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An analytic method for separating local from regional effects on macroseismic intensity

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Abstract
Interpretation of macroseismic data is hazardous, due to its qualitative nature. This, linked with errors in evaluations and the variations of local intensity, makes it difficult to draw valid conclusions. This study presents a statistical method as the basis for distinguishing the diverse components that constitute a macroseismic field. The method is based on the polar transformation of the coordinate system and on the analysis of the fractal dimension of the intensity values, exposed to the gradually increasing action of a two-dimensional filter. The fractal dimension is shown to be an ideal parameter with which to measure out the filtering process in order to separate the local components from the regional trend. This method has been applied to two Italian events and to an earthquake which took place in the Former Yugoslavian Republic of Macedonia (FYROM).

Key words *macroseismic intensity – fractal dimension – filtering*

1. Introduction

Macroseismic investigations are a vital part of earthquakes analysis because they provide the necessary information with which to create a pattern of the damage incurred during an event, and can also be used as means of studying events of the past, for which no instrumental data are available. Unfortunately, this kind of analysis is made up of many stages where it is necessary to interpret data of a prevalently qualitative character. This interpretational component leads to subjectivity, followed by different schools of thought or groups that have developed their own separate «tradition» of macroseismic analysis.

Many authors have shown an awareness of this problem and have attempted to create a method able to trace an isoseismal map (Shebalin, 1974; Bottari *et al.*, 1980; Papazachos, 1992) and to assign a macroseismic degree (Ringdal *et al.*, 1978) in a way that is both uniform and objective.

However, there are those who have criticized the various methods, proposing, as an extreme consequence, to abandon the tracing of isoseismals (Berardi *et al.*, 1990).

This study is based upon the conviction that the statistical approach is the only reliable tool for macroseismic data analysis. Presuming the dissolution of any problem derived from the interpretation of reported damage due to an event, and having fixed the macroseismic intensity values (for example according to the Mercalli, Cancani, Sieberg, M.C.S., scale), our approach tackles the analysis of information in order to construct a macroseismic field.

As macroseismic field we consider the geographic representation of effects, caused by the seismic events within the involved areas, cleared, as far as possible, of errors in the evaluation of damage. A field is characterized by a certain continuity. Taking the information referring to individual centers, our intention is to build up a picture of the entire territory, as if it were ideally completely urbanized. The aim of this is to recognize the influence of diverse components on the damage pattern. The role of the seismic source is predominant, followed by the geological setting of the area (tectonics, rock formation types, topographical characteristics, nature of the soil), the structural resistance of the buildings and the urban typology. The possibility of differentiating among these factors rests in their diverse scales of impact. The source and the geological setting condition the entire macroseismic field, whilst the remaining ones operate on a reduced scale. In the characterization of a macroseismic field, greater interest is placed on the definition of large scale effects, considering the other factors as background noise.

This approach was established in a previous study by the same authors (De Rubeis *et al.*, 1992), where, through the use of trend analysis within circular areas of territory, local components were filtered out from the macroseismic data. It is necessary to point out that in that case no intrinsic characteristic of spatial distribution of macroseismic intensity was taken into consideration. No distinction was made between the epicentral area (where within a relatively limited space there is great intensity variation) and the other zones. It is therefore necessary to produce a method suitable even for the epicentral zone, based on a model that respects the radial nature of the effects produced by a seismic event. Moreover, in the above mentioned paper, the choice of the component to be filtered out was too dependent on the quality of data and sometimes affected by a certain degree of subjectivity.

A solution to these problems is here presented, with the introduction of a transformation coordinate and the application of a fractal dimension analysis.

2. Method

The method used to filter and to interpolate the whole macroseismic field is based on trend analysis. It is known that this kind of analysis presents problems when there is an anomalous data distribution. Problems are also encountered in the interpolation of high polynomial degrees (greater than 4), as the round-off effects introduced by the computer become weighty (Davis, 1986). Such limitations are tangibly present in the treatment of the macroseismic data, as data comes from the inhabited centers, which, due to the geomorphological characteristics of the territory and pertinent historical factors (both social and economic), are not distributed in an homogeneous way. Moreover, if one wants to interpolate the complete macroseismic field with a single two-dimensional polynomial expression, it would be necessary to use a high degree to follow the fundamental variations.

In an attempt to overcome these difficulties, the macroseismic field was divided into circular sub-areas centered on a regular grid and the polynomial coefficients were calculated within each sub-area. Such a subdivision increases the number of polynomial expressions and reduces the number of points to interpolate for each sub-area, obtaining a marked reduction in variability and the possibility of maintaining a lower polynomial degree: in our application the choice of degree 2 was always adopted, because all past experiences indicated it as the most suitable one. The trend value for the central point of each sub-area was then calculated, so limiting the edge effects.

