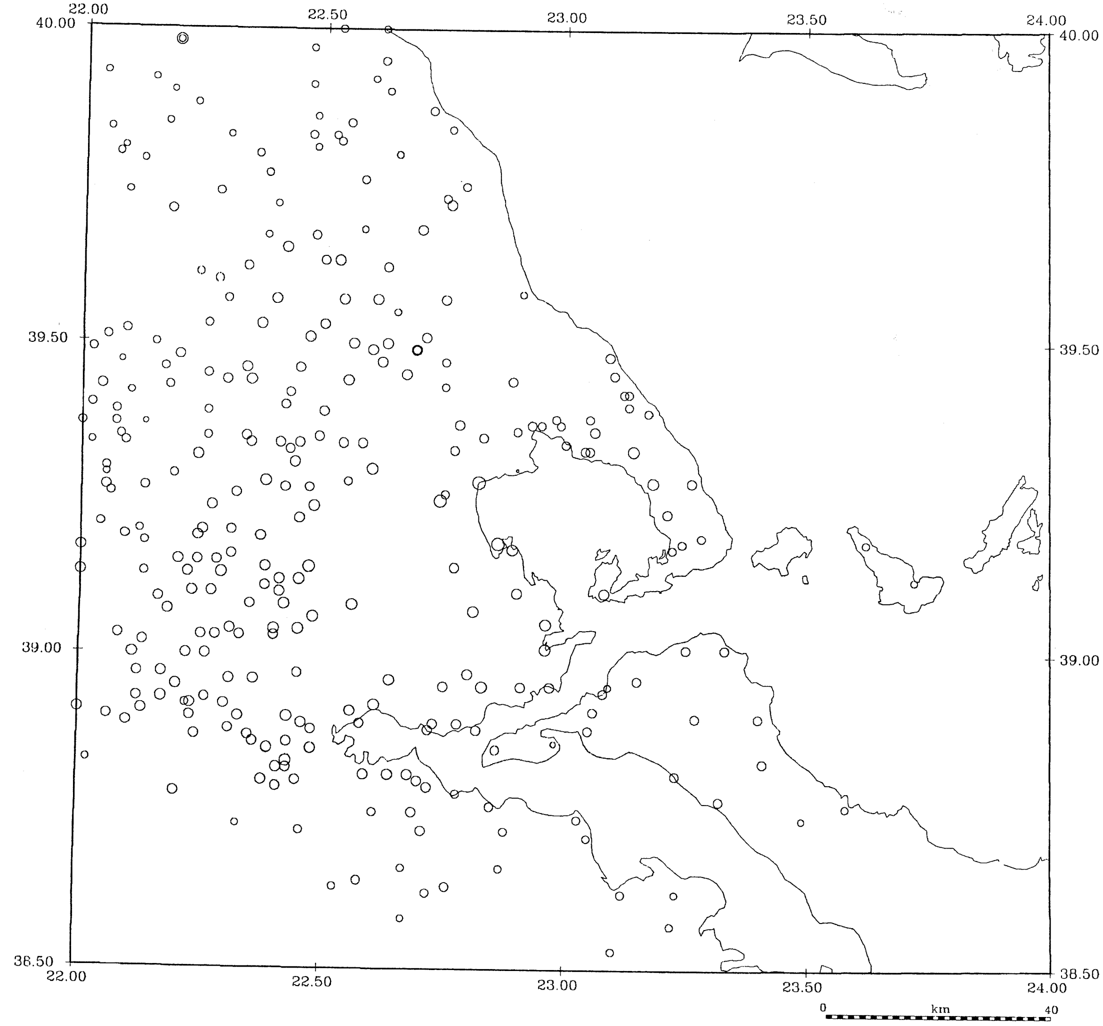

Fig. 3. Spatial distribution of intensities observed corresponding to the 1980 earthquake. Maximum intensity reached VIII-IX degrees.

the reasons for choosing these four specific earthquakes was that they belong to two different time periods as far as the macroseismic scales used are concerned: for the first two earthquakes it was assumed that the local version of MM scale was used, and for the other two earthquakes the MSK-64 scale was applied. The intensity data of the first two earthquakes were converted to equivalent MSK-64 values, using the relation proposed by Shebalin *et al.* (1974). In addition, all four earthquakes have enough macroseismic information for further analysis.

