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Macroseismic Surveys in Theory and Practice

INA CECIĆ[1]⋆ and ROGER MUSSON[2]
[1]*Ministrstvo za okolje, prostor in energijo, Agencija Republike Slovenije za okolje, Dunajska 47/VI, SI-1000 LJUBLJANA, Slovenija (E-mail: ina.cecic@gov.si);* [2]*British Geological Survey, West Mains Road, Edinburgh, EH9 3LA, UK (E-mail: rmwm@bgs.ac.uk)*

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Abstract. Macroseismology is the part of seismology that collects and evaluates non-instrumental data on earthquakes, i.e., effects on people, objects, buildings and nature. The methods that seismologists use for collecting and evaluating the macroseismic data are often based on long (trial-and-error) experience more than on some formal procedure. Until very recently manuals or guidelines on how to do a macroseismic survey were rare and often superficial. After an earthquake is felt in some region, the data are usually collected by means of questionnaires. Field survey is an obligatory tool that complements the questionnaires in the case of a damaging earthquake. An overview of the approaches to deriving the earthquake parameters (epicentre and barycentre, epicentral intensity, magnitude, depth, source parametres) from macroseismic data, as well as a review of some existing practices is given.

Key words: macroseismology, macroseismic methods, questionnaires, field surveys, earthquake parametres, Warwick, Raka.

1. Introduction

Although macroseismic methods are among the oldest known in seismology, there is little written about the mechanics of everyday practice. Macroseismology is the part of seismology that collects and evaluates non-instrumental data on earthquakes, i.e., effects on people, objects, buildings and nature. The first known descriptions of earthquake effects are a few millennia old, but data (at least in Europe) started to be collected in an organised way in the 19th century. The methods used then are still in use today, with some changes. The rapid development of technology has significantly shortened the time required for the collection of information after the earthquake, but many of the descriptions of effects have not changed much. People are still being awakened because of the clatter of glasses and window panes, they panic and leave their homes when things start to fall from the shelves and are still in general terrified when the ground beneath them shakes, much the same way today as in the 15th or any other century. However, the dragons appearing in the air, that seemed to accompany numerous strong medieval events were not reported lately, or at least the authors are not aware of it.

⋆ Author for correspondence.

The methods that seismologists use for collecting and evaluating the macroseismic data are often based on long (trial-and-error) experience more than on some written procedure. One of the reasons for that might be that the methods themselves are essentially simple and easily understandable, and therefore the authors/users do not feel they need more explanations. Also, macroseismic methods depend a lot on the region where they are deployed, as well as on the population sample that was chosen for a survey. The manuals or guidelines on how to do a macroseismic survey were rare and often superficial until recently. In the last few years there has been an improvement in this direction, so extensive texts were included as parts of the New Manual of Seismological Observatory Practice (NMSOP) (Bormann, in press), the new IASPEI handbook (Lee *et al.*, in press), and in the explanatory material accompanying the European Macroseismic Scale, EMS-98 (Grünthal (ed.), 1998). However, those working on particular problems often miss more specific instructions, as well as descriptions of solutions for specific situations.

2. Data Collection

After an earthquake is felt in some region, there are several possibilities as to how to collect the data. The final choice depends on many factors, such as:

(a) how strong the earthquake was, and, therefore, how important the data are;
(b) whether it was a single shock or a part of a long sequence;
(c) if there is already existing network of earthquake observers in the region, and whether the network is dense enough;
(d) financial situation of the institution that collects the data, etc.

These points will now be considered in more detail.