In order to give greater detail to the epicentral area and considering the radial nature of the seismic phenomenon, the kilometric coordinates, associated with those villages for which there exists information on damage incurred, were transformed into a system of polar coordinates centered on the epicenter. This conversion creates a disparity in the units of measurement of the coordinates, in that: one is a kilometric distance from a point representing the epicenter, whilst the other is an angular value. The angular quantity, expressed in radians, was therefore multiplied by an suitable value (δ) representing the mean distance in kilometers of towns from the epicenter. As a consequence the villages located at a lesser distance from the epicenter at this value, underwent an expansion, whilst those at a greater distance resulted compressed.

A requisite to the polar transformation is the definition of the macroseismic epicenter, for instance by calculating the barycenter of the points with greater macroseismic intensity. In several cases, however, the anomalous disposition of towns or the presence of errors in the evaluations can influence the position of the barycenter. If this occurs, it will be possible to redefine the barycenter using a «try and wedge» technique or by adopting an instrumental epicenter. However, it has been noted that slight variations of epicenter position do not cause significant differences to the filtered field.

Figure 1 shows the intensity map of the event which occurred in the southern region of ex-Yugoslavia (FYROM) after the polar transformation (the geographical representation is shown in fig. 4a). The area to the left in the polar representation refers to the epicenter, whilst on the extreme opposite are located the points with the lowest intensity values and with greater distance from the source. This brings about the disappearance of the radial characteristics of the field (in that a sheaf of straight lines intersecting at the epicenter is represented by a set of parallel straight lines) and a relative expansion of values near the epicenter compared to those further away.

At this point it is necessary to determine the dimensions of the circular sub-areas, within which to calculate the second degree polynomial trend. The use of small ranges gives a representation similar to that of the original values (weak filter action), whilst larger ranges induce a greater filter effect because each interpolation is made on a larger number of points. So the variation of the filtered surfaces with increasing range was examined, studying the changes of roughness through the analysis of the fractal dimension.

The use of the fractal dimension for the study of surfaces is not new. Mandelbrot (1975, 1982) showed how it is possible to represent the irregularity of a topological surface via the generation of a fractal surface. Kaye (1993, and reference therein) specifies that the ruggedness of a line (or surface) comes from the difference between its fractal dimension and its topological dimension (1 for line, 2 for surface). This measurement also constitutes,

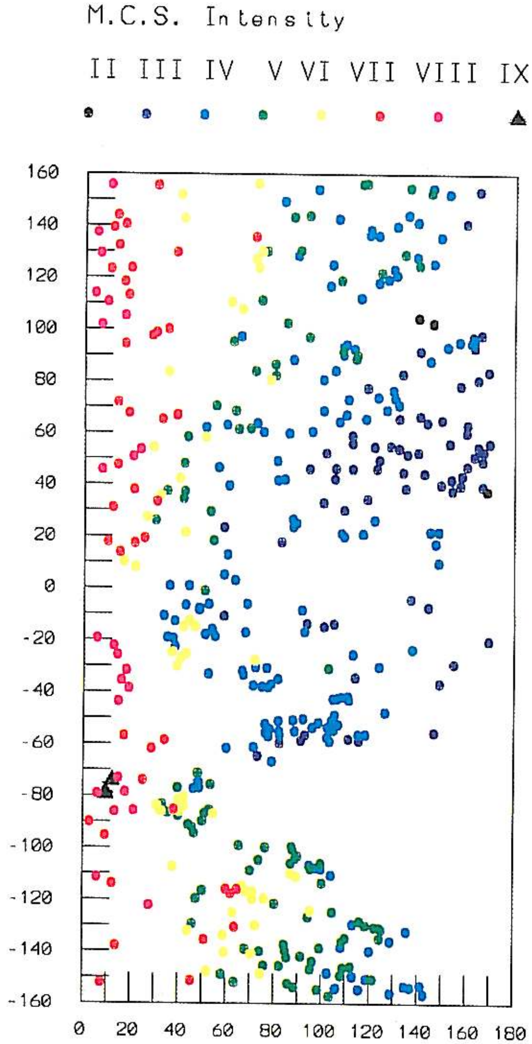


Fig. 1. Intensity distribution in polar coordinates for the earthquake of July 26, 1963, in ex-Yugoslavia (FYROM); the abscissa shows the distance in km from the macroseismic epicenter, the ordinates are proportional to the angular distance from the reference direction (0 = South; ± 160 = North). The left side of the figure identifies the epicenter, whilst the right part holds the points at greatest distances from the epicenter and therefore with the lowest intensities. It results in a relative expansion of values near the epicenter and a relative compression for those further away.