For computing reasons the intensity values were considered with one decimal point and therefore a value between *e.g.* 8-9 was taken as 8.5.

Apart from the digitised geographical co-ordinates of the sites, their local geological conditions were also taken into account. Previous

Table II. Ground character classification used in the study.

Type of soil	Category	Description
Soft soils	1	Alluvial deposits
Medium soils	2	Neogene formations and flysch
Hard soils (a)	3	Metamorphic rocks
Hard soils (b)	4	Limestones

analysis (Kouskouna, 1991) implied that the third geological category (hard soils) should be expanded into two sub-categories, and therefore the final geological groups are reported in table II.

Some sites were found to be located on the contact of two or three of the above categories. In such cases these sites were considered separately in order to explain any possible irregularities arising during the analysis.

The geological maps (scale 1:50000) of the studied area were digitised at 0.1 degree intervals, with each element carrying information on the predominant geological conditions, according to the categories described in table II.

3. Methodology

In order to study the distribution of macroseismic intensities and the possible influence of local surface geology in it, a method introduced by Evernden *et al.* (1973) and Evernden (1975) was followed. The basic assumption of the method is that during an earthquake associated to a fault, the energy is released homogeneously along this fault. Thus, the fault can be substituted by n equal point sources, and the macroseismic effects of the earthquake at a site away from the fault can be calculated by the integration of the individual effects of each point source.

In a homogeneous earth crust the peak ground acceleration, a, at a point of its surface due to an earthquake associated to a fault of length $2\ L$ can be calculated by the formula:

$$a = A\left[\frac{\varepsilon}{2L}\int_{-L}^{+L}\frac{dl}{(R^2+C^2)^{4k/2}}\right]^{1/\gamma} \tag{3.1}$$

where

ε =released energy (ergs) during an earthquake. Usually it is taken equal to $10^{11.8+1.5M}$ (Richter, 1958, p. 366). M is the magnitude of the earthquake;

R = distance, in kilometres, between the site on the earth surface and the point source;

C = pseudo-depth term so set as to give proper near-range die-off of intensities;

k = attenuation coefficient of acceleration ($a \propto \Delta^{-k}$) and subsequently of intensity I (see formula (3.2));

γ= ratio of the logarithm of the arriving energy at a point, to the acceleration of the point due to this energy (assumed to be equal to 4);

A = arbitrary coefficient selected as to give correct intensity values at uniform ground conditions for a particular earthquake.

The intensity at a surface point is directly related to the peak ground acceleration by a formula of the type:

$$I = \mathrm{a} + \mathrm{b}\ \log a \tag{3.2}$$

(Richter, 1958), where a and b are empirically assessed coefficients, depending on the particular area under consideration. Furthermore, by substituting a from formula (3.1), formula (3.2) can express expected intensity.

To incorporate the influence of surface geology in the expected intensity, the best possible knowledge of the detailed geology is necessary. The usual procedure is to classify the existing surface geological formations into categories according to their geotechnical characteristics. The corresponding coefficient due to different geological categories is then determined and added to the expected value of intensity from eq. (3.2). This procedure is described in the next section.

In practice, the geological conditions are digitised in a grid, where the elements are considered to describe the dominant geological conditions in each rectangular area around the relevant grid point. The dimensions of the grid intervals are chosen according to the desired detail of the study and the dimensions of the studied area. In what follows the details considering the application of the above mentioned formulas (3.1) and (3.2) in the area of Central Greece are presented.