(a) In many countries there is a practice that macroseismic data are not collected for every single felt earthquake, but a certain threshold is set. It might be that the data are collected only if the magnitude or intensity of the earthquake was larger than some threshold value, or even only in cases that the earthquake has caused some damage. For example, in the UK surveys are normally done for all earthquakes with onshore epicentres and magnitudes greater than 3 ML, and for offshore events with a significant felt area. In Italy the magnitude threshold is also set to 3, but questionnaires are sent out even for weaker events if the maximum intensity exceeded 5 MCS (Mercalli-Cancani-Sieberg scale). On the other hand, some smaller countries, as well as countries with low seismicity, like Hungary, Austria, Slovenia etc., can afford to collect data actively for almost every earthquake felt on their territory. In areas where earthquakes are rare, the data for even a weak earthquake might be much more valuable and useful for the study of seismicity than the data for a stronger event in the region where the average activity is high.

(b) After a strong main shock there is often long and recurrent aftershock activity. In such cases, people feel so many earthquakes that after some time they start to forget what they felt during any particular event. Also, in the aftershock sequence there tend to be several, or even many, events of approximately the same maximum intensity, as well as magnitude and co-ordinates. Getting the macroseismic data for all the aftershocks is impossible; therefore in practice seismologists often have to make decisions and collect the data only for some events. (In some cases also, the resources of the responsible institute may be exhausted by the extra work involved in handling such a sequence.)

(c) Several seismological institutions have organised permanent networks of voluntary observers in the field. In the case of an earthquake, the questionnaire forms are distributed to them by mail, or they already have some at home, office etc. For small earthquakes such a method is usually enough. However, for a damaging earthquake even the best network of observers is not sufficient, so additional field work is necessary in order to get as many data as possible from the epicentral area.

(d) Although it might sound trivial, the method that is going to be used in collecting macroseismic data depends heavily on the financial situation of the institution. Regardless of the scientific reasons, it is unfortunately frequent that in everyday practice data are not collected even for important events due to a momentary lack of funds for stamps, films, daily allowances or other material necessary for field trips.

3. Questionnaire Design and Distribution

3.1. QUESTIONNAIRE DESIGN

Macroseismic questionnaires are forms consisting of questions about the earthquake; some forms have built-in already the selection of possible answers, so the observer can choose among them (multiple choice questions); others give the observer the possibility to express his impressions in his own words (free-form questions). The point of having a questionnaire is primarily to have all the data in more or less the same format, which means that all the questions are asked of the whole population of observers in precisely the same way. It makes the collected data comparable within the data set for the same earthquake, as well as between different events (for which the same type of form was used).

There are several types of questionnaire forms being used, depending mostly on the target population and the type of the data that one wishes to collect.

The commonest case is a general form, consisting of a set of questions that follow the chosen macroseismic scale. In many cases the questionnaire includes also some additional questions, that are not strictly included in the scale, but might be useful in having a more complete description of the earthquake effects.

Some institutions have two versions of the same form, with and without the questions on damage, for strong and weak earthquakes respectively. The point of having the shorter version of the questionnaire is not to burden the observers with too many questions in case of weak events. Since one usually relies on the goodwill of observers to fill in a questionnaire at all, it makes sense not to make the questionnaire unnecessarily long, difficult, or otherwise discouraging.

Generally the questionnaire form will be too complicated for children in primary schools, although they can be a very valuable source of data, especially in rural areas, where in the same class can be children from a relatively large area. Therefore a special form can be arranged for them; instead of the printed form, the questions are read to them one after the other, and all the necessary explanation is given.

After a damaging earthquake, there are a lot of data to be collected in the field; special forms can be constructed in order to make this procedure easier. The use of the EMS scale requires from the seismologists to collect detailed data on type of objects and damage. The experience from the recent damaging earthquakes in Europe (1997 Central Italy, 1998 NW Slovenia) has resulted in some preliminary forms for describing damage to single structures, as well as for whole settlements. An example of the questionnaire form for the assessment of damage on single buildings was proposed by Tertulliani *et al.* (1999).

3.2. QUESTIONNAIRE DISTRIBUTION

There are several ways of distributing questionnaires that are being routinely used by seismologists:

(a) by mail;
(b) by press;
(c) by email;
(d) by phone;
(e) by making a request through the radio/TV; and
(f) by direct distribution.