according to Kaye, the basis for the description of the structure under examination. Herzfeld *et al.* (1993), analyzing the topographical structure of the sea floor in two zones of oceanic expansion, showed that, even though it may not be described by a self-affine process, it «may well have a fractal Hausdorff dimension». Elliot (1989) examined the variations over time of the surface roughness in the topography of a zone of Western Norway, adopting the analysis of the fractal dimension to quantify the effects of the surface shaping processes. Vergne and Souriau (1993), analyzing topographical data of South-West France with the study of the power law dependence of the semivariogram (a relation deeply connected to the fractal dimension), identified two topographical components: a meso-scale texture and a large scale tectonic pattern.

We think that quantitative analysis of the surface structure can be applied even in macroseismic studies. In particular, the measurement of the fractal dimension of the intensity map and of those produced by the steadily increasing filter action can be useful for distinguishing the regional field from local irregularities.

The surface that represents the macroseismic field is determined by diverse measurements units: kilometric distance on the horizontal plane and macroseismic intensity on the vertical axis. In order to measure a fractal dimension, a specially adapted method is required which can deal with self affine surfaces. Such methods include: box counting with reference boxes of diverse dimensions, spectral techniques (Turcotte, 1992) and the study of experimental semivariogram (Matheron, 1963, 1972; Guillaume, 1977; Korvin, 1992). The latter is expressed by:

$$\gamma(l) = \frac{\sum_{i=1}^{n} \sum_{j=1}^{f_i} [I(X_i) - I(X_j)]^2}{2 \sum_{i=1}^{n} f_i} \qquad (2.1)$$

where I is the macroseismic intensity at the point X, l is the distance between the points X_i and X_j, f_i is the number of points at distance l from X_i and n is total number of points.

If the data display a drift, an estimate must be made and this component must be subtracted from the semivariogram to obtain a residual value (Herzfeld *et al.*, 1993). The drift component m is calculated with the following equation:

$$m(l) = \frac{1}{n} \sum_{i=1}^{n} [I(X_i) - I(X_j)] \qquad (2.2)$$

whilst the residual semivariogram is expressed thus:

$$\gamma_{res}(l) = \gamma(l) - \frac{1}{2} m(l)^2 . \qquad (2.3)$$

If the macroseismic intensities were stationary: $m(l) = 0$ and $\gamma_{res}(l) = \gamma(l)$.

In the case in which $\gamma(l) = kl^{\alpha}$, the fractal dimension D of the surface is defined by:

$$D = E - \frac{\alpha}{2} \qquad (2.4)$$

where E is the embedding dimension, in this case equal to 3.

Effectively, once the experimental values of $\gamma(l)$ are obtained, they are plotted onto the bilogarithmic diagram versus l. The slope α of the straight line, best fitting the linear portion of $\gamma(l)$, identifies D according to (2.4).

It must be pointed out that in the data used, as in most experimental data, the fractal behaviour is evident over a limited dimensional range. With the intention to minimize errors, this range is closely studied in the semivariogram and D is calculated only in the straight portion of $\gamma(l)$.

For each intensity map, a fractal dimension is calculated. The measured set is constituted by points embedded in a 3-dimensional space: then the fractal dimensions can assume values ranging from 0 to 3. Values under 2 seldom occur in this analysis because the filtered points tend to approach a smooth surface (with topological dimension of 2): values slightly under 2 are due essential to the discrete sampling. With the increase in the radius of the circular subareas – essentially a filtering increase – a decrease of the fractal dimension D is attained, which is gradually nearer to 2. The graphic representation of the process shows two distinctly different tracts (figs. 2b, 3b, 4b and 5b). In fact, the random noise, that can be assimilated to the local component, always increases the fractal dimension of the original signal (Möller *et al.*, 1989). This increase is relatively high, because a random distribution of points tends to fill the space in which the set is contained. Consequently the initial sharp decrease of D is due to the fact that the noise is the first component to be eliminated by the filter action; the end of this portion coincides with the end of the noise effect, then the radius of the sub-areas corresponding to this point is the ideal range for filtering the sole local random component.

Once the range is determined, the original values are interpolated with trend surfaces of this size, centered on the nodes of a regular grid and maintaining the calculated values only at the coordinates of the nodes.