Several formulas relating intensity to acceleration have been proposed for the area of Greece. In this study the following, introduced by Theophanopoulos (1987) was adopted:

$$I = 29\left(\log_{10}(a) - \left(\frac{1}{4.5}\right)\right). \qquad (3.3)$$

The fault length is related to the magnitude of the earthquake via laws which are characteristic for each area (Shebalin, 1972; Evernden, 1975). For the area of Greece, the following law is usually adopted (Papazachos, 1989):

$$\log 2L = 0.51M - 1.85. \qquad (3.4)$$

The derivation of eq. (3.1) was based on empirical expressions relating the peak ground acceleration to the focal distance, R. These expressions are of the form

$$a = b_1 e^{b_2 M}(R+20)^{-b_3} \qquad (3.5)$$

where b_1, b_2, b_3, are empirical constants. The coefficient b_3 is often regarded as the attenuation factor of ground acceleration (equivalent to k in eq. (3.1)). Usually such expressions represent the uniform distribution (smoothed isoseismals) of macroseismic intensities. In the present study the corresponding formula for Greek earthquakes and for bedrock conditions, suggested by Makropoulos and Burton (1985), was adopted:

$$a = 2164^{0.7M}(R+20)^{-1.8}. \qquad (3.6)$$

Following Evernden's (1975) procedure for the final estimation of A, which corrects intensities at uniform ground conditions, in eq. (3.1), the expected intensities from formulas (3.1) and (3.2) were first calculated, using the necessary parameters from eqs. (3.4) and (3.6) for one of the studied earthquakes. Then the appropriate value of A was estimated in such a way that the calculated intensities fit to the observed ones. This value was then used for all the earthquakes analysed in the present study.

4. Analysis

For each one of the four earthquakes the associated fault parameters were considered: the fault length was calculated from the respective magnitude (formula (3.4)) and its direction from fault plane solutions assessed from relevant studies (*e.g.*, Drakopoulos and Delibasis, 1982; Kouskouna *et al.*, 1992; etc.). Using the attenuation formula (3.6) for the area of Greece, and by substituting acceleration with intensity, the expected intensity distribution for each earthquake was determined. For each site the difference of the expected (calculated) intensity from the observed one was found (I_{obs}-I_{cal}) and the distribution of these differences, as well as the expected isoseismals are presented in figs. 4 and 5. Then, the mean of these differences for each category was calculated. If this mean is taken into account in each I_{obs}-I_{cal} value, then the overall resulting difference will be decreased. For each geological category the average correcting factor (which will be added to the value of intensity from eq. (3.3)), as well as its standard deviation is presented in table III.

These factors were used for the minimisation of the differences I_{obs}-I_{cal} for each site (for observed intensities) and each grid element (for calculated intensities), and the resulting map (fig. 6) shows the corrected isoseismals due to site geology as well as grid geology. In the same figure the smoothed, cyclical part of the isoseismals (white areas) is hypothetical and corresponds to the sea (no geological corrections).

In table IV the average, standard deviation, minimum and maximum values of the differences I_{obs}-I_{cal} for each earthquake is shown. The left part shows these values before corrections are made for surface geological conditions. Also, the 1955 and 1957 earthquakes are expressed in the MM scale, which explains