Taking these point by point:

(a) The most commonly used method for the distribution of questionnaires is surely by mail. In some countries it can be done free of postal charges, while others are not so fortunate. Generally the method is the following: after an earthquake, the addresses of the observers from some database are printed onto the questionnaires and sent to them; the answers are then sent back using the spare envelope that was included or folding the card according to the instructions. The address database can be one constructed especially for use in macroseismology, or a more general one (phone book etc.) can be used. The ideal procedure is to send questionnaires to a completely random sample of respondents in the affected area, the sample being derived from some source such as electoral rolls. The advantage of this is that accurate statistical conclusions can be drawn about effects on the whole population from the analysis of the sample; the methodology is well known in the social sciences. The drawback is that setting up an appropriate random sample can be time-consuming, and such a task may be difficult to manage in the immediate wake of an earthquake. If one waits too long before distributing questionnaires, the chances are that many people will have forgotten the details of their experience already.

Experience shows that a very good percentage of answers can be achieved, especially with a selected database of respondents, if the database is kept promptly updated. It takes a relatively short time to print and pack the mail, but in cases where the postage has to be paid and in cases of either a large earthquake or a very busy year it might become quite costly. On the other side, it gives homogeneous and comparable data, and the preparation of the intensity list is fast, because the co-ordinates of the places are already prepared.

One way to encourage response is to combine the questionnaire survey with some sort of raffle; the sender of one randomly-drawn questionnaire wins some small prize such as a box of chocolates. This gives the respondents an additional motivation for sending in a reply, which might be useful particularly in making sure negative data are adequately represented.

(b) Some countries, like the UK, have very good experience with having questionnaires printed in local or national newspapers (Musson, 1992); in other, like in Italy, the idea seems not to work so well (Riggio and Slejko, 1989). After an earthquake is felt in the region, the questionnaire is printed in one or more local or regional newspapers, and the readers are encouraged to fill in the answers and send them back. The method does not take much time to launch (the questionnaire form is usually already prepared and ready to be used), but it can be quite time-consuming afterwards, especially in the case of large number of answers, that need to be sorted and the co-ordinates for every single place defined. Another disadvantage of this method is that the questionnaire sample is not truly random and may be biased towards those people who felt the earthquake. It can also be expensive, if the questionnaire has to be placed as a paid advertisement in a national newspaper.

(c) Lately there is some experience with collecting macroseismic data using electronic media. Several institutions have their questionnaire forms on their Internet home pages, and they receive some answers by email. It is possible to foresee that this method may become more and more used in future. There is particular interest in this method in the United States, where there is probably a higher proportion of people on-line than in most other countries. Experience in the UK has shown a rapid increase in the number of responses received this way in the last year (this written in 2001). However, there is again a probable bias towards positive observations in data gathered in this way.

(d) Collecting data by telephone cannot be treated as a regular questionnaire distribution, but more like polling. Of all the methods mentioned here, it is the most time-consuming and possibly the most expensive as well. However, if a seismologist cannot send questionnaires or print one in the newspapers, or go into the field, the telephone is left as the only available method to collect the data. One should be very careful when asking questions, in order not to suggest the expected answer to the person who is giving the data. In some countries, e.g., USA, this method of collecting the data would not be possible for governmental institutions owing to legal restrictions. Telephone data collection is perhaps best suited for establishing whether a small event at the threshold of perceptibility was felt at all, especially in rural locations, where a few farms and perhaps a hotel are the only places that need be consulted.

(e) After each strong earthquake, there is usually a lot of interest from the media about the details. This gives the seismologist an opportunity to speak (on the radio or TV) directly to the population, explaining briefly what data are of particular interest and asking people to write down their descriptions of the earthquake and send them to the institution that collects the data. An experience from Slovenia showed an unexpectedly good response of listeners to the national radio that broadcast the request several times (for an earthquake of 4.1 ML and maximum intensity 5 MSK in 1990 approximately 160 letters were received).