The filtered surface obtained is therefore subject to inverse transformations of the procedures previously applied (rescaling, polar to cartesian transformation, passage to geographical coordinates).

3. Application

The described method was applied to two Italian earthquakes and to a strong event which occurred in ex-Yugoslavia (FYROM).

The first of the Italian events took place in the Friuli Region on February 1, 1988 (M_L = = 4.3), with instrumental coordinates: 46.31°N, 13.15°E. The macroseismic investigation was made by sending out questionnaires to Public Bodies within the interested area (Gasparini and Vecchi, 1988). The intensity values resulting from the analysis of the questionnaires reached the sixth degree of the M.C.S. scale. Figure 2a shows the intensity map as coloured dots. Some irregularities in the intensity distribution may be noted: for example, there are very different intensity values that occur relatively near each other.

Figure 2b shows the evolution of the fractal dimension of the points of the filtered macroseismic field versus the sub-area range (variation of the filter action). It is evident from the figure that small differences in the lower values of range cause significant variations in fractal dimension, whilst over the 30 km limit the fractal dimension is much more resistant to the filter action. It must be pointed out that the value of the range expresses the effective kilometric distance only in the radial direction of the macroseismic field centered on the epicenter, for the other directions the real values of the range depend on the relative compression or expansion owing to polar transformation and on the choice of the value δ. Figure 2a displays the isoseismals of the macroseismic field obtained by filtering with a range of 32 km. There are not sufficient data for the satisfactory characterization of the eastern direction of the field due to the nearness of the state confines. However, an elongation of the macroseismic field towards West is indicated by the isoseismals of VI, V and IV degree and another less pronounced elongation is to the South. The center of the polar transformation was set at the instrumental epicenter.

The other Italian earthquake analyzed occurred near the city of Potenza on May 5, 1990. The instrumental epicenter was also used in this case as the center of the polar transformation of the data. It was estimated at 40.64°N and 15.86°E and the magnitude was evaluated to be M_L = 5.2. This quake was the most important in a sequence of over 200 events (Azzara *et al.*, 1993). The macroseismic analysis was conducted through questionnaires in conjunction with direct investigation (Tertulliani *et al.*, 1992). Figure 3b shows that the optimum filtering range is approximately 55 km. The isoseismals of the macroseismic field filtered at this range value is displayed in fig. 3a. Also for this case the pattern is not isotropic but it gradually becomes more regular after the isoseismal of V degree.

The event which occurred in the southern part of ex-Yugoslavia (FYROM) on July 26, 1963, had its epicenter at coordinates 42.0°N and 21.4°E. Its high magnitude (M_S = 6.1) provoked damage of up to IX degree on the M.S.K. scale. The macroseismic analysis was conducted by Hadžievski (1971) and Shebalin (1974). The center of the polar transformation, in this case, coincided with the macroseismic