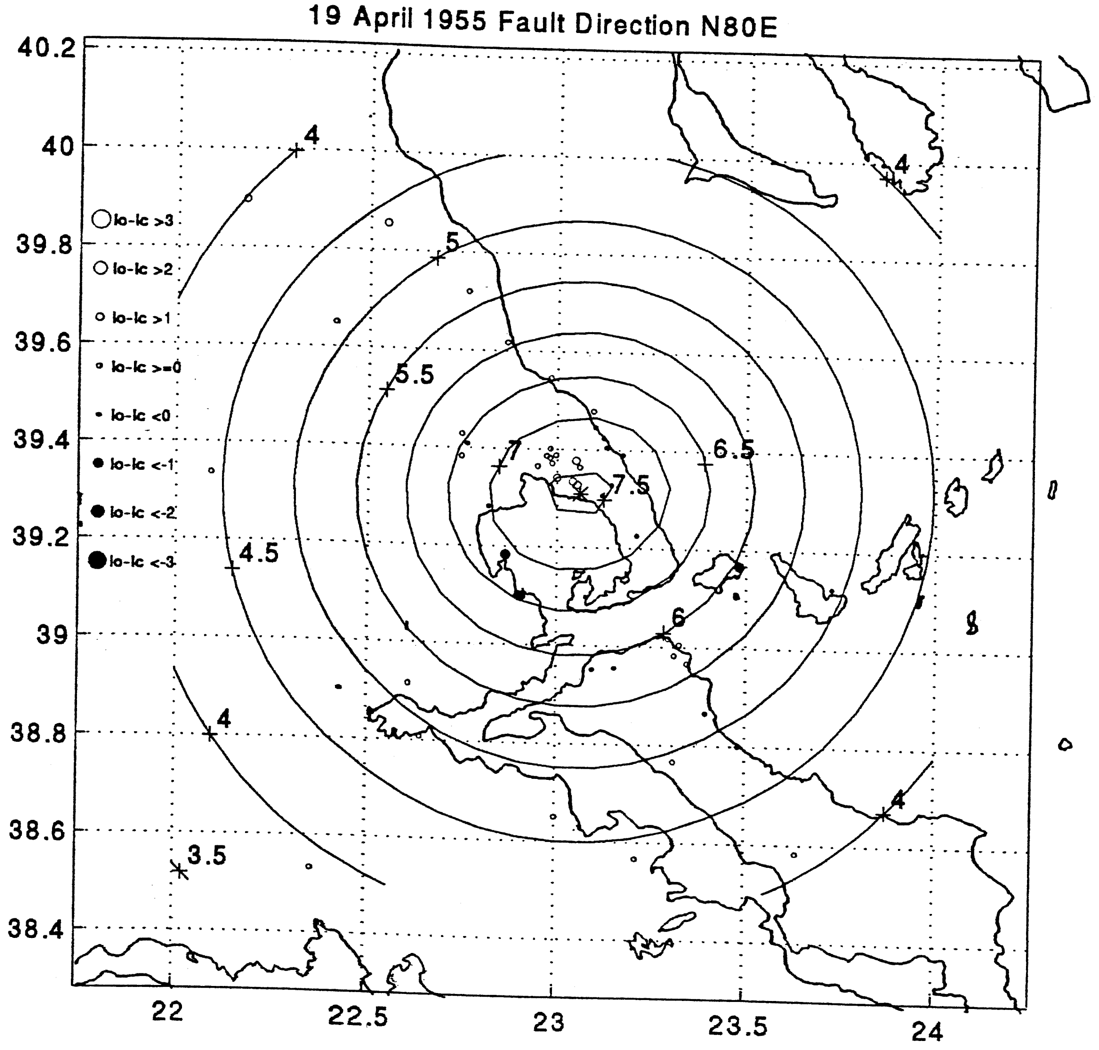

Fig. 4. Distribution of differences I_{obs}-I_{cal} and expected isoseismals of the 1955 earthquake.

why the differences I_{obs}-I_{cal} are larger for these earthquakes than those for the 1980 and 1985 earthquakes. This means that the MM scale produces slightly overestimated intensity values. In the right part, where the intensity values for the 1955 and 1957 earthquakes were expressed in the MSK-64 scale, the differences I_{obs}-I_{cal} were found to be in the same level for all earthquakes. Also, in the right part, where the correction for geology was applied according to the correction factors of table III, some decrease of these differences is apparent in all earthquakes.

For the specific cases of sites on two or more geological conditions, it was found that they responded according to the softer soil of all, and therefore this soil was taken as their representative geological category.

