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Do seismologists agree upon epicentre determination from macroseismic data? A survey of ESC Working Group «Macroseismology»

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Abstract
In contrast to the case of instrumental data, the procedures for epicentral parameter determination (coordinates and I_0) from macroseismic data are not very well established. Although there are some «rules», upon which most seismologists agree (centre of the isoseismal of largest degree, and so on), the practical application of such rules displays many problems. Therefore, it is commonly seismologists' practice to find their own procedures and solutions; this is particularly evident in the more complicated cases, such as offshore epicentres or, as in many cases of historical earthquakes, poor sets of data. One of the major consequences is that parametric catalogues are not homogeneous with respect to macroseismic parameters; moreover, merging catalogues compiled according to different criteria can introduce high noise in any catalogue built in such a way. In order to survey the current practice of epicentre determination from macroseismic data in Europe, a set of cases was distributed to the participants of the first meeting of the ESC WG «Macroseismology». A comparison of the 15 sets of results provided by 16 authors, who gave their own solutions and the explanations of the adopted procedures is given, showing that in some cases the ideas and results are rather distant.

Key words *macroseismic data – epicentre – intensity*

1. Introduction

Macroseismic data, and especially those derived from historical records, play a major role in the assessment of seismicity and seismic hazard; however, procedures according to which they are elaborated remain rather disparate.

The first step of elaboration, intensity assessment, recently gained a new, improved tool with the publication of the «European Macroseismic Scale» (Grünthal, 1993); the benefits, though, are still under evaluation.

The next step, earthquake parameter determination, is of great importance, as quality and coherency of parameters which populate earthquake catalogues strongly depend on it. It is generally agreed that the assessment of macro-

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seismic parameters is currently being performed according to procedures which are generally neither equivalent, nor clear. Moreover, in many cases they are unknown; under such circumstances data sets and catalogues compiled according to different procedures are not comparable. On the contrary, procedures by which instrumental data are processed are known and, to a certain extent, standard: instrumental data are therefore comparable and their reliability can be assessed, at least to some degree.

To deal with this problem, in 1992 the European Seismological Commission (ESC) established a Working Group on «Macroseismology», in the frame of Subcommission F «Engineering Seismology», with the following main goals:

– development of criteria and recommendations for the organisation of a European database of intensity data;

– development of rigorous procedures for processing macroseismic data.

The first goal was addressed by preliminary considerations (Stucchi, 1994) and is currently under discussion in the frame of the EC project «A basic European earthquake catalogue and a database for the assessment of long-term seismicity and seismic hazard».

With respect to the second point, the idea described in the WG programme was that «the WG will review the existing procedures, evidence the main problems and develop new rigorous procedures». This paper deals with the first step of the programme, that is reviewing current procedures; specifically we address two issues: the determination of macroseismic epicentres and epicentral intensities.

2. Historical perspective

2.1. *Macroseismic epicentres*

Early attempts to use macroseismic data to locate earthquake epicentres generally proceeded to do so either by tracing back estimates of the direction of shock (from cracks in walls, toppled items, or human observations), or by attempting to discriminate small differences in time between different observations. A well-known example is Mallet's celebrated success in using such methods in his study of the Neapolitan earthquake of 1857 (Mallet, 1862). Less well-known is the complete failure of these methods in an earlier case that came to Mallet's attention – the Caernarvon (N. Wales) earthquake of 9 November 1852. This was located by Mallet (1854) in the Canary Islands, an error of about 2800 km. The use of macroseismic time observations is associated with the work of Seebach (1873) who developed the concept of coseismal lines, which indicate places at which the earthquake waves arrive at the same time.

In Milne's (1893) textbook on earthquakes, only these types of approach are described – not the use of isoseismals. (As Montessus de Ballore, 1916, remarked «It is a noteworthy fact that John Milne almost never made any use of intensity scales, nor did he delineate isoseismal curves in his many seismological papers ...»). Milne's colleague Knott gave more attention to macroseismic methods: «The highest isoseism determines the epicentre; but the exact localisation is usually complicated by the fact that the shock has radiated from two or more centres or from a long drawn out source of disturbance ... In the case of the many earthquakes which originate under the ocean, the epicentre can be only approximately localised» (Knott, 1908).

Davison (1921a) in his «Manual of Seismology» gives three methods for determination of epicentre, of which the first is the method based on time and the second the method based on direction. The third is the method based on intensity – «the centre of the innermost curve being either close to, or within, the epicentral area». It will be noted that Davison distinguishes an «epicentral tract», equivalent more or less to the rupturing area. Any point description of epicentre is thus «the mean position of the epicentre». Similar is the remark in Rothé's discussion of macroseismic methods: «la notion d'épicentre ponctuel est une fiction mathématique et c'est plutôt une région épicentrale qùil y a lieu d'envisager» (Rothé 1925).

Sieberg (1923) considered that: «*Allgemein gültige Regeln lassen sich für die makroseis-*

mische Epizentralbestimmung nicht aufstellen». (No generally valid rule for macroseismic epicentre determination can be established). However he discusses some rules, mainly with the help of the shape of the pleistoseismal line (innermost isoseismal), related to the local geological conditions and characteristics of the fault which caused the earthquake.

With the increasing improvement of instrumental methods during the 20th century, macroseismic methods fell into a corresponding decline. One may consider in this light the dismissal by Richter (1958): «The practice ... of drawing isoseismals and then locating an 'epicentre' at the centre of figure should be discontinued». This may go some way to explain the lack of attention in references such as the Manual of Seismological Observatory Practice (Willmore, 1979).