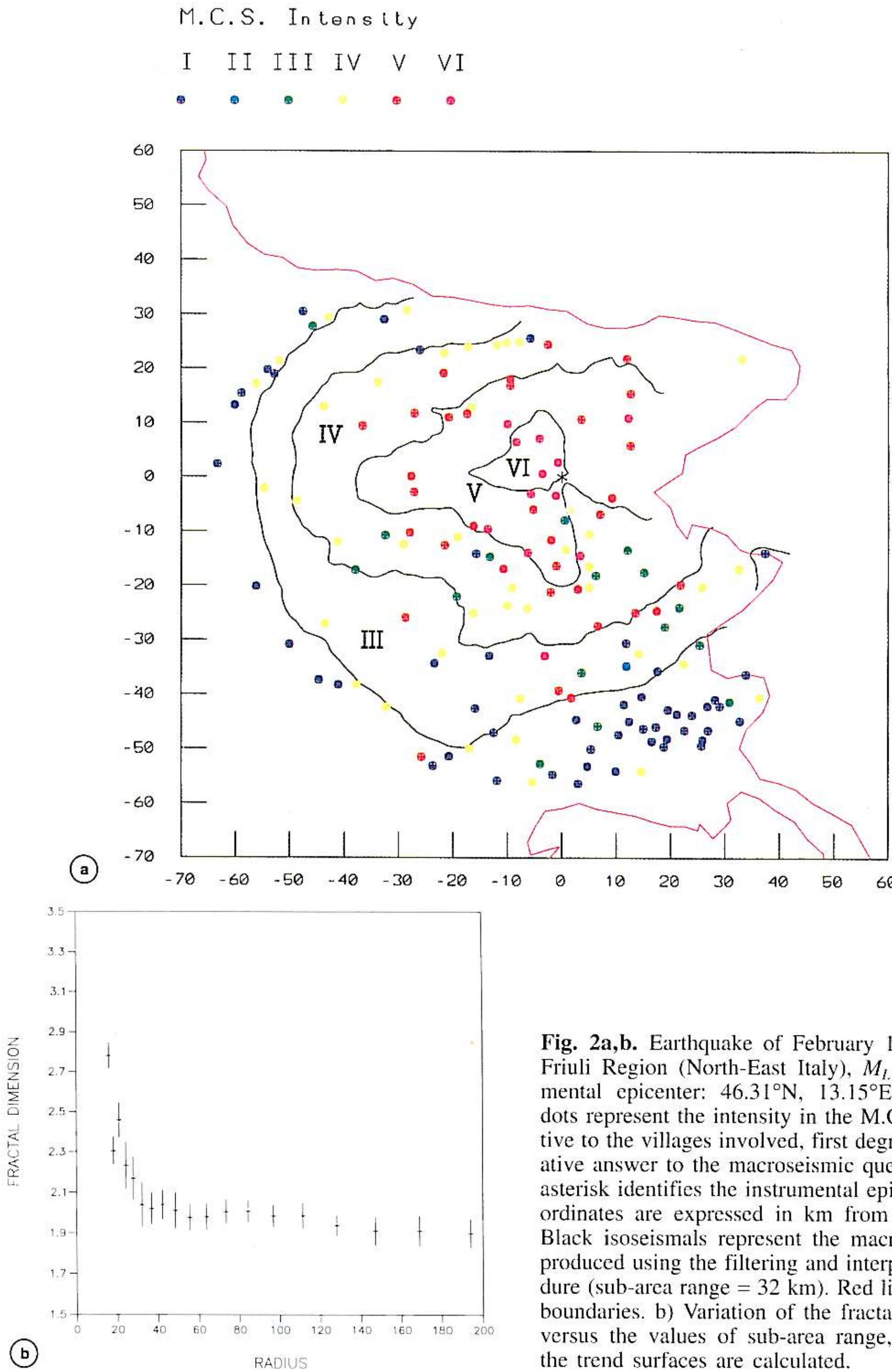
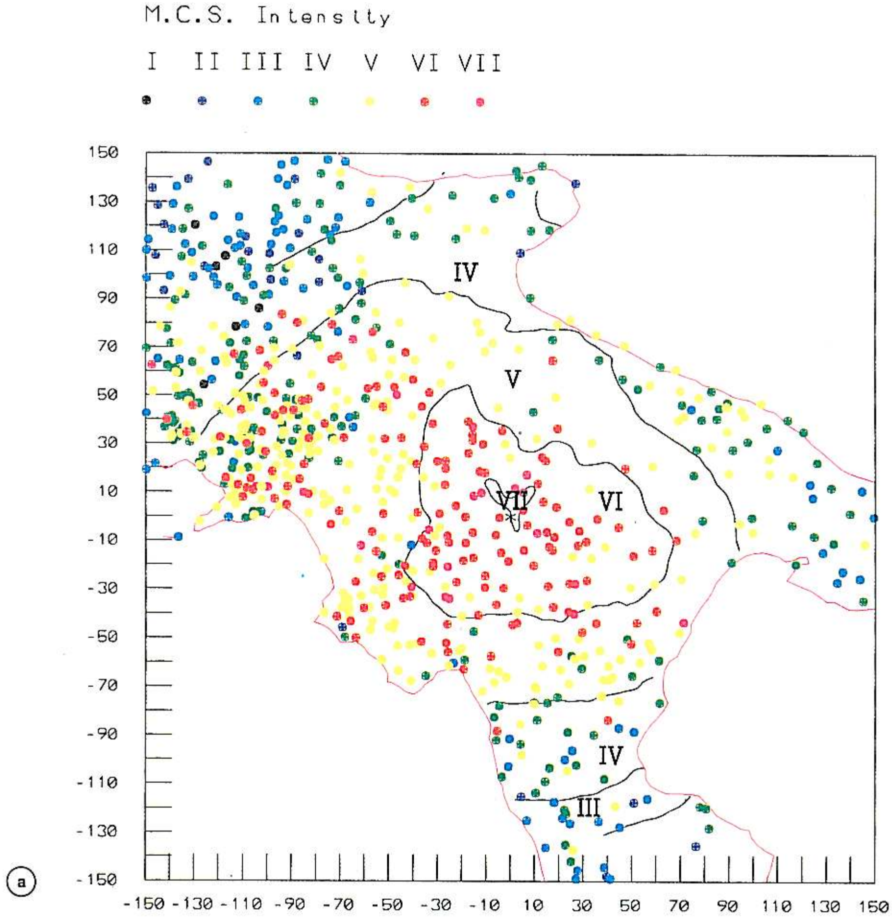