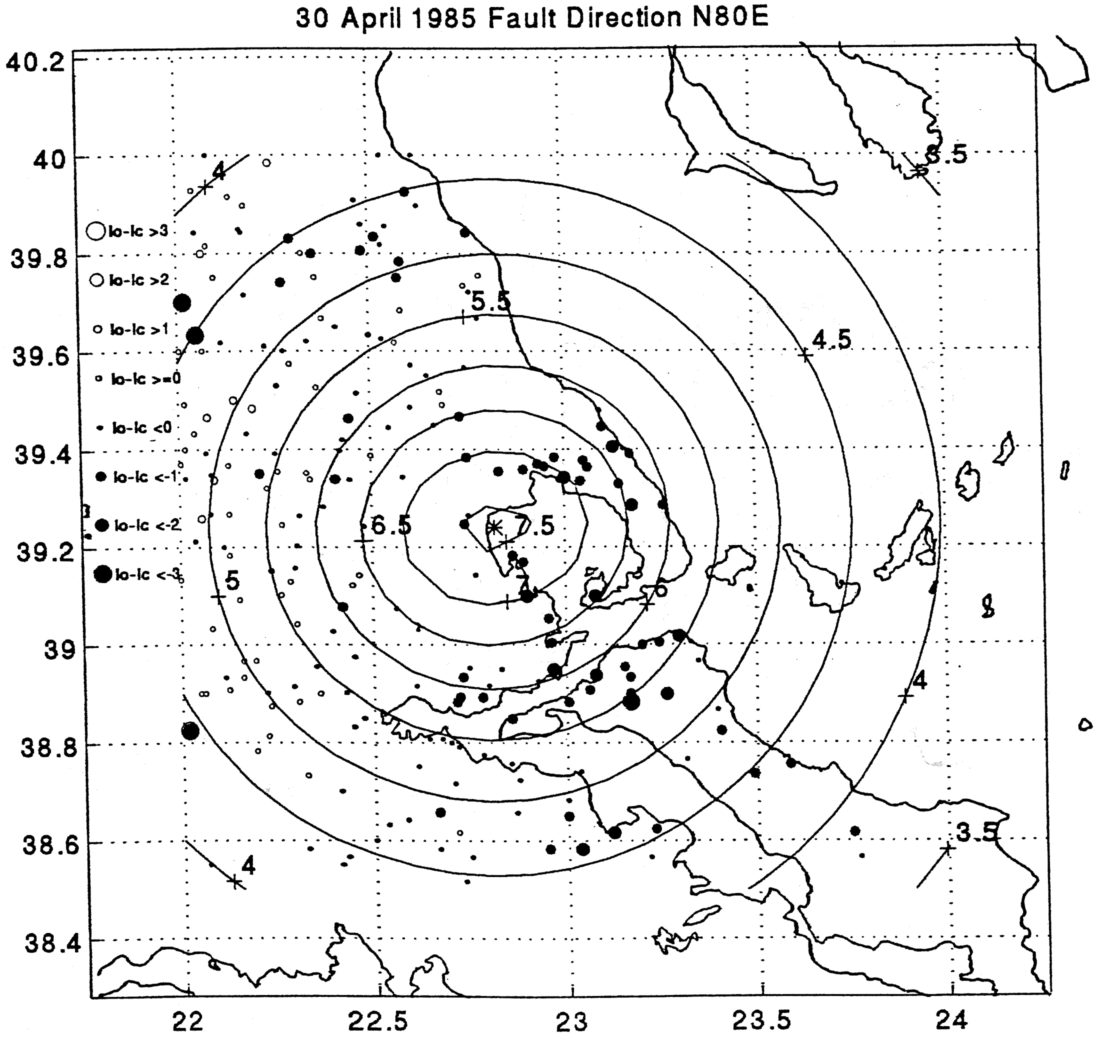

Fig. 5. Distribution of differences I_{obs}-I_{cal} and expected isoseismals of the 1985 earthquake.

Table III. Correction factors for the different ground characters.

Category	Correction factor	Standard deviation
1	0.397	0.523
2	0.574	0.476
3	0.388	0.254
4	0.394	0.317

5. Conclusions

The macroseismic intensities describe the overall effects of an earthquake on a town or a village. In this sense any influence by the local geological conditions cannot be as well defined as in similar peak ground acceleration measurements. However, the general geological categories considered in the present study

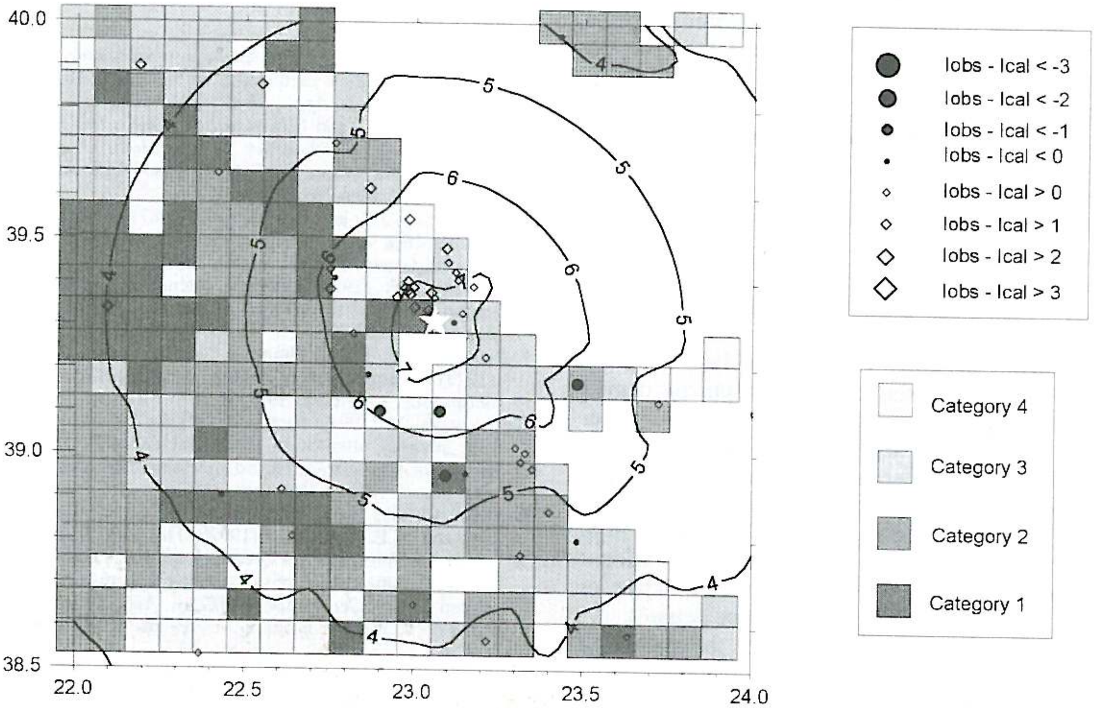

Fig. 6. Distribution of I_{obs}-I_{cal} after taking into account the correction factor due to geology and resulting theoretical isoseismals of the 1955 earthquake.

Table IV. Statistics of the differences I_{obs}-I_{cal} obtained for each studied earthquake.

	I_{obs}-I_{cal} before geological corrections				I_{obs}-I_{cal} after geological corrections			
	1955	1957	1980	1985	1955	1957	1980	1985
Average	0.631	0.71	0.018	−0.336	0.383	0.424	0.004	−0.308
Standard deviation	0.735	0.920	0.825	0.792	0.574	0.732	0.647	0.528
Minimum	−1.398	−2.71	−2.867	−4.465	−1.022	−1.719	−1.653	−3.607
Maximum	1.809	3.059	2.84	1.195	1.304	2.165	1.534	1.084
No. observed	51	151	297	226	51	151	297	226

showed a systematic deviation from the values expected, when only the distance from the epicentre is taken into account.

As far as the amount of correction due to surface geological conditions is concerned (tables II and III), it was found to be rather low (around or less than half a degree of intensity), lower than the error following the definition of macroseismic intensity. However, there was a clear difference between the values of category 2 from all the others, which is in agreement with previous studies.

In many cases, the values of difference were systematic, and their variation due to different geological categories could be attributed to the following: as the analysis was based on expected values of acceleration and intensity corresponding to bedrock, the correcting factor for category 2 seems to be reasonably higher than the one for categories 3 and 4. On the contrary, the low values of correction factor for category 1 could be explained by the considerable thickness of the alluvial deposits (up to 100 m), in several sites, which have often proved to be an attenuating, rather than amplifying medium.

The expected intensities were corrected to a promising degree, considering the sampling rate of digitisation (0.1 geographical degree squares) of the geological information. Further remaining differences could be attributed to errors in the assessment of intensity, to larger scale geological or tectonic features, such as the cluster of high differences in the area NE from the epicentre (fig. 6), *i.e.* the area of Mount Pelion, which is a well known tectonic nappe, or to local scale differences within the squares.

In the case presented herein, the relatively high standard deviations of the estimated correcting factors for geology, which are due to specific clusters of high differences, do not allow the implementation of the above simulation procedure in reversing the problem, in order to assess structural attributes at this scale. However, at a smaller scale, where the differences I_{obs}-I_{cal} are very small, this procedure can apparently show the influence of local geology on intensity.

Further analysis should be concentrated in smaller areas at a more detailed geological character classification and in more homogenous tectonic regimes.

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