This attitude had to change in the 1970s as it became apparent that it was necessary to revisit historical earthquakes for the purpose of seismic hazard assessment, and this meant returning to macroseismic methods. Even in the early 20th century it had been realised that the use of macroseismic observations of direction and time were of questionable utility; consequently modern macroseismic location methods are based exclusively on intensity. As an example, some attempt to describe, although very briefly, the way in which earthquake parameters are assessed can be found in the introductory part of the UNDP/UNESCO Balkan Catalogue (Shebalin *et al.*, 1974). The emphasis is on the definition of the epicentre as «the central point, and the error as the radius of the first isoseismal» for the earthquakes with an isoseismal map; the description is followed by the discussion what to do in case of a remarkably deformed first isoseismal, for intermediate events or an epicentre in the sea.

Other studies have also given some indication of their methods in greater or lesser detail. In dealing with historical earthquakes in Persia, Ambraseys and Melville (1982) write «The macroseismic 'epicentre' of an earthquake was therefore defined by the geographical co-ordinates of the centre of the ellipse [the highest isoseismal], and the size of the epicentral region by the radius of the equivalent circle».

They also describe loosely the methods employed in the absence of isoseismals. This is very similar to the rule given by Davison (1921b); less similar is the approach of Burton *et al.* (1984), who obtained macroseismic epicentres by «a consideration of the spatial distribution of the highest observed intensities, the highest intensity value isoseismal which could be plotted and a consideration of the probable location of foreshocks and aftershocks in relation to the main shock». This description introduces new ideas, firstly that the drawing of isoseismals does not preclude consideration of the data points also, and secondly that other phenomena such as reports of accessory shocks may be considered. (The point being that an aftershock observed over a very small area may be more easily located than a main shock observed over a very large area.)

General discussions of such methods are less common, though recently Console *et al.* (1990), Peruzza (1993), Gasperini and Ferrari (1995) discussed some formal methods for assessing macroseismic epicentre. Musson (1989) presented problems connected with parameters assessed from poor datasets: the same problems were discussed by Castelli and Monachesi (1996), Glavcheva (1994), Musson (1996), Shumila (1994) and Vogt (1996) at the Symposium on «Quantification of non-instrumental earthquake data» at the ESC XXIV Assembly, Athens, 1994 September 19-24, where this paper was also presented.

2.2. *Epicentral intensity*

Significant attention has been given in the literature to the applications of macroseismics in terms of the assessment of attenuation and depth (the well-known works of Kövesligethy, 1907, Blake, 1941, etc.).

In these cases, I_0 is taken to be the mathematically determined extrapolated intensity exactly at the epicentre. In many other cases, I_0 is not specifically defined, presumably because the concept is deemed to be self-evident – the epicentral intensity is the intensity at the epicentre, and in practice this devolves to the highest assigned intensity.

This is sometimes explicitly stated. In the two examples cited above, Ambraseys and Melville (1982) define I_0 as «the highest intensity», while Burton *et al.* (1984) give a more elaborate definition: «the intensity expected at the macroseismic epicentre in the light of the observed intensities without formal extrapolation from isoseismal intensity data using an intensity attenuation law». The catalogue of Shebalin *et al.* (1974) employs both «highest observed» and «extrapolated» I_0 values. Many authors (including the last two cited) distinguish between I_0 and I_{max} for offshore epicentres where I_{max} is the highest intensity observed on land, and I_0 cannot be observed (but may be extrapolated).

It is worth stressing that the results provided by the GSHAP survey on European parametric earthquake catalogues (Stucchi and Bonnin, 1995) point out that in 72% of cases only (18 catalogue considered) $I_0 = I_{max}$; moreover, this percentage goes down below 50% for 5 catalogues and is 0 for two of them.

3. Basic assumptions and methods

When asked about real practice, seismologists do not quote literature in their answers: the most common working definition for epicentral parameters is «maximum intensity» for I_0 and «the centre of highest degree (closed) isoseismal» or «the centre of mass of the highest intensity data points» for the coordinates.

The idea of putting the macroseismic epicentre in the centre of the highest isoseismal line is often taken as an unwritten rule. But, seismologists do not always agree drawing isoseismals (Berardi *et al.*, 1990; Cecić, 1992). Next, what happens when isoseismal lines cannot be drawn, for instance when only a few data points are available? This is not an infrequent case for historical earthquakes; however, their importance is such that no investigator is ready to disregard such earthquakes.

Therefore, how are macroseismic epicentres defined and determined – for example, those found in European parametric catalogues, a preliminary outlook of which can be found in Stucchi and Bonnin (1995)? Is there any computer programme, any published manual on determination of earthquake parameters from macroseismic data? Apparently not: most investigators seem to have their own method for estimating macroseismic epicentral parameters, which probably follows from their ideal epicentre «archetype» to which they stick in their everyday practice. By the way, personal archetypes are by no means isolated cases in macroseismology; for example, during the discussion about updating the MSK intensity scale, it became obvious that most investigators had their own «archetype» of what each intensity degree should represent, and each of them was holding very firmly to it.

From such considerations came the idea of a survey in search of current, practical procedures and possible common archetypes.