(f) Direct distribution of questionnaires after the earthquake can be used if the problem of returning the questionnaires to the institution in charge is solved. Then a pile of questionnaires could be left e.g., in post offices with the sign "Please take one" and clear instructions what to do afterwards. If the questionnaires are free of postal charges, then they can be simply posted back. If not, a box for collecting them or an alternative method should be arranged.

4. Field Surveys

A field survey is an obligatory tool that complements the above-mentioned methods in the case of a damaging earthquake (producing intensities of 6 EMS or higher). It can be used also for weaker events, in cases where the expected number and spatial distribution of returned questionnaires would not be enough to make a clear picture of earthquake effects in some part of the felt area.

Field surveys require some necessary equipment, such as detailed road maps of the area to be surveyed, questionnaires, notebooks and pencils, copies of the macroseismic scale, a camera, and of course clothes suitable for the conditions likely to be encountered. A portable tape-recorder and a laptop computer might also come in handy.

Field surveys are usually best done by car, although some other methods of transport can be used in cases where there are several teams working on the same earthquake. The ideal team consists of a seismologist and a driver. In extreme cases (e.g., the road network is impassable due to bridge damage) a helicopter may be required, preferably in collaboration with civil defence teams, the military, etc.

While interviewing people, one can use several methods: the answers can be filled directly into a questionnaire form, or written in free format in a notebook. The answers can be recorded on tape directly (if the person who is giving the data agrees, which is not often in rural areas) or the seismologist can repeat a summary of what was said into the voice recorder after finishing the conversation. In any case one must be very careful to label all the data carefully, in order to avoid any mix-up.

Collecting the data in a small settlement is done the following way: usually soon after the car is parked people come around and start telling what happened. Their answers, as well as their addresses are written in the notebook or recorded on the tape. If the earthquake caused some damage, this is the fastest way to learn where to find it. If possible, it is very desirable to take photographs of damage and keep record of it. Then a short survey of the settlement should be done, taking notes on the total number of buildings of each category (if EMS is used) and the number of damaged ones, as explained in the scale.

If the locality is still populated after the earthquake, it is usually very useful to visit briefly some points where people come together (shop, post office, parish office, hairdresser, local pub etc.). A visit to a school in rural area can give a lot of data in relatively short time, because in the same class one can find children living in many different villages or isolated farms.

If the intensity in some locality was high and the houses are badly damaged, the inhabitants are usually living in some improvised shelters and not in the village. In that case the entrance to the settlement can be closed and the field team should contact the local authorities in order to obtain the necessary documents to visit the damaged area. They (civil defence, firemen, police etc.) are also a very useful source of data on the damage and usually can point out some interesting cases. Some identification (like a badge with the name of the member of the team as well as the name of the institution one works for, or at least a letter of certification) is very useful to have, as well as a helmet and a battery lamp.

In a case of a large settlement (small or big town) it is impossible to make a complete detailed survey and count every house. One should then contact the local authorities and see which would be the areas of particular interest. If the locality is still populated, the fastest method to collect data is a visit to schools, preferably for older children. The whole address including street and number written on their answers is necessary in order to be able to divide the town into smaller fractions (quarters, wards) when doing more detailed intensity studies. However, where heavily damaged areas have been evacuated and cordoned off, damage data on a house-to-house basis may be ultimately available from co-operation with the civil defence authorities.

It is necessary to stress that a good macroseismic survey for a damaging earthquake cannot be done without co-operation with civil engineers. It is especially important to establish such co-operation in the cases when the damaged area is large; although it is highly recommended to include a civil engineer into field teams every time there is damage, however slight it might be. Seismologists generally lack training and experience in civil engineering, and identifying the building vulnerability class may be difficult, especially in cases of engineered structures and buildings which have been modified to include some sort of earthquake resistance. Examples from recent earthquakes have shown that without close co-operation with civil engineers, the accurate assessment of damage, and intensity as well, would be difficult, if not impossible (Cecić *et al.*, 1999).