Fig. 2a,b. Earthquake of February 1, 1988, in the Friuli Region (North-East Italy), $M_L = 4.3$, instrumental epicenter: 46.31°N, 13.15°E. a) Coloured dots represent the intensity in the M.C.S. scale relative to the villages involved, first degree means negative answer to the macroseismic questionnaire; the asterisk identifies the instrumental epicenter, the coordinates are expressed in km from the epicenter. Black isoseismals represent the macroseismic field produced using the filtering and interpolation procedure (sub-area range = 32 km). Red lines show state boundaries. b) Variation of the fractal dimension D versus the values of sub-area range, within which the trend surfaces are calculated.



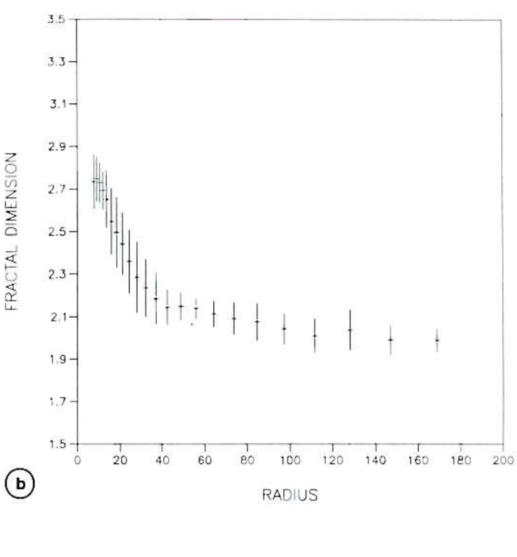
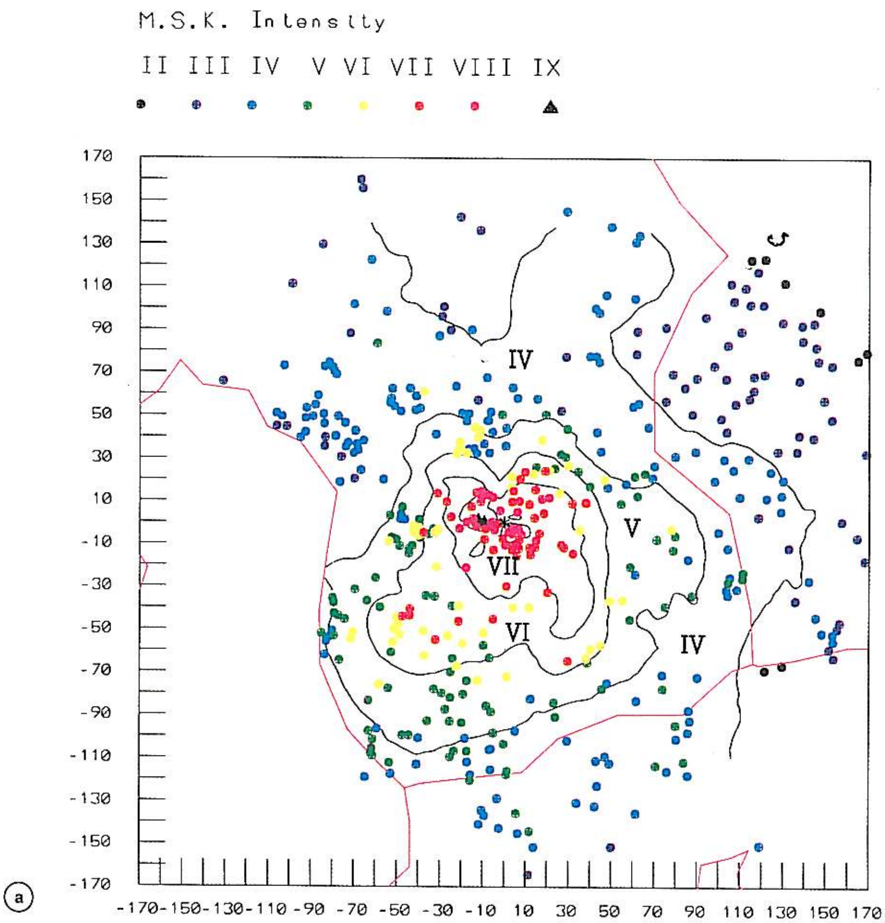