The survey was developed as «homework» for the 1st Workshop of WG Macroseismology (Milan, 1993): it consisted of intensity data distributions for several earthquakes located in Italy or surrounding areas, without additional data. Participants were asked to determine geographical co-ordinates and I_0 and to explain briefly criteria adopted and procedures used.

Though no theoretical introduction, nor references were supplied, the case studies were selected in order to survey a few, major hidden questions:

– *Definition* – Is there a common definition of macroseismic earthquake parameters and a common criterion for determining them? In other words, which (hidden) definitions of earthquake parameters does each seismologist adopt, more or less explicitly? And, finally, is a common definition of epicentral parameters, and a common criterion of determining it, needed or not?

– *Starting data* – Are intensity data points the basic data upon which seismologists usually work to determine earthquake parameters? Which kind of data do seismologists require further than intensity data points (earthquake date and time, original sources, isoseimals, etc.), and how do they use them? Do seismologists consult primary information (sources), and to which purpose, in everyday practice ?

– *Processing* – Is it possible to delineate a specific «rule» according to which each seismologist operates? Does he/she always follow this rule? How different are the rules among individuals? Is it possible to see some trends? In connection with this, are epicentral co-ordinates and intensity assessed jointly or separately? (That is: does the assessment of one influence the other?).

With respect to the data, participants were supplied with no other information except the intensity data points; for some events, data did not even incorporate the date of the event; at least that meant that authors had really the same starting point.

After the discussion during the Workshop, participants were asked to submit written solution. Sixteen authors from 11 European countries supplied 15 different sets of solutions. Here follows a preliminary analysis of 14 solutions; the one provided by Shumila refers to an innovative computer approach and cannot be reported according to the adopted scheme.

Although the original «homework» consisted of 15 cases, here we will deal with only seven among them, taken as the most representative.

4. Case analysis

The analysis of the answers showed that some authors were inclined to be very «conservative», giving results with many restraints; on the other hand, some authors were very precise and sure about the quality and quantity of data being sufficient. Some considered that sometimes an area is a better solution than a single point, or that the co-ordinates should be assigned with an error radius (table I). There was also a suggestion, shared by two authors, of the «characteristic point» for some earthquakes represented with poor data set. It would not be the epicentre, but the point with the maximum intensity, or some «unreliable» epicentre; this should be clearly marked by a special symbol or a quality coefficient (table II).

Despite differences in methods, in most cases there was not actually much difference between the results. It was especially evident for well documented cases with more or less regular data distribution (A, F), or even for some less documented ones (C, E). When it comes to more complicated cases, the differences start to be larger.

It should be mentioned that eight authors did not give explicit values of co-ordinates, but only drew the epicentres on the maps. Two authors gave only a description about the place where, in their opinion, the epicentre should be, but not the map co-ordinates. Two authors supplied only the epicentres drawn on the maps, and four authors sent both descriptions and maps. Where possible, missing co-ordinates have been filled in for the purposes of comparison from whatever was supplied by the authors. In some cases this results in an apparent precision greater than was intended by the author.

We now consider the individual cases.

Case A – This case was considered to be the most straightforward (fig. 1). Most authors agreed about epicentre and I_0. The epicentre was placed in most cases in the barycentre of the highest intensity points, which in this case coincided with the centre of the innermost isoseismal. However, some authors had different ideas: one author defined the epicentre as an area, based exclusively on the isoseismals, with the co-ordinate error of $\pm 5'$. Four authors determined the epicentre considering exclusively the isoseismals and its shape, with even some suggested improvements to them. Most authors agreed that $I_0 = X$; one voted for X-XI.

Case C – Somewhat more complicated than case A, as data were fewer. Most authors located the epicentre between the points with intensity IX and VIII-IX, but closer to the IX point (fig. 2). One opinion was that elements of topography on the map would help to understand the reasons for such a poor data distribution. Another idea was the introduction of an error radius drawn on the map around the epicentre. One author supposed that the intensities V and IV-V could be underestimated; the possible reason is that the earthquake was during the night. Also, one author introduced the concept of «characteristic point», already mentioned. Finally, some authors considered the data insufficient to determine the parameters.

Table I. Summary of the results of the cases A-O (co-ordinates of the epicentre).

Author	Case						
	A	C	E	F	K	L	O
A	41 05 15 07	43 32 12 12	40 45 13 54	44 38 11 50			44 18 13 29
A1					41 09 14 32	38 08 13 45	
A2					42 15 13 55	38 08 14 45	
A3					41 35 14 26		
B	41 05 15 00 ±5′	43 30 12 15 ±5′	Tyrrhenian Sea	44 40 11 50 ±5′	41 30 14 30 ±10′	38 10 14 25 ±5′	44 00 14 05 ±0.5°
C	41 05 15 05	43 26 12 17	–	44 40 11 52	41 30 14 32	38 07 14 47	44 06 15 18
D	41 06 15 06	–	Offshore, North	44 36 11 54	41 30 14 30	38 18 14 30	–
E	40 59 14 59	43 30 12 13	–	44 36 11 52	41 32 14 28	38 07 14 32	44 07 13 11
F	41 06 15 07	43 26 12 17	40 45 13 53	44 25 11 51		38 12 14 42	44 06 13 30
F1					41 42 14 18		
F2					41 30 14 30		
F3					41 06 15 00		
G	41 05 15 07	43 29 12 13	40 45 13 54	44 37 11 50	41 34 14 28	38 10 14 30	44 38 13 28
H	41 05 15 06	43 30 12 13	40 46 13 53	44 37 11 50	41 40 14 19	38 12 14 43	–
I	41 07 15 01	43 30 12 14	40 45 13 55	44 37 11 50	41 40 14 24	38 11 14 44	–
J	41 04 15 07	43 31 12 12 ER 7 km	40 45 13 54 ER 7 km	44 37 11 50 ER 3 km	41 30 14 33	38 15 14 30	–
K	41 06 15 07	43 31 12 12	40 45 13 54	44 40 11 52	41 31 14 31	38 10 14 43	44 33 13 45
L	41 06 15 07	43 31 12 12	40 46 13 54	44 38 11 52	41 31 14 35	38 10 14 12	–
M	41 05 15 07	43 31 12 12	40 45 13 54	44 36 11 52			–
M1					42 12 13 55	38 07 13 35	
M2					41 42 14 14	38 12 14 42	
M3					41 30 14 30		
M4					41 06 15 00		
N	Barycenter of the two first isoseismals	–	–	–	Between Campobasso and Isernia	–	–