5. Review of Some Existing Practices

5.1. ITALY

In Italy the practice of collecting and evaluating the macroseismic data has been a long and fruitful one. Istituto Nazionale di Geofisica e Vulcanologia (INGV – National Institute for Geophysics and Vulcanology) in Rome is at present the largest institution in Italy that collects macroseismic data.

Italy is a country with relatively high seismicity, and every year there are many earthquakes felt on its territory. Therefore at INGV intensity data are not collected for every earthquake, but only for those that exceed 3.0 in magnitude. Even so, the questionnaires are still sent even for weaker events if the maximum intensity exceeded 5 MCS. The questionnaires are based on the MCS scale and consist of 79 questions, that cover the effects between 2 and 10 MCS. The questionnaire is shown in (http://www.ingv.it/∼roma/attivita/pererischio). Field surveys are made after damaging events.

ING maintains a network of correspondents that report on earthquake effects and fill in the questionnaires (Tertulliani and Maramai, 1992). The network involves some public bodies, like municipal authorities, the Forest Corps and the Carabinieri Police Corps, that is approximately 13,000 correspondents. This configuration has been operative since 1987.

When evaluating the intensity data an algorithm is used, in order to make the evaluations more objective (Gasparini *et al.*, 1992). The intensity evaluations and the intensity maps are regularly published in quarterly Macroseismic Bulletins. ING exchanges macroseismic data with neighbouring countries on a regular basis.

5.2. AUSTRIA

Austria is a case of a country with relatively low seismicity. The history of collecting macroseismic data on the territory of present-day Austria begins at the end of the 19th century, when an “Earthquake Commission” was established in order to compile the earthquake catalogue for the Austro-Hungarian Monarchy, as well as to establish a network of both seismograph stations and of permanent macroseismic observers (Fiegweil, 1989). Since then the macroseismic data have been collected and evaluated on regular basis. Today the institution in charge is Zentralanstalt für Meteorologie und Geodynamik (ZAMG – Central Institute for Meteorology and Geophysics) in Vienna.

In 1947 an arrangement was made with the Ministry of the Interior providing that in the case of an earthquake each police station from the region where it was felt should send a report to ZAMG. Today police stations are still the principal contributors, beside the people who send their reports spontaneously. In the case of a stronger and larger earthquake, additional questionnaires are sent to schools, municipal offices, post offices etc., and a short announcement with the request for reports is given to Austrian News Agency, the radio and the TV station.

The reports are interpreted according to the EMS scale. The isoseismal lines are drawn and the focal depth and the macroseismic magnitude of the earthquake are calculated. Finally, the maps and a short description are printed and mailed to everybody who contributed to it. Austria exchanges macroseismic data with neighbouring countries on a regular basis.

6. Macroseismic Studies of Historical Earthquakes

Macroseismology is among the few branches of seismology that can be applied to the research of events that happened before seismological instruments were invented, and for regions where no such instruments were ever installed. The necessary condition is that the region was populated and that the inhabitants left some record about the earthquakes that happened in their time. Moreover, macroseismic methods are the only means by which one can produce earthquake catalogues for the time before the 20th century, very important in studies of hazard.

When dealing with pre-instrumental earthquakes, the seismologist often encounters several problems that can not be solved without the close co-operation of a trained historian. Institutes in some countries, for example Austria and Italy, make it a practice to employ professional historians, who study the historical material (chronicles, newspapers, reports, letters etc.) and prepare it for seismological interpretation. Many studies of historical earthquakes that were compiled in the earlier part of the 20th century (or in the 19th century) made many errors because of a lack of understanding of the precepts of historical studies on the part of the seismologists who conducted them; for example, confusing secondary and primary sources, and taking at face value exaggerated texts that should only be interpreted with caution.