Fig. 3a,b. Southern Apennine earthquake, May 5, 1990, $M_L = 5.2$, instrumental epicenter: 40.64°N, 15.86°E, localized near the city of Potenza. a) Coloured dots represent the intensity in the M.C.S. scale relative to the villages involved, first degree means negative answer to the macroseismic questionnaire; the asterisk identifies the instrumental epicenter, the coordinates are expressed in km from the epicenter. Black isoseismals represent the macroseismic field produced using the filtering and interpolation procedure (sub-area range = 55 km). Coastlines are reproduced in red. b) Variation of the fractal dimension D versus the values of sub-area range, within which the trend surfaces are calculated.



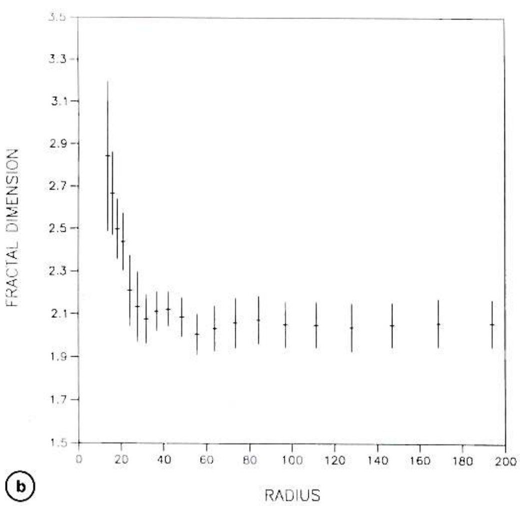
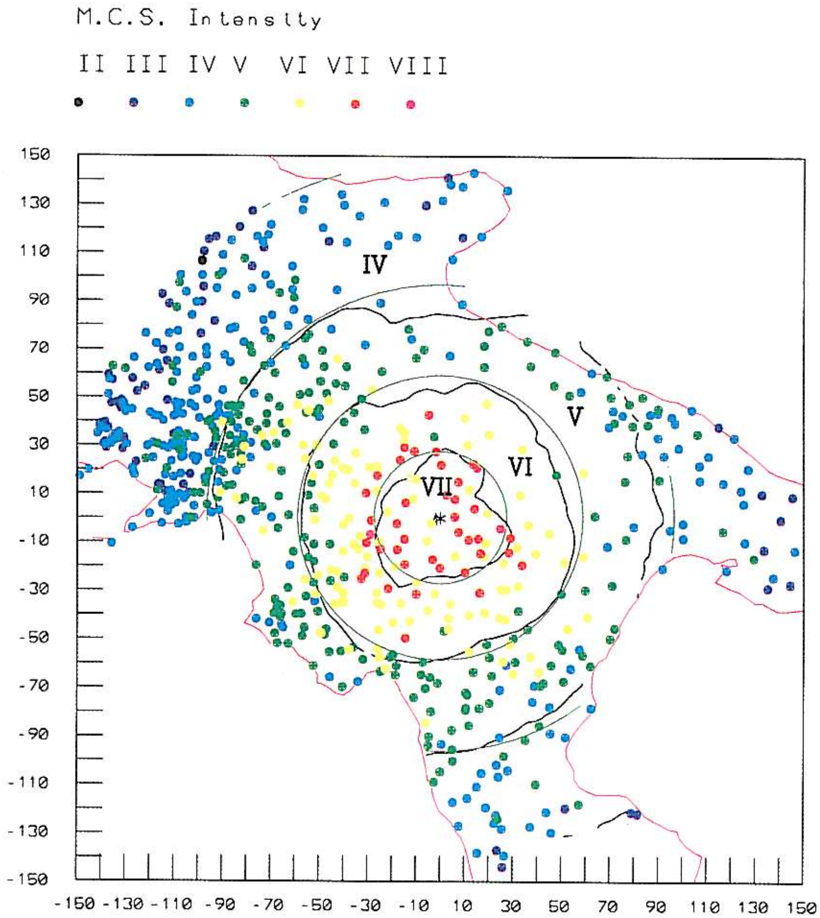
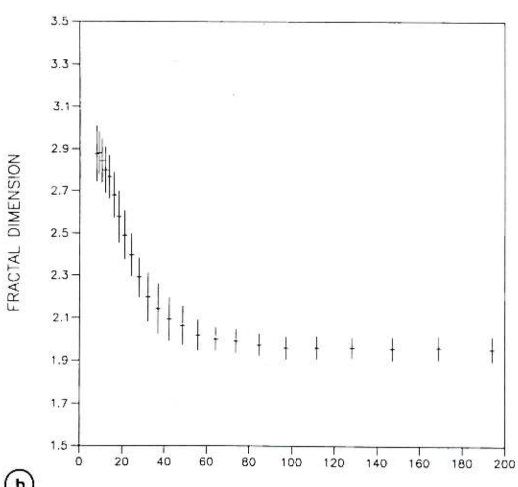