Case E – A case of an event felt on an island, with rather poor data distribution (fig. 3). Five authors considered the epicentre to be on the shore, near to the point with the highest intensity value. Another five decided it to be slightly offshore to the north. Two authors found the data set to be insufficient to determine the parameters. Some of the additional ideas were that the «not felt» reports should be checked or deleted. Two authors emphasised that in case of an offshore epicentre there is no I_0, but only an I_{max} value. Once again there was the introduction of error radius drawn around the epicentre.

Case F – For this event (fig. 4), two slightly different data sets were supplied. Two of the authors requested to see the full reports before

Table II. Summary of the results of the cases A-O (epicentral intensity).

Author	Case						
	A	C	E	F	K	L	O
A	X	IX	VII-VIII (VII)	VIII			VIII to X
A1					X	IX	
A2					IX-X	IX	
A3					X		
B	X-XI	IX-X	–	VIII	X-XI	X-XI	VIII-IX
C	–	–	–	–	–	–	–
D	X	–	VII-VIII	≈ IX	X	IX-X I_{max}	–
E	X I_{max}	IX I_{max}	–	IX I_{max}	XI I_{max}	X I_{max}	V I_{max}
F	X	IX	VII-VIII		X	X	VII
F1				IX			
F2				X			
F3				X			
G	X	IX	VII-VIII	–	X	IX-X I_{max}	V I_{max}
H	X	IX	–	–	–	–	–
I	X	<IX	VII-VIII	IX	X	IX-X I_{max}	V I_{max}
J	X	IX I_{max}	VII I_{max}	IX I_{max}	X I_{max}	IX-X I_{max}	–
K	X	IX	VII	VIII	X	X	(V-VI)
L	X	≥I X	VII-VIII I_{max}	VIII-IX	X	IX-X I_{max}	V I_{max}
M	X I_{max}	IX I_{max}	VII-VIII I_{max}	VIII			–
M1					X	VIII	
M2					XI	X	
M3					X		
M4					X-XI		
N	X	< IX	–	VIII	–	–	–

making a final judgement. The opinions about I_0 were divided: five authors proposed I_0 = VIII and assumed that intensity value IX was a high singularity due to local factors; on the other hand, five authors proposed I_0 = IX, but with some uncertainty. One author added that the data set is insufficient to decide whether the high intensities are due to topographical effects or superficial soil conditions.

Case K – In this event some authors suggested considering it not as a single earthquake, but as an intensity distribution caused by the possible combination of the effects of three different earthquakes (taken only as a model, and not as physical solution). Apart from those, the majority of the authors did not have much disagreement about the position of the epicentre (fig. 5). Seven authors had cho-

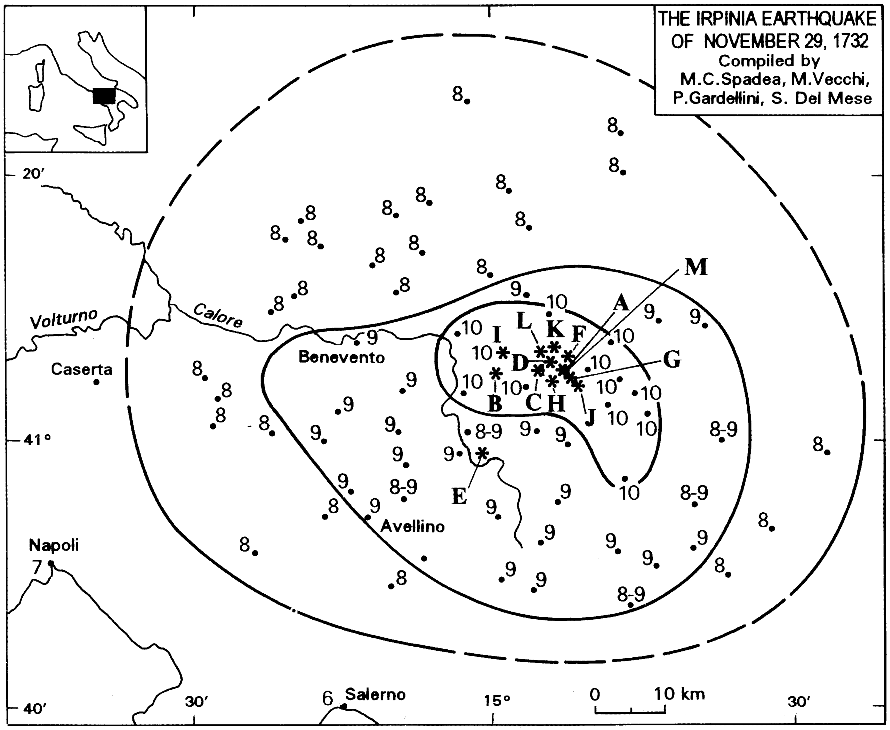

Fig. 1. The solutions for the position of the epicentre for case A.