7. Deriving Macroseismic Parameters

There are two basic approaches to deriving most earthquake parameters from macroseismic data. The first is to draw isoseismals and use the enclosed areas, or the average radii. The second is to base the calculations on the intensity data points themselves, without drawing isoseismals. The advantage of the second approach is that any subjectivity in the isoseismal drawing is entirely circumvented. The disadvantage is that the results may be biased by heterogeneity in the distribution of intensity points as a result of variations in population distribution.

7.1. EPICENTRE AND BARYCENTRE

The epicentre of an earthquake as derived from macroseismic data is something which has been approached in the past in different ways (Cecić *et al.*, 1996). The following usage is proposed for the future:

(a) *Macroseismic epicentre*: The best estimate made of the position of the epicentre (i.e., the point on the earth's surface above the focus of the earthquake) without using instrumental data. This may be derived from any or all of the following as circumstances dictate: position of highest intensities, shape of isoseismals, location of reports of foreshocks or aftershocks, calculations based on distribution of intensity points, local geological knowledge, analogical comparisons with other earthquakes, and so on. This is a rather judgmental process with some subjectivity, and does not lend itself to simple guidelines that can be applied uniformly in all cases.

(b) *Barycentre*: The point on the earth's surface from which the macroseismic field appears to radiate. This is often the centre of the highest isoseismal or the weighted centre of the two highest isoseismals. Other methods have also been proposed, such as the point from which application of an attenuation equation to the whole data set produces the lowest residuals (e.g., Peruzza, 1992). Such methods have the advantage of not requiring the drawing of isoseismals at all. However, to determine the barycentre by calculating, say, the geometric mean of the data points equal to the highest and second highest intensity value, would run the risk of the resulting location being pulled towards the area with the highest number of settlements. This is a good illustration of the value of drawing isoseismals. Other synonymous terms proposed are "intensity centre" (Bakun and Wentworth, 1997) and "macrocentre" (Cecić, 1994, personal communication).

The macroseismic epicentre and barycentre are often the same, but need not be. As an example, in the case of the 1989 Loma Prieta earthquake the apparent point of origin of the macroseismic field was, for various reasons, to the north of the actual instrumental epicentre. If one were to attempt to locate a similar event from macroseismic data alone (for example, a historical Californian earthquake) one might be inclined to compensate for this effect by choosing epicentral co-ordinates to the south of the highest isoseismal. This would not affect the location of the barycentre.

Both these concepts have their uses. For any study of the tectonics of an area, the macroseismic epicentre is more useful. For studies of seismic hazard, especially those using a technique like extreme value statistics, the barycentre may give a better indication of the hazard potential of an earthquake.

7.2. EPICENTRAL INTENSITY (I_o)

Epicentral intensity, usually abbreviated I_o, is a parameter commonly used in earthquake catalogues but rarely defined, and it is clear that different usage exists in practice (Cecić *et al.*, 1996). The meaning of the term is clearly the intensity at the epicentre of the earthquake, but since it is likely that there will not be observations exactly at the epicentre itself, some way of deriving this value is necessary. The two main techniques that have been used in the past are:

(a) Extrapolation from the nearest observed data to the epicentre without changing the value, or use of the value of the highest isoseismal. Thus if there are a few data points of intensity 9 near the epicentre, the I_o value is also 9. If the epicentre is significantly offshore, I_o cannot be determined.
(b) Calculating a fractional intensity at the epicentre from the attenuation over the macroseismic field, using a formula such as that by Kövesligethy (1906) or Blake (1941). In this case, because this is not an observed value (and not a "true" intensity) it may be expressed as a decimal fraction without contravening the rule that intensity values are integer. This value can be determined for earthquakes with sufficient data to draw at least two (preferably three) isoseismals. This is only possible if one is using the concept of the barycentre (see Section 7.1. above), since the true epicentre may not be central to the macroseismic field. The term "barycentral intensity" might be preferable.

It is recommended that these two methods be discriminated between by the notation used. Thus an integer number (IX or 9) indicates method (a) and a decimal number (9.0 or 9.3) indicates method (b). It is recommended that one should not add arbitrary values to the maximum observed intensity when deriving an I_o value; the arbitrary amount is too subjective.

As well as epicentral intensity, a useful parameter is maximum intensity, abbreviated Imax. This is simply the highest observed intensity value anywhere in the macroseismic field. For onshore earthquakes, I_o and Imax may be equal. For offshore earthquakes it is often not possible to estimate I_o (never if method (a) is used), but Imax can be given.

7.3. MAGNITUDE

The use of macroseismic data can give surprisingly robust measures of earthquake magnitude. This is an extremely important part of macroseismic studies, as in this way earthquake catalogues can be extended into historical times with consistent magnitude values. Such extended earthquake catalogues are of great benefit to seismic hazard studies.

Early studies attempted to correlate epicentral intensity with magnitude; however, epicentral intensity can be strongly affected by focal depth (as is well known; an extreme case is cited by Musson, 1998), so such correlations may perform poorly unless either (a) depths are known and taken into consideration, or (b) one is working in an area where seismogenic depth is narrowly constrained.

The total felt area (A) of an earthquake, or the area enclosed by one of the outer isoseismals (usually 3 or 4), is a much better indicator of magnitude, being not much affected by depth except in the case of truly deep earthquakes. For earthquakes below a threshold magnitude (about 5.5 Mw) magnitude and log felt area scale more or less linearly, and so equations of the form

$$M = a \log A + b \tag{1}$$

can be established regionally by examination of data for earthquakes for which macroseismic data and instrumental magnitude are both available. For larger earthquakes, differences in spectral content may affect the way in which earthquake vibration is perceived, and a different scaling appears to apply. In Frankel (1994) the form

$$M = n \log(A/\pi) + 2m/(2.3\sqrt{\pi})\sqrt{A} + a \tag{2}$$

is used to represent the full magnitude range, where n is the exponent of geometrical spreading and

$$m = (\pi f)/(Q\beta), \tag{3}$$

where f is the predominant frequency of earthquake motion at the limit of the felt area (probably 2–4 Hz), Q is shear wave attenuation and β is shear wave velocity (3.5 km/sec). Using this functional form and comparing world-wide intraplate earthquakes with interplate earthquakes from one region (California), Frankel found the difference in magnitude for the same felt area to be on average 1.1 units greater for California.

Other forms that have been proposed include

$$M = a\mathrm{I}_o + b \ln r + c, \tag{4}$$

where r is the radius, rather than the area, of the total macroseismic field, and

$$M = a\mathrm{I}_o + \sum b_i \ln r_i + c \tag{5}$$

in which all isoseismals (values for each i) are used as well as the epicentral intensity (see Albarello *et al.*, 1995).

The method of Bakun and Wentworth (1997) is of particular interest in making a joint determination of epicentre and magnitude by drawing contours of goodness-of-fit to the intensity data set of possible epicentres and magnitudes. This method is especially suited in cases where the intensity data set is sparse.

In the above equations, M has been used for generic magnitude; for any particular magnitude equation it is important to specify what magnitude type the derived values are compatible with (Ms, ML, Mw etc). It is also useful to determine the standard error, which will give a measure of the uncertainty attached to estimated magnitude values.

7.4. DEPTH

The estimation of focal depth from macroseismic data was first developed by Radó Kövesligethy. His first paper on the subject presented the formula

$$I - \mathrm{I}_o = 3 \log \sin e - 3\alpha(r/R)(1 - \sin e) \tag{6}$$

where sin $e = h/r$ and R is the radius of the Earth (Kövesligethy, 1906). