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THE UNCERTAINTY AND AMBIGUITY OF ISOSEISMAL MAPS

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SUMMARY

The problem of defining objective isoseismal maps is as yet unresolved. The aim of the work, here presented, is to show how the studies of different authors and eras can produce contrasting, even contradictory, interpretations of the macroseismic data set for the same earthquake.

At this point in time, the principal macroseismic end (i.e. that which furnishes seismology, seismotectonics and studies of seismic risks with descriptions of the effects of earthquakes, as far as possible exempt from interpretation) is in danger of failing.

Throughout this work, we have sought to bring to light how certain anomalies of macroseismic maps principally reside in the diversity of data interpretation, and how it is possible to put in evidence these by applying appropriate statistical analysis to the macroseismic fields.

The Sicilian earthquake of 11 January 1683 ($I_0 = \mathrm{XI}$) was taken as an example, as a sufficient quantity of information was available; a filter procedure was then applied to the macroseismic data. Finally we also show that such procedures are very useful in the treatment of border earthquakes, in an attempt to homogenize macroseismic fields from different countries.

INTRODUCTION

Traditionally seismology has always singled out the tracing of isoseismal maps as being the valid manner in which to characterize the trends of earthquake effects. Also in the production of comparisons with historical events, the isoline technique is still held to be irreplaceable, in as much as it allows the immediate visualization of effects.

Already the problem has been dealt with by Davison,[1] in terms of the scientific correctness of drawing isoseismals, if these were not based on a very high number of observations. For a number of years several authors have sought to make the criteria for isoseismal traces, as homogenous as possible and less susceptible to subjective interpretation.[2–4] The comparison of isoseismals with the source parameters of an earthquake[5] has also opened the way for various authors, in the specification of algorithms with which to trace synthetic isoseismals, based on models of the breaking process.[6–8]

Thus, whilst on one hand, it was possible to apply contouring programs to the area distribution of the effects, on the other hand, it was concluded that the isoseismals should be eliminated, as they were based on excessive interpretational licence.[9]

However, the problem of the graphic representation of the effects of an event is only one important aspect of the movement towards the revamping of the macroseismics, which invests collectively all the methodology, spanning from the research into the interpretation of information, to the assignment of intensity, the inhomogeneous use of the macroseismic scales and to the question of intermediate degrees. In this study, we do not deal with all these aspects, for which other specific studies are necessary.

We believe that the analysis of a strong earthquake, for which contrasting interpretations exist, can be tested by investigating the ambiguity of the definitions of the isoseismal fields. The use of macroseismic maps conditions seismotectonic, statistical or seismic engineering studies, and can therefore lead to diverse, or even contrasting considerations by attributing an unreal weight to the interpretations of macroseismic fields.[10–12] The authors, using the macroseismic data obtained from the Istituto Nazionale di Geofisica, have been able to verify that, if these are dealt with numerically, according to statistical principles—i.e. elaborated with

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suitable filters valid for the spatial distribution of points, whether random (in the plains and in large valleys), or clustered (along the coasts, the lake sides and the small river valleys)—they acquire a homogeneous and comparable regional significance.

The earthquake here used, known as the Val di Noto earthquake, dates from 11 January 1693, and occurred in South East Sicily, provoking destruction and taking around 70 000 victims, completely destroying Siracusano, Ragusano and Catanese, with an epicentral intensity equal to XI Mercalli–Cancani–Sieberg (MCS).[13] The destruction was total for several villages and cities; in Catania alone 70 per cent of the inhabitants perished. There were strong effects on the environment, and a tsunami was primed on the Ionic coast of Sicily.

There exists much literature regarding this earthquake, written both at the same time and at a later date, which over the years, has enabled the studious to analyse and reconstruct this event in detail. The comparison between the conclusions reached by various authors about the macroseismic field relative to this earthquake, shows differences in the tracing of the isoseismals, similar to that present in the three cases examined respectively by Baratta[14] (Figure 1), by Barbano[13] (Figure 2) and from the historical study made by Guidoboni[15] (Figure 3). See also Tables I and II.

Our study of the definition of the macroseismic field stems from analysis and comparisons taken from the bibliographic sources utilized by the above cited authors, keeping in consideration the diverse historical periods in which these authors operated. From this comparison, it emerges that all three studies examined utilize essentially the same contemporary sources; in addition, Guidoboni's historical relation oozes information gathered from numerous public and private libraries and commemorative tombstones. The use of a greater number of sources by Guidoboni produces the effect of increasing the number of localities investigated, circa 20 per cent more in respect to the other essays; only in the peripheral felt zone no substantial differences occur in the assignment of intensity degrees. Then, analysis of principal components (PCA) has been utilized, with the aim of ascertaining the effective dependence of the three variables (Table III).

DATA ANALYSIS

The problem of interpretation of damage testimonies being resolved, the information is then converted into the corresponding macroseismic degree [16,17] and a collection of values irregularly distributed over the territory is thus obtained. The uncertainty increases keeping count of all the errors (whether accidental or attributed to local causes) that go towards the regional macroseismic signal. Let us suppose, however, that all the causes of dispersion of signal adhere to a reduced geographical scale, these being errors of interpretation of damages for an inhabited centre, the diverse structural resistance of the constructions, particular effects of site, etc. The separation of these two elements (regional macroseismic components and local errors) is the most delicate phase of the entire macroseismic analysis. For a critical examination of the past interpretations of the above cited earthquake and another more recent one we have adopted a bidimensional filter (see the Appendix) already experimented within the macroseismic analysis of recent events.[18,19] As can be observed in Figures 1, 2 and 3, the unfiltered isoseismals taken into consideration present at least two substantial differences: the first, most importantly resides in the orientation of the area of maximum intensity, different for all three isoseismals. In fact it can be noted that the isoseismal of XI degree for Guidoboni is orientated NW–SE while Barbano shows it as SW–NE. Whereas, the map designed by Baratta demonstrates an elongation around N–S. In addition to this, unlike the other authors, the isoseismal of XI degree for Barbano remains open on the coast. Another main difference is encountered in the mapping of the SW part of the isoseismal of X degree, which though greatly stressed by Baratta and Barbano, is totally ignored by Guidoboni. These two macroscopic divergences, accompanied by numerous other minor, but very evident, differences, demonstrate a strong interpretative presence on behalf of the contour drawer.

To filter the original macroseismic fields we chose a range at which the slope of the curve of fit changes trend, passing from a rapid fall to a slight incline, revealing a quality of fit constant even over great distances. The polynomial degree chosen, maintaining the same quality of fit, was the lowest possible, to guarantee a sufficient level of smoothness of isolines. Once the coefficients of various trends are calculated (see the

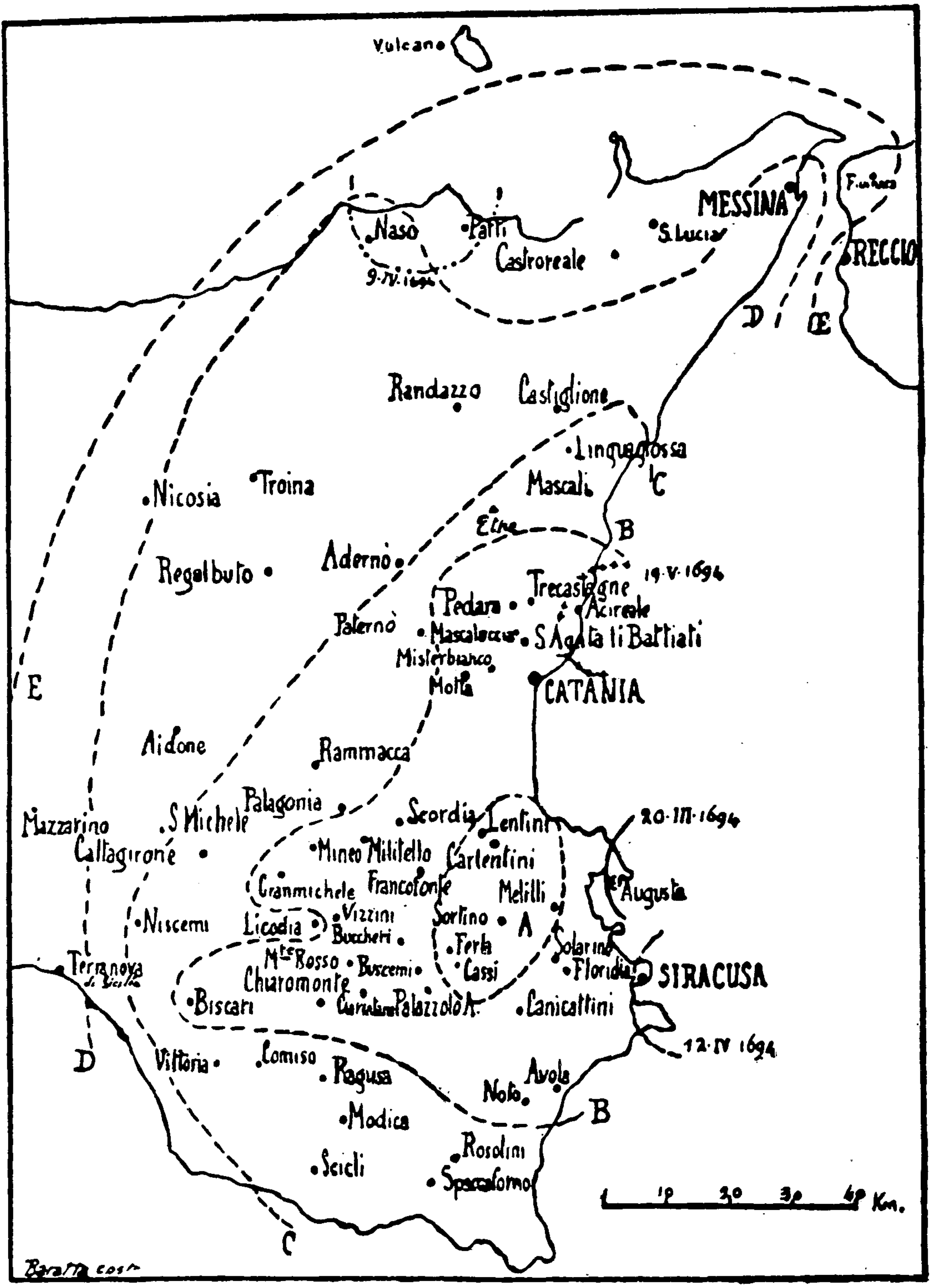

Figure 1. Isoseismal map for the earthquake of 11 January 1693 according to Baratta[14]

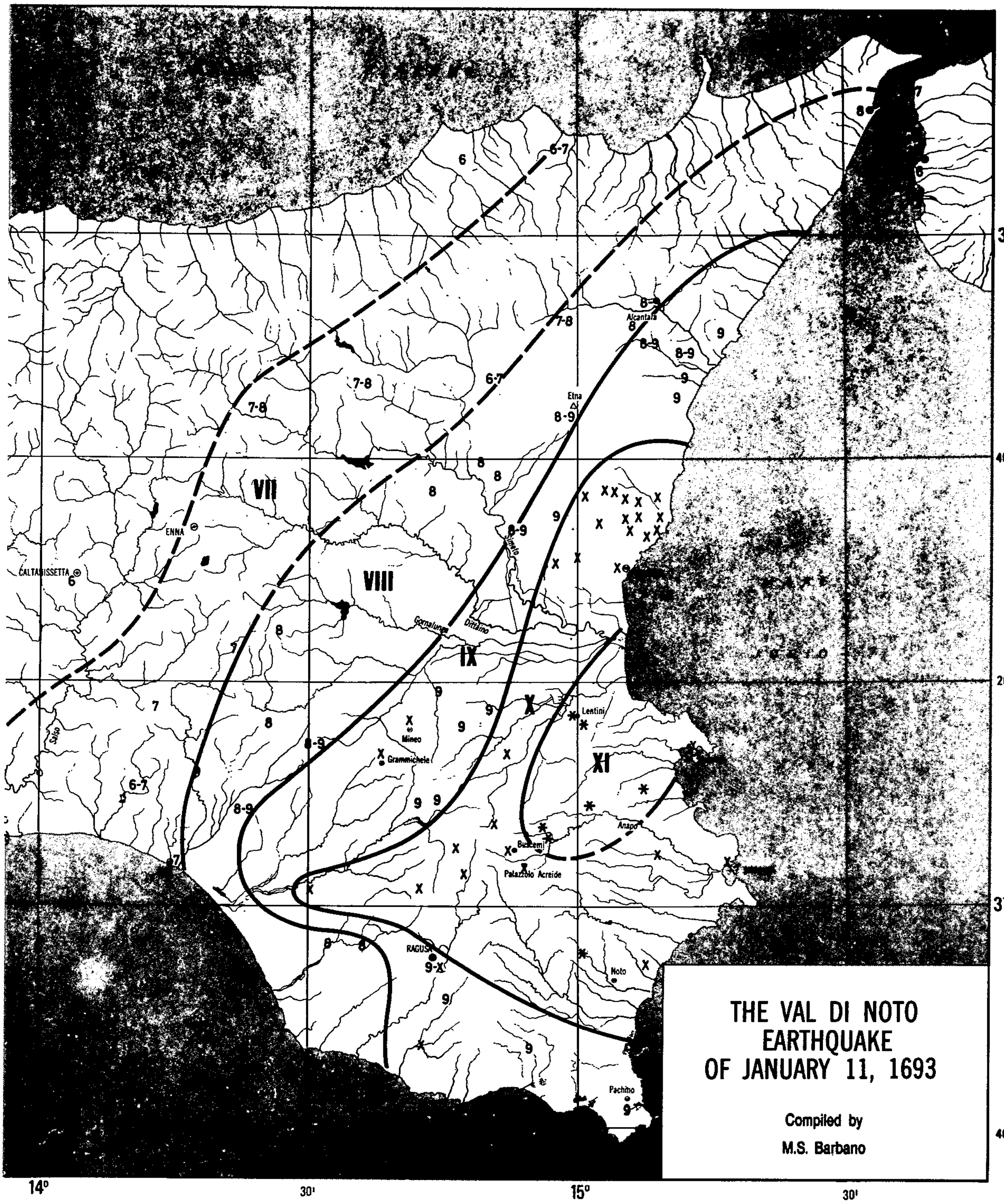

Figure 2. Isoseismal map for the earthquake of 11 January 1693 according to Barbano[13]

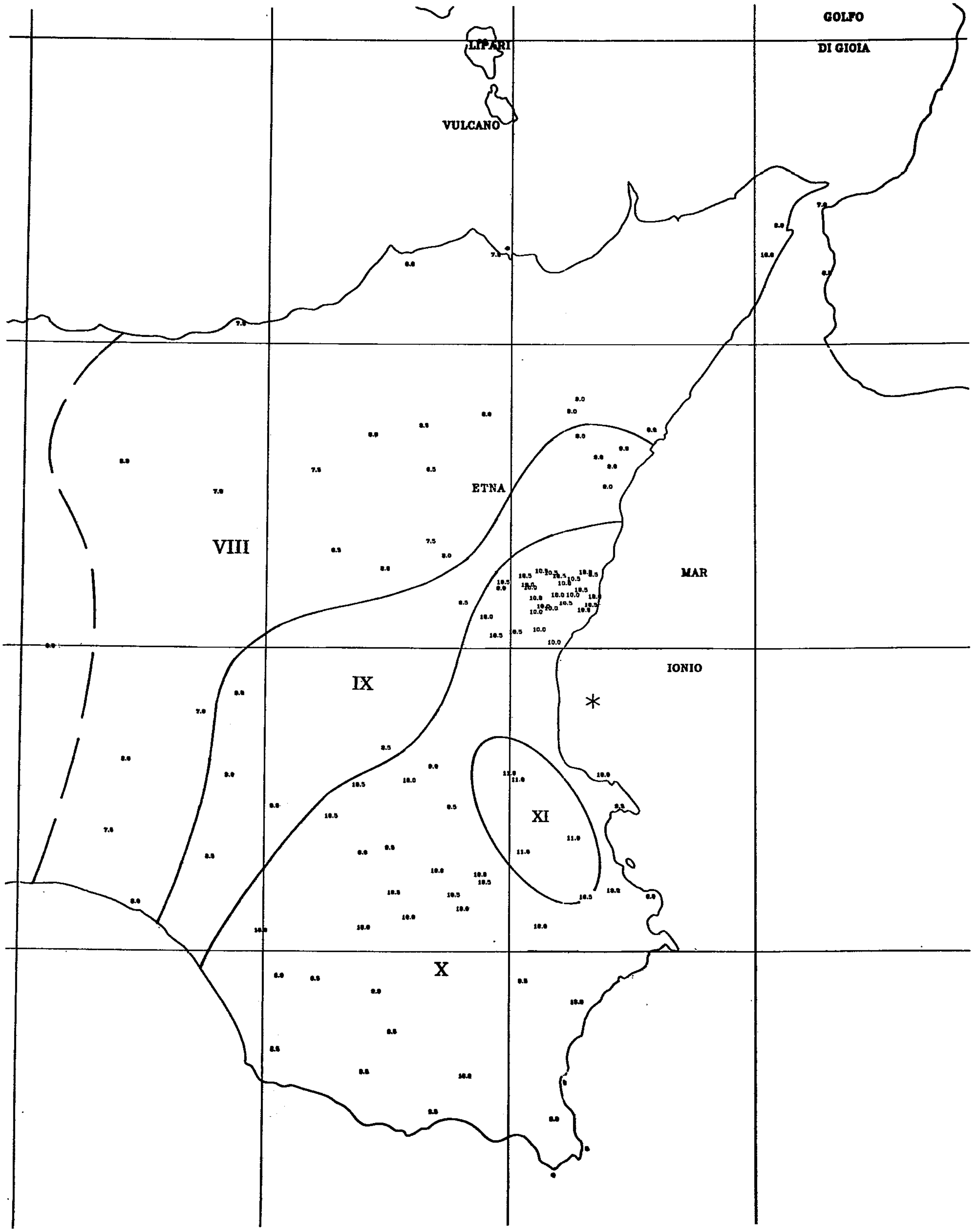

Figure 3. Isoseismal map for the earthquake of 11 January 1693 according to Guidoboni[15]

Appendix), only the central points of the surfaces considered are utilized for the approximation of the original data; consequently the border effects are reduced. After filtering, it can be observed that the three intensity fields do not differ very much from each other. From Figure 4(a)–(c) it can also be noted that the isoseismal of XI degree, for all three of the studied essays, maintains the same direction circa N–S and nearly the same area space. There then appears, in all the maps, a smoother and less decisive lobe in the isoseismal of X degree than that presented in the two original works of which it was part.

We observe also that Baratta's data are less influenced by the filter because they came directly from the isoseismals instead of a quoted plan: a personal author's filter has been already used.

Finally, the data set was treated in a single filter procedure, thus providing three information sets for each locality. The result is clearly a medium of single cases, though significant for the fact that the starting data

Table I. Comparison of MCS intensities attributed to the localities of interest in the 11/1/1693 earthquake by the different authors (1 Guidoboni, 2 Barbano, 3 Baratta)

Locality	Coordinates		1	2	3
Acate	37·025	14·494	10	10	10
Aci Bonaccorsi	37·598	15·107	10	10	10
Aci Castello	37·554	15·146	10	10	10
Aci San Filippo	37·587	15·140	10·5	10	10
Aci Sant'antonio	37·605	15·126	10·5	10	10
Aci Trezza	37·562	15·161	10·5	10	10
Acireale	37·612	15·165	9·5	10	10
Adrano	37·666	14·834	7·5	8	8
Aidone	37·415	14·446	9	8	8
Augusta	37·231	15·220	9·5	10	10
Avola	36·908	15·134	10	10	10
Belpasso	37·589	14·978	9	9	10
Biancavilla	37·643	14·866	8	8	9
Borrello	37·960	14·170	10·5	10	10
Buccheri	37·125	14·851	10	10	10
Buscemi	37·085	14·884	10·5	10	10
Butera	37·187	14·183	7·5	6·5	7
Calatabiano	37·820	15·228	9	8·5	9
Caltagirone	37·230	14·520	9	8·5	9
Carlentini	37·274	15·015	11	11	11
Cassaro	37·105	14·948	10·5	11	11
Castiglione di S.	37·881	15·121	8	8	8
Catania	37·501	15·087	10	10	10
Chiaramonte G.	37·030	14·702	10	10	10
Comiso	36·945	14·605	8·5	8	9
Ferla	37·118	14·939	10	11	11
Floridia	37·081	15·152	10·5	10	10
Francavilla di S.	37·901	15·138	9	8·5	8
Francofonte	37·229	14·880	9·5	10	10
Giarratana	37·047	14·793	10	10	10
Grammichele	37·213	14·636	10·5	10	10
Ispica	36·785	14·909	10	9	9
Lentini	37·284	14·998	11	11	11
Licodia Eubea	37·154	14·700	9	9	9
Linguaglossa	37·841	15·139	9	9	9
Mascali	37·757	15·195	9	9	9
Mascalucia	37·573	15·049	10	10	10
Massa Annunziata	37·591	15·039	10	10	10
Mazzarino	37·304	14·216	8	7	7
Melilli	37·178	15·127	11	11	11

Table I. (*Contd.*)

Locality	Coordinates		1	2	3
Messina	38·186	15·549	8	8	8
Militello	37·273	14·793	10	9	10
Mineo	37·265	14·690	10·5	10	10
Misterbianco	37·518	15·008	10·5	10	10
Modica	36·858	14·760	9·5	9	9
Monterosso Almo	37·088	14·763	10·5	10	10
Motta Sant'anastasia	37·512	14·969	10·5	10	10
Naso	38·121	14·787	8	6	8
Nicosia	37·747	14·398	7	7·5	7
Niscemi	37·146	14·389	8·5	8·5	9
Noto	36·890	15·070	9·5	11	10
Palagonia	37·326	14·745	8·5	9	9
Palazzolo Acreide	37·061	14·903	10	10	10
Paterno'	37·565	14·901	9	8·5	9
Patti	38·138	14·965	7·5	6·5	7
Pedara	37·617	15·061	10·5	10	10
Ragusa	36·925	14·728	9	9·5	9
Randazzo	37·876	14·947	8	7·5	8
Reggio Calabria	38·108	15·646	6·5	6	6
San Giovanni la Punta	37·578	15·094	10	10	10
S. Michele di Ganzaria	37·280	14·427	9	8	8
Sant'agata li Battiati	37·557	15·082	10	10	10
Scicli	36·792	14·705	9·5	10	9
Scordia	37·295	14·842	9	9	10
Siracusa	37·082	15·285	9	10	10
Sortino	37·156	15·026	11	11	11
Trecastagni	37·614	15·081	10·5	10	10
Tremestieri Etneo	38·137	15·525	10	10	10
Troina	37·783	14·598	7·5	7·5	8
Valverde	37·578	15·124	10	10	10
Vittoria	36·950	14·531	8	8	9
Vizzini	37·162	14·755	9·5	9	10

Note: It becomes evident that these values coincide for more than 50 per cent of the localities considered in all three studies. If the town of Naso is excluded, for which there is a difference of two degrees more between the studies of Baratta and those of the other two, it is possible to note that, in less than 10 per cent of cases the difference in the attribution of intensity reaches the maximum of one degree, generally occurring in localities not near the epicentre. It is also interesting to note that, concerning the localities in the epicentral area, all three studies report equal intensity values, although there are several cases which reveal differences, though these are of the order of half a degree.

conform to them (Figure 4(d)). Where the density of the original data is too low, a calculation of a partial surface is not carried out, leaving empty that portion of space. In this way the tracing of the isoseismal is substituted by the definition of a filtered surface, being significant only in the zones sufficiently dense with data, and with values relative to a sole regional component in the macroseismic field. Thus we have obtained that which seems to be the most realistic image of this earthquake with a sure lobe in the sector SW of the isoseismal of X degree and orientated around N–S of the area of maximum intensity.

The filtering of another event is also carried out; a Greek earthquake (15/11/59, $M = 6{\cdot}6$) coming from the Balkan Catalogue,[2] for which two maps are available: one by Delibasis (Figure 5(b)) and a second one by Shebalin (Figure 5(a)), conceptually different one from the other.

Table II. Correlation matrix of the intensity relating to the localities common to all three authors

Correlation matrix			
**	Guidoboni	Barbano	Baratta
Guidoboni	1·0000	—	—
Barbano	0·8964	1·0000	—
Baratta	0·8889	0·9307	1·0000

Note: the correlation values are very high for all the variable couples.

Table III. Values of the variance (per cent) for each independent factor obtained through analysis of principal components (PCA)

Principal components loadings			
Factor	I	II	III
Guidoboni	– 0·9588	– 0·2835	– 0·0186
Barbano	– 0·9738	0·1187	0·1938
Baratta	– 0·9712	0·1608	– 0·1759
Eigenvalues	2·8108	0·1203	0·0689
Variance (%)	0·9369	0·0401	0·0230

Note: in this table the percentage of variance of each independent factor and the representativity of the original variables (the three different macroseismic studies) are shown. The first factor is sufficient to explain almost 94 per cent of the total variance; in fact, we find all the original variables well represented (the values of factor loadings are all greater than 0·95). We can therefore assert that the stages quoted by the three studies do not show significant statistical differences.

Also in this case the drawing style overbearingly emerges, forcing users to make a choice. In Figure 6 the map obtained from Greek filtered intensities only is shown. We can observe how many involutions present in the Delibasis map are deleted by filtering, without falling in the extreme synthesis of Shebalin isoseismals.

REMARKS ON NATIONAL BORDERS EARTHQUAKES

As Shebalin[2] already remarked, the compilation of isoseismal maps in border territories reveals two main defects; first of all, non-conformity conventions and style in drawing maps, and in the use of macroseismic scales, together with differences in data collection. The second problem resides in the poor use of neighbouring countries data, probably due to insufficient cooperation between nations. An attempt to limit those defects was carried out in Reference 18 studying some French–Italian border earthquakes. In Figure 7 the December 26, 1989 ($M_d = 4{\cdot}1$) macroseismic field is shown. We underline that this event implies most of the problematic aspects of macroseismic studies, like the epicentre offshore, the national border and the intensity assessment made by two different macroseismic scales, MSK and MCS. As regards the December 26 earthquake hand-made isoseismals do not exist, because this is the first official attempt of an automatic intensity assessment and map drawing, with data homogenization between France and Italy.

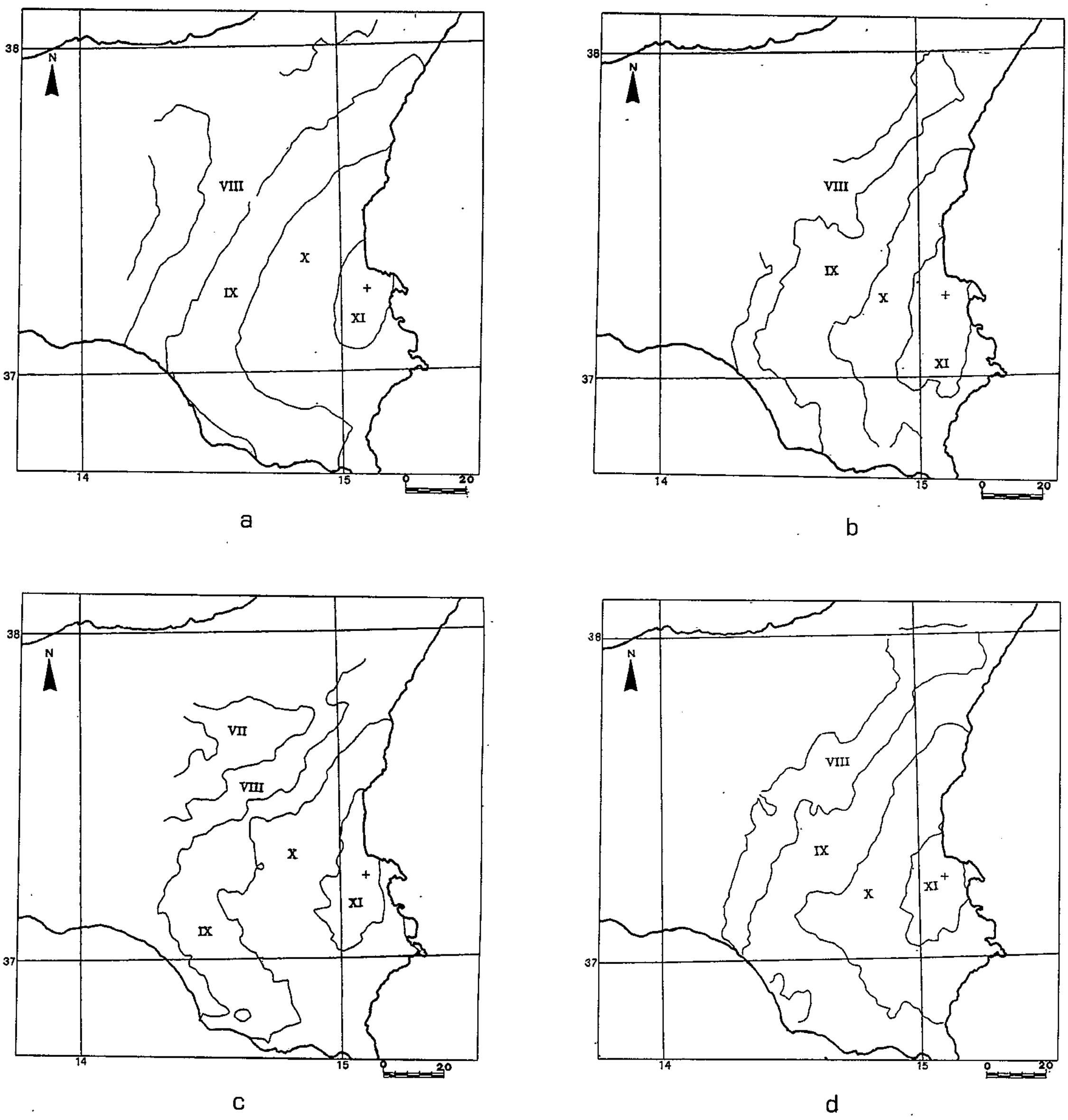

Figure 4. Filtered macroseismic field, obtained from: (a) the plan quoted by Baratta;[14] (b) the plan quoted by Barbano;[13] (c) the plan quoted by Guidoboni;[15] (d) the whole data set with three intensity values for each locality

It is anyway probable that the different origin of data would contribute to increase the ‘noise’ of the macroseismic signal. It is evident, for this kind of earthquake that, the big true problem is the unification of intensity assessment techniques, and only then, having availability of homogeneous data, we could correctly use an algorithm to draw isoseismals.

CONCLUSIONS

From the tests made, several relevant considerations emerge, regarding the true necessity of utilizing statistical processes for the modulation of macroseismic fields and concrete possibilities are demonstrated for the application of these procedures on real cases.

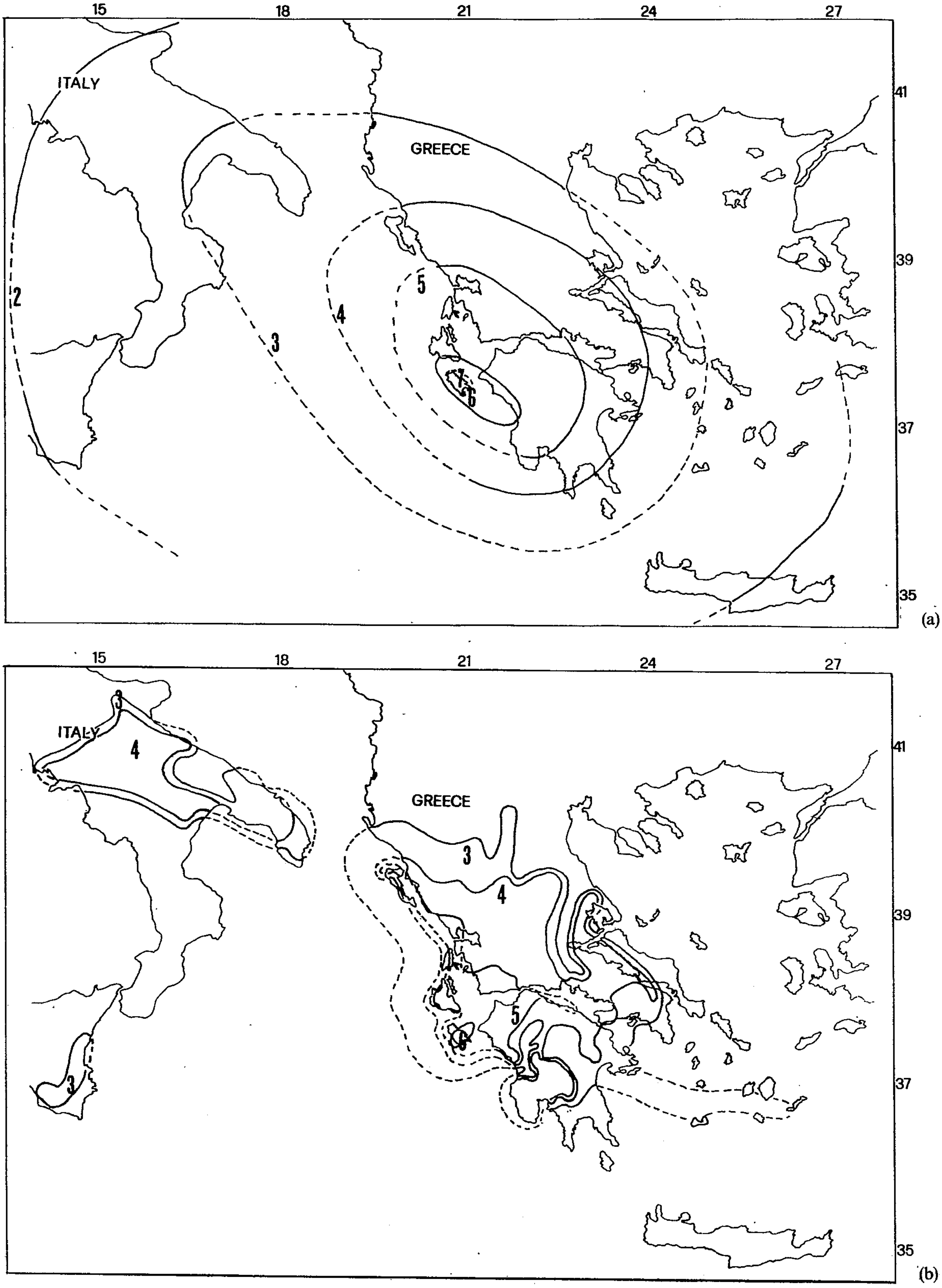

Figure 5. Isoseismal maps for November 15, 1959 earthquake: (a) by Shebalin; (b) by Delibasis. Redrawn from Shebalin[2]

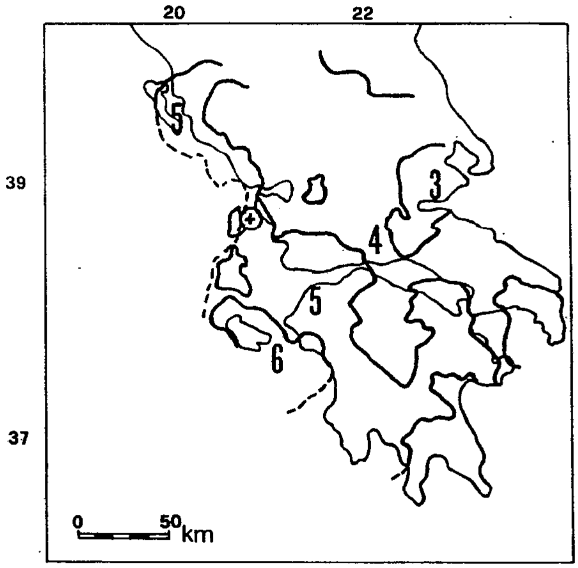

Figure 6. Filtered macroseismic field, obtained from the whole data set of the November 15, 1959 Greek event

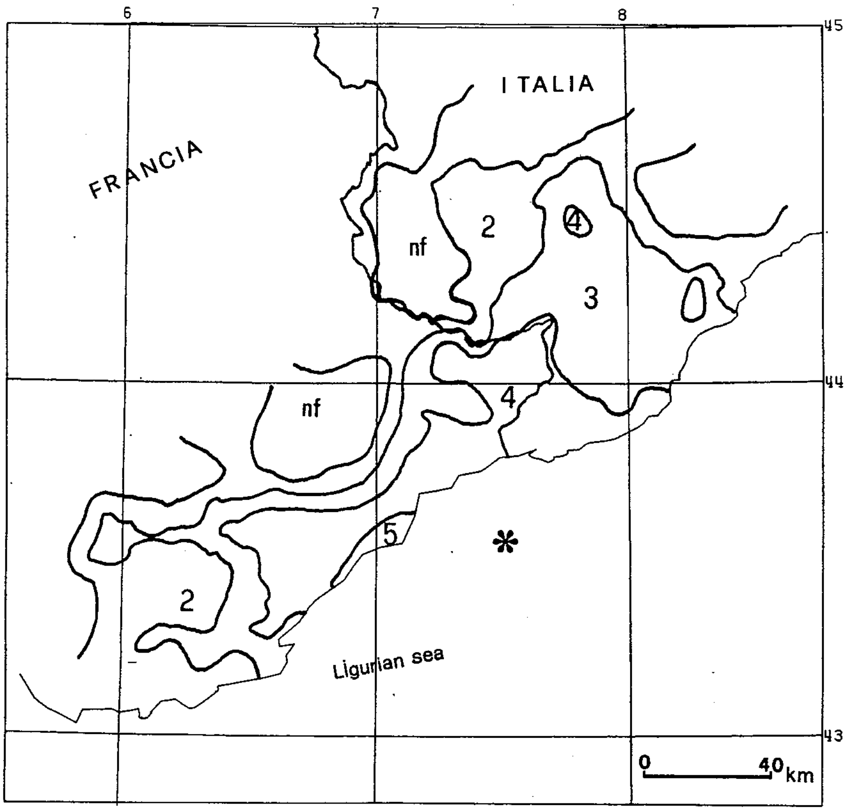

Figure 7. Filtered macroseismic field of the December 26, 1989 Ligurian Sea event. The analytic location is shown by the asterisk. Redrawn from Tertulliani *et al.*[18]

The comparison of the three macroseismic fields proposed has in fact brought to light the subjectivity of interpretation of each single author influencing in a determinant manner the choice of tracing criterion of the isoseismal and the final form of the isoseismal itself.[9,12] In reality, in the case of the Noto earthquake, significant differences are not encountered between the original data sets, that is between the intensity values attributed to various localities by the three authors.

The tests of Figure 4 clearly show that the three macroseismic fields obtained using filters on original data are essentially similar. It is interesting to note how the isoseismal of the maximum degree (XI) keeps the same orientation of N–S and roughly the same dimensions, in all three cases, contrary to that found in the three fields proposed by the considered works. From Figures 4(a), 4(b) and 4(c) it can also be observed that the constant presence of an accentuated lobe in the isoseismal of X degree is well evidenced by two of the works examined,[1,13,14] but completely ignored by Guidoboni.[15] In other cases a different philosophy of tracing isoseismals produces maps absolutely inconsistent between them, as for the Greek earthquake just presented.

A problem apart is about events occurring near national borders, for which the study of precise solutions and conventions is required. Our technique allows us to unify the interpretation of intensity maps across national borders, whenever such previous agreement had been made.

All these discrepancies are particularly significant if one considers that seismotectonic or seismic risk scope is often made from the isoseismal map; in fact the choice of one or the other of the macroseismic fields examined can easily lead to antithetical considerations, a risk which can be eliminated using the same macroseismic fields after filtering. If we consider the regional component of the macroseismic signal as the representative part of earthquake effects (as traditional macroseismics demands), we can certainly accept the use of a technique like that described.

The application of a filtering procedure on intensity data thus allowed the reduction, if not the elimination, of the anomalies derived from a subjective approach, or owing to the presence of an insufficient data-base, as often occurs in the case of historic earthquakes. This procedure appears particularly useful in the cases of doubtful events, for it allows a more objective re-examination of them, with the aim of eliminating the sources of uncertainty, as in the case of the earthquake in hand. Also, taking into consideration the macroseismic fields that are obtained from the filtering of data and so are unaffected by subjectivity, it is possible to operate a correlation with the mechanisms of the source to look for confirmations of the propagation models, and formulate forecasts on the oscillation of the ground.[20,21] In conclusion, it must be pointed out that the isoseismals can have significance only where they represent a general picture of attenuating seismic phenomena and they do not pretend to be attempts at inappropriate seismic zoning.

APPENDIX

A variable that is a function of geographical coordinates is assumed characterized by a principal (regional component) and a local component (noisy component). The noisy component is random, and acts in a local spatial context, well distinguished from the principal component. The representation of these two principal components of the macroseismic field is

$$Z_i = f(X_i, Y_i) + \varepsilon_i \tag{1}$$

where X_i and Y_i are the geographical coordinates in kilometres for the original point i, Z_i is the intensity value and ε_i is the local contribution. The regional component $f(X_i, Y_i)$ is approximated by a polynomial series of various degrees, using

$$f(x,y) = \sum_{r+s \leqslant p} a_{rs} x^r y^s \tag{2}$$

where p is the polynomial order.

The technique adopted is based on a repeated use of many trend surfaces of low degree, on portions of the area investigated. More particularly, starting from a regular grid, a trend surface of a given degree is calculated for each grid junction, comprising the original values within a determined spatial range. That range is large enough to include sufficient data and to allow overlap with adjacent grid points: in this way all the original data participate in more trend surfaces (Figure 8).

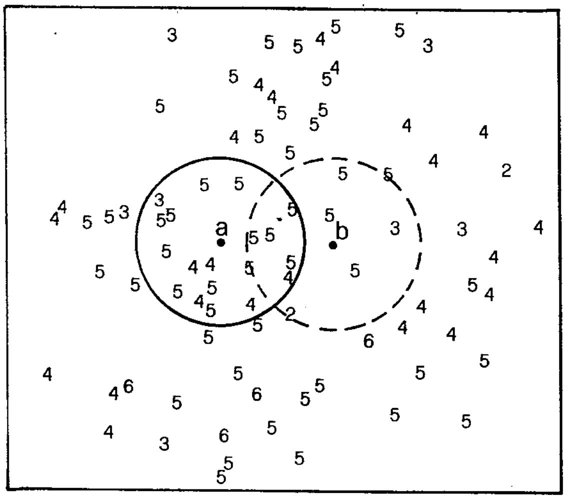

Figure 8. Calculating the coefficients of the trend surface of a chosen degree from data inside the solid circle only, we obtain the filtered value for the point a, so reducing the edge effects in the trend analysis. The same procedure is performed for the point b, using data in the dashed circle only. The superposition of the circles provides a grade of continuity to the final result

Once the coefficients of one trend surface are calculated, only the central points of the surface considered are utilized for the approximation of the original data; consequently the border effects, that can influence the trend surfaces, are reduced. Another characteristic of the filter is its great flexibility: in fact varying the degree of the trend surfaces and the spatial range of influence, the effect of the filter itself can be proportioned. Ranges of little value and elevated degrees of surfaces permit very good approximations in the original procedure, obtaining a little filtered definite result, whereas extending the ranges, so that each point of the grid comprises all the original data, and at the same time adopting the degree 0 (that simply gives the average value of the original points), a steady surface equal to the average for all the macroseismic intensities is obtained: the filter effect is thus at its maximum.

As criteria for the choice of these parameters a relative goodness of fit was defined:

$$F_r = 1 - \frac{\sum_{i=1}^{n}(\hat{Z}_i - Z_i)^2}{\sum_{i=1}^{n}(\bar{Z} - Z_i)^2} \tag{3}$$

where $\hat{Z}_i$ is the calculated value, Z_i the original one, while $\bar{Z}$ is the average for all the data. In this preliminary stage the analyses are not centred on the junctions of the grid, but only on the original data. The denominator expresses the maximum action of the filter, equivalent to a degree of 0 and a range large enough to permit each centre to include all the original values.

Mapping the values of F_r for each polynomial degree and for various spatial ranges, there can be seen a path similar to those of Figure 9: after a brusque fall of fit, the original data demonstrate a greater resistance to the filter. We hold that this resistance is due to the presence of the regional component (regional macroseismic signal). The degree of the surface and the range of influence are chosen so as to safeguard that regional component and to eliminate the local one that operates over a reduced distance. These parameters are also chosen as a function of the density of original data: the minimum number of points, necessary to calculate the surface for a given order, is equivalent to the number of coefficients present in the equation

$$\mathrm{nc} = \frac{(p+1)(p+2)}{2} \tag{4}$$

where p is the degree of the surface and nc is the number of coefficients. Obviously when this limit is reached (i.e. the number of data points is equal to the polynomial coefficients) the corresponding surface will fit

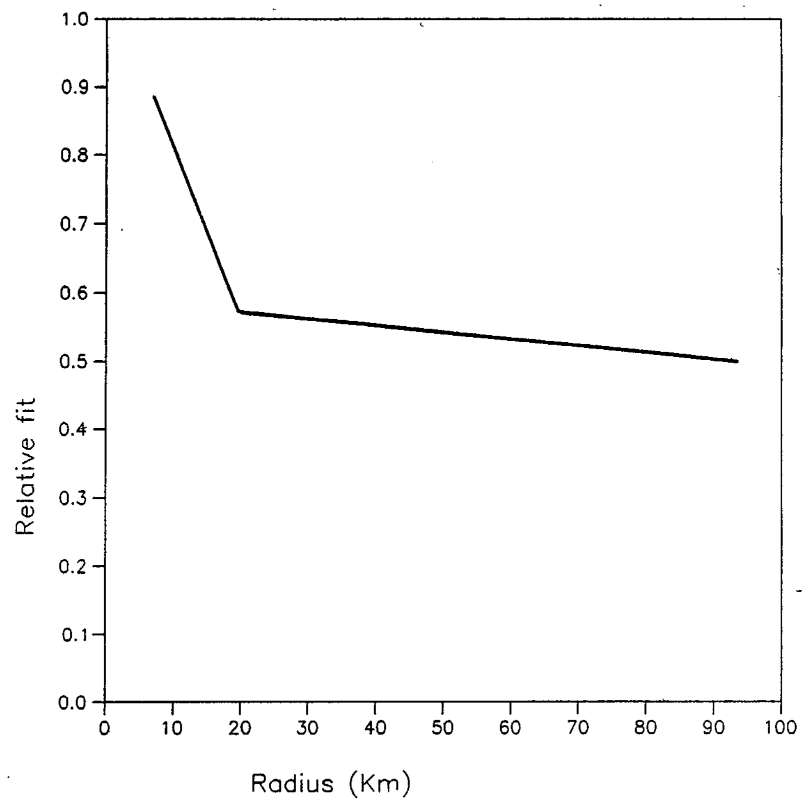

Figure 9. Values of F in relation to the various polynomial degrees. In the abscissa the range in kilometres is reported, while in the ordinate the values of the relative fit are reported

exactly the data points, with the result that the filter effect is a minimum (i.e. no elimination of the random component). The examination of the relative fit (3) reveals when this problem arises.

The whole procedure can be summarized as follows.

1. Construction of the relative fit diagram: the computation of the trend surfaces is performed on the locations of original data points only using, in turn, different values of radius and polynomial degree. The application, for every radius–degree couple, of equation (3) gives the diagram.

2. Choice of the *correct* values of the filter parameters: the aim is to eliminate the local component. The radius value is fixed where the slope of the curve changes, while the degree is taken as low as possible (to allow calculation also where the density of data points is reduced and to avoid round-off errors that can arise when high order surfaces are involved).

3. Application of the filter, with the appropriate parameters. The analysis is centred at a regular node grid: only the central point value of each surface is retained.

4. Automatic drawing of macroseismic fields using the regular node grid values.

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