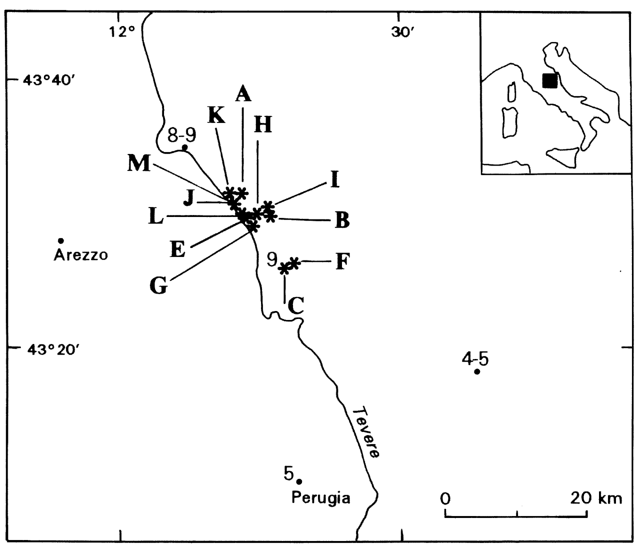

Fig. 2. The solutions for the position of the epicentre for case C.

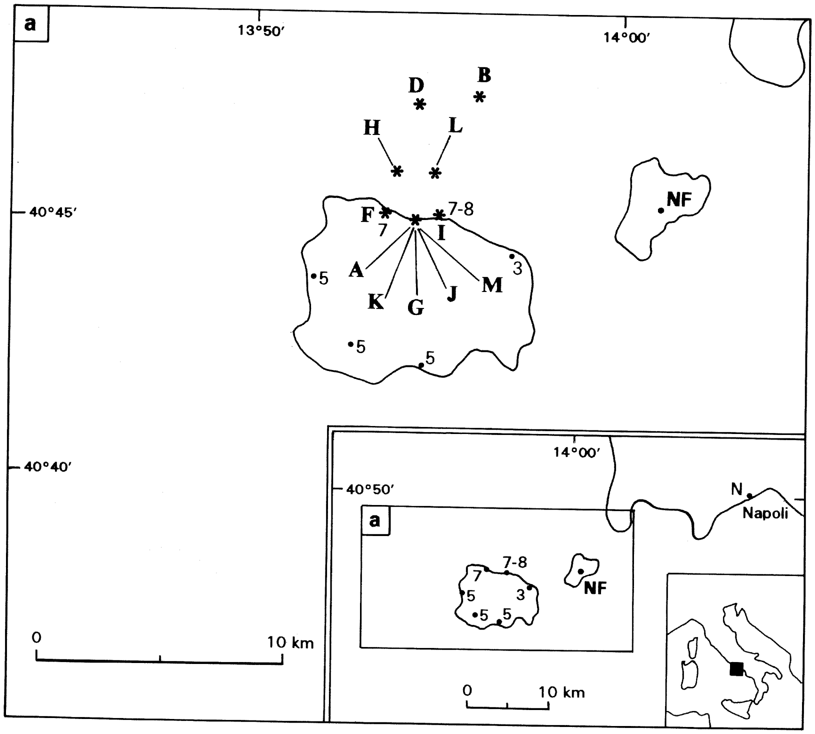

Fig. 3. The solutions for the position of the epicentre for case E.

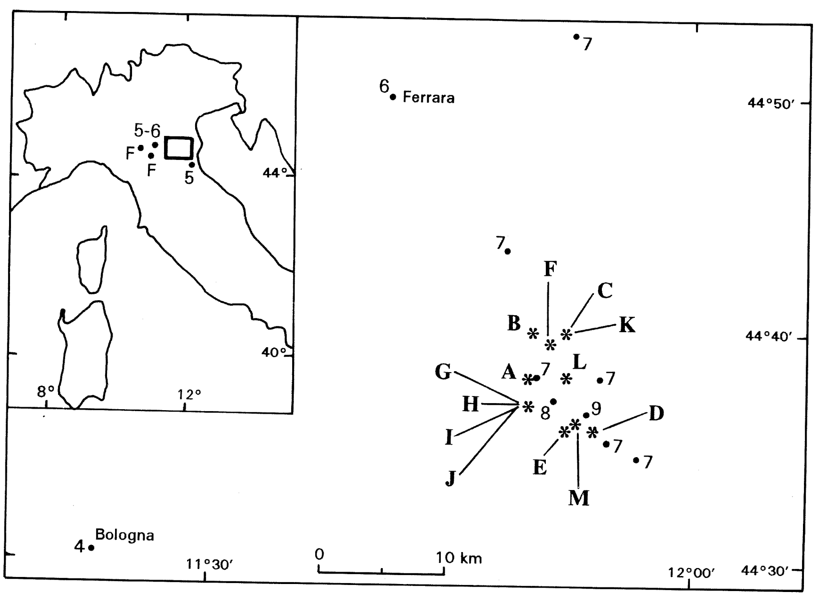

Fig. 4. The solutions for the position of the epicentre for case F.

sen I_0 = X to be the reliable solution; one among them preferred the idea that X was caused by the local site conditions, and chose I_0 = IX. General remark: although the isoseismals were not a point of the discussion here, it should be noted that most authors agree that putting less than 3 intensity points in an «island» or making a «bay» for less than 3 points is normally not a correct way of drawing them.

Case L – This time it was clearly an offshore epicentre, at least for the majority of authors; however, two authors had a different opinion and placed the epicentre on the shore (fig. 6). In this case the dispersion of the epicentral positions is visible; the clusters of solutions are placed near the point of the maximum observed intensity and near the longitude 14°30'. A couple of authors presented the solution as a combination of effects of two events, one located offshore and the other on the shore. As with the previous case, multiple events are used as a way of regenerating an approximation to the intensity field using epicentres and attenuation rates – it is not necessarily implied that two physically separate earthquakes occurred in this instance. It is ob-

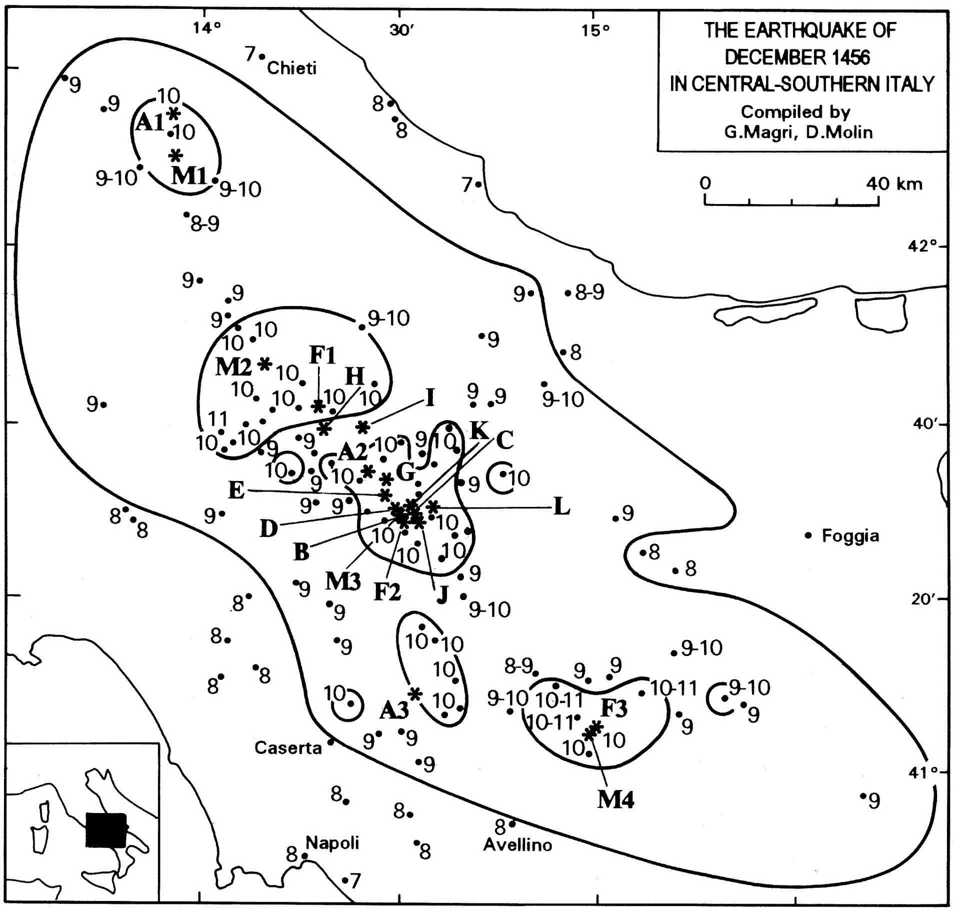

Fig. 5. The solutions for the position of the epicentre for case K.

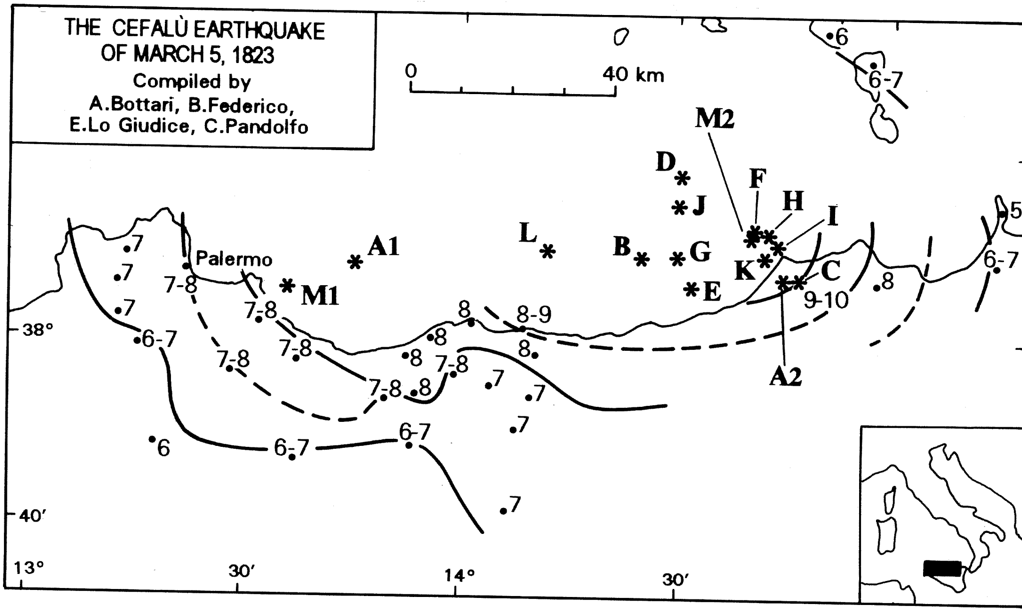

Fig. 6. The solutions for the position of the epicentre for case L.

viously a case for which there should be an accepted common procedure for solving the problem.