Fig. 4a,b. Earthquake of July 26, 1963, in ex-Yugoslavia (FYROM), $M_b = 6.1$, macroseismic epicenter: 42.00°N, 21.55°E. a) Coloured dots represent the intensity in the M.S.K. (Medvedev, Sponhauer, Karnik) scale relative to the villages involved; the asterisk identifies the macroseismic epicenter, the coordinates are expressed in km from the epicenter. Black isoseismals represent the macroseismic field produced using the filtering and interpolation procedure (sub-area range = 30 km). State boundaries are reproduced in red. b) Variation of the fractal dimension D versus the values of sub-area range, within which the trend surfaces are calculated.



a



b

Fig. 5a,b. Example of the application of the filtering procedure on a synthetic macroseismic field. a) Green contouring: intensity field derived from the Blake model used in the approximation of the Potenza earthquake. Referring to the eq. (4.1): $I_0 = 7$, $s = 6$, $h = 40$. Coloured dots: the intensities obtained adding to the theoretical Blake intensities a Gaussian noise with standard deviation equal to 0.5 macroseismic degrees. Black contouring: macroseismic field obtained with the application of the filtering procedure (sub-area range = 55 km). Note the elimination of nearly all the noise. b) Variation of the fractal dimension D versus the values of sub-area range, within which the trend surfaces are calculated.

epicenter (42.0°N, 21.6°E). The plot of the variation of the fractal dimension versus the sub-area range shows that over the value of 30 km, D remains practically constant, thus rendering unambiguous the choice of the optimum filtering range. The filtered field shows an elongation towards NW-SE for the zone of greatest intensity, whilst the area of V and VI degree shows an elongation to SW direction (fig. 4a).

4. Testing the method

In order to be sure that the final forms of the macroseismic fields treated were not induced by the filter model or by the interpolation, it is necessary to carry out a test on the method itself. To this end, the above described procedure was applied to a theoretical macroseismic field, perturbed by a Gaussian noise.

The attenuation of the theoretical intensities was assumed to be homogenous, and was calculated using Blake's formula (1941):

$$I_i = I_0 - s \log (d_i / h) \tag{4.1}$$

where I_0 is the maximum intensity, d the distance from the hypocenter, h the hypocentral depth and s is a parameter linked to the attenuation, that Blake presumed to vary between 3 and 6.

This test was carried out for each earthquake, I_0 being the maximum recorded intensity; the parameter s and the depth h were assigned in such a way that the synthetic macroseismic field reflected, as far as possible, the real one. For each earthquake, the theoretical intensity was calculated at the coordinates of the inhabited centers that contributed to the construction of the real macroseismic field (as example it is shown the test for the quake near Potenza in fig. 5a). The original coordinates were respected to test the possibility that the isoseismal pattern could be influenced by the peculiar data distribution.

The procedure previously described, was applied to the theoretical fields obtained, utilizing the same parameters. The results show that the isoseismal lines were not distorted by the filtering processes or by the interpolation.

Successively, a random Gaussian noise was added to the theoretical field with a standard deviation of 0.5 macroseismic degrees (coloured dots in fig. 5a). Figures 5a,b show that the application of the filtering procedure eliminated most of the noise. Even though the most internal isoseismal is not perfectly circular, it can be seen that the anomaly of its shape remains isolated and does not continue through to the other isoseismals.

It is therefore possible to conclude that the shapes of the real filtered macroseismic fields are neither induced by the polar transformation nor by the territorial distribution of data.

5. Conclusions

This study shows that the treatment of macroseismic information by means of a statistical method can give quantitative results thus avoiding the subjective character of data interpretation. The difficulty lies in the choice of the specific statistical method to apply, when aiming to produce a representation of damage really incurred, that can constitute a reference point to subsequent investigations.

The measure of the fractal dimension quantifies the effect of smoothing, allowing the recognition (and thus separation) of a local scale component in the macroseismic data. The transformation of the geographical coordinates of the villages into polar coordinates, respects the radial nature of the phenomena and highlights the eventual anisotropy of the attenuation field. This transformation also allows a better analysis of the epicentral area disclosing more detail.

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