Case O – This was the case with the largest differences between proposed epicentres (fig. 7). Although some authors considered the data set to be large enough for a (more or less) reliable determination of the epicentre, others disagreed, being sure that the data for eastern coast of the Adriatic sea were missing. There was also an idea, represented by five authors, that the data could represent the effects of a far off event. This case also showed the widest range of I_0 suggested: from V to X. It seems clear, however, that anyone who considers a value X for this case probably does not mean the same thing as the person who proposes V. Distinction between «observed» (observed intensity at the nearest place to the epicentre) and «calculated» I_0 (estimated value derived from extrapolation) was suggested. Two authors again found it important to outline that in case of an offshore epicentre there is no I_0, but only an I_{max} value.

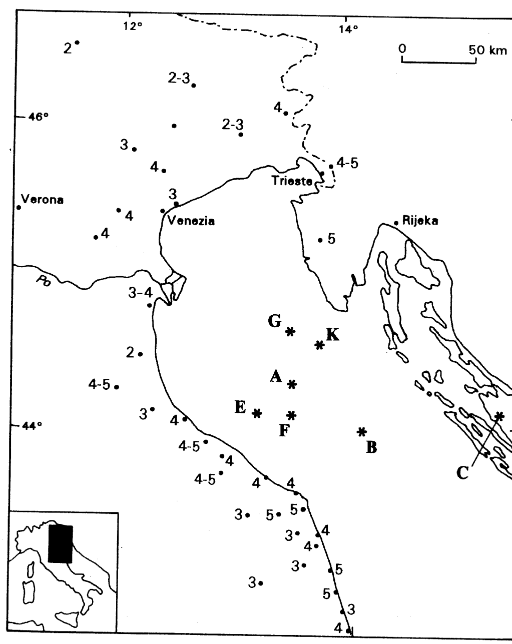

Fig. 7. The solutions for the position of the epicentre for case O.

5. Discussion

The answers supplied were analysed with respect to the main questions summarised above.

Definition – Apparently hidden definitions exist and can be grouped in two main categories, each one carrying a number of variations:

a) the macroseismic epicentre represents the best estimate of the rupturing area, or the best estimate of the position of the instrumental epicentre, as determined from macroseismic data.

b) the macroseismic epicentre is that point which, taken as origin, will enable one to recreate the best intensity distribution of an earthquake using an appropriate attenuation law. According to this definition, relation to physical source parameters (such as depth) is not strictly necessary.

Apparently, the concept expressed by definition (a) is more commonly intended by seismologists in practice. However, it seems clear that the two definitions may lead to different determinations; furthermore, it is also clear that epicentres determined according to definition (a) are commonly used as if determined according to the concept behind definition (b). It was also argued that a different technical term («barycentre» would be good) would probably reduce, if not eliminate, the confusion. Authors generally agreed on the need of common definitions.

The confusion goes back to the historical roots – it is clear that those early seismologists who attempted to use macroseismic estimates of direction or time were trying to determine the source of the seismic waves, even if they did not understand the principles of fault rupturing. But the common practice of taking the centre of the highest isoseismal by default when using intensity data is probably closer to definition (b). Richter's objection to macroseismic epicentres was that the centre of the highest isoseismal frequently fails to coincide with the instrumental epicentre; he did not consider that this could be a separate concept, useful in itself.

Starting data – It seems that the two definitions also drive the request for additional data, with respect to intensity data points. For instance, though it was suggested to stick to intensity distributions, not taking into account the isoseismals already drawn on some test cases, some authors felt that the shape of the isoseismal was important information, so in some cases they based their conclusions mostly upon that part of the information. In general, it seems that authors referring to definition (a) were more likely to request additional data than those referring to definition (b). This can be explained by the argument that definition (b) only requires one to recreate the observed pattern of intensities, not to explain it. However, extra information can still be relevant for definition (b), as for instance explanation as to why data are lacking from some part of the map.

Requests made included:

– checking adjacent countries for further data;

– clarification of the reasons for lack of data in a particular area;

– date of event;

– information about association with volcanic eruption (a special case);

– information on local tectonics;

– information on places deemed anomalous, *e.g.* settlement size, soil conditions;

– time of event;

– topographical information;

– sight of the original reports (check for overestimation, quality of assessment).

Of these, information on local soil conditions and topography were most commonly requested. It should be mentioned that none of these requests were met in the course of the exercise – authors had to manage without the information they said they wanted. It is also possible that some authors would have used information had they known it was relevant or available, but which they would not thought to have asked for in a routine way. For example, in case K, confusion in the time and date information in the original reports lends some credibility to the idea that multiple earthquakes may be represented on the map. This is information that was used by some authors who were previously familiar with the original data, but not suspected by others.

Isoseismals present a different case, assuming that one regards them in this context as additional information. In retrospect it was a weakness in the experiment that some maps had isoseismals drawn on them already; it was not always possible to tell what influence these had. However, it is clear that many authors drew their own isoseismals on test cases without such lines, or in some cases redrew the preexisting isoseismals.

Processing – This problem showed a variety of positions. Some of the different processing procedures came from the two definitions, but with some overlap.

The following «rules» were found for epicentral determination:

- arbitrary values where data are poor;
- barycentre of all points;
- barycentre of highest intensity points (not isoseismals);
- barycentre of highest isoseismal;
- barycentre of the first two isoseismals;
- epicentre coincident with I_{max};
- middle point between two highest intensity points;
- point which minimises the residuals with calculated intensities from an attenuation model.

Not all of these are applicable to all cases; some authors clearly had a «palette» of techniques from which one would be selected to meet the demands of a particular case. For instance, one author was quite consistent about choosing first the barycentre of the highest isoseismal, then the middle point between the two highest intensity points, then the I_{max} position as the data permitted. Other authors seemed more inclined to follow a hunch, and many were unspecific as to the procedure they followed. Unsurprisingly, the difficult cases, such as those with offshore epicentres, gave the greatest variations as «rules» started to break down; it was interesting to note in which cases some authors would refuse to assign an epicentre at all, while others would give an arbitrary one or an approximate one, perhaps with a different symbol. The most commonly declared rule was the barycentre of the highest isoseismal – which is of course the traditional definition as shown earlier.

The last rule in the list above is a special case in that it must be applied computationally, and was therefore only available to two authors who happened to have data files of the various points. This is a very non-traditional approach but interesting in that it can be applied quite consistently and in a more objective fashion. It is evidently highly attuned to definition (b). It was this approach that led to the demand for a multiple epicentre solution in case L – not for any supposition that this was truly a multiple event but only in order to minimise the residuals to a greater degree than could be managed with one epicentre and a non-directional attenuation model. A different computational model for assessing macroseismic epicentre was proposed by Shumila (1994).

By comparison, determining the epicentre according to definition (a) tends to lead to a less uniform approach in which any clues offered by individual cases will be utilised.

Rules for assessing I_0 also varied. Usual was $I_0 = I_{max}$ for cases with epicentres on land. The group was split according to those who defined I_0 as an extrapolated value and those who defined it as an observed value (the majority). As shown earlier, this is a long-standing discrepancy. Where I_0 is defined as an observed value, the rule for assessing it is straightforward, but not always consistently applied, *e.g.* where it is felt that one value may be overestimated. The «extrapolators» were not always explicit (and apparently not always consistent) about their methods, though one quoted the formula of Blake (1941) as a basis.

Some connection between epicentral determination and I_0 choice could be seen, chiefly in cases where one data point had a higher intensity than any other. Some authors accepted this as the location of the epicentre, and therefore the high intensity value became the I_0. Others would question the value, move the epicentre away from it, and quote a lower I_0.

6. Conclusions

There has been a long-standing confusion as to the precise meaning of the concept «macroseismic epicentre», originating from the way in which instrumental methods of location took over from macroseismic methods. Initially it is clear that the physical source of the earthquake was intended, but the failure of macroseismic methods based on direction or time estimates directed seismologists to a method (centroid of highest isoseismal) which was actually determining something other than the instrumental epicentre. There are now clearly two meanings of the term, one being the best estimate of what would be the position of the instrumental epicentre, but working from macroseismic data. The second is the point which is the centre of the macroseismic effects, irrespective of whether this has anything to do with instrumental epicentre or fault rupturing. We propose that a new terminological distinction is necessary, and suggest the term «barycentre» for the second definition.

The study reported in this paper illustrates some of the different methods employed by seismologists in determining epicentral/barycentral co-ordinates and I_0 values. Since it was not an exhaustive survey, no conclusions can be made with certainty as to which methods are most common in seismology in general. However, the following conclusions are clear:

– There are two different conceptions of macroseismic epicentre in use today, and also two different definitions of epicentral intensity (I_0). There is no clear matching of these definitions, but those who treat the macroseismic epicentre as being what we term the barycentre are the ones more likely to favour definition of I_0 as an extrapolated value.

– Most of the authors in the study converted intensity data points to isoseismals wherever possible before deciding parameters; a small minority (who were in the barycentre camp) were definitely opposed to this practice.

– Authors who attempted to estimate the «true» epicentre were more likely to be interested in data other than the intensity information presented in order to look for clues that might assist them. The types of extra data requested were quite wide-ranging, and it is clear that in real practice other types of data (*e.g.* aftershock information, accuracy of timing) might also be employed.

– As a result of this, authors in the «true epicentre» camp are more likely to modify their methods according to the amount of data available, while those in the barycentre camp are more likely to take a method and apply it consistently, leading to more objective results. Computer methods are possible for the second group.

It should be emphasised that we do not see any superiority of one definition over the other for either epicentre or I_0. In the case of epicentre it is particularly clear that both are valid and useful concepts once they are understood, one being useful for seismotectonics and the other for hazard studies.

For the future we recommend, firstly, that authors be more aware of potential confusion of concepts and choose their terminology with care; better documentation of methods would also be welcome. Secondly, the evaluation of formal procedures is needed. If standard procedures can be introduced, it will greatly facilitate the construction of mutually compatible parametric earthquake catalogues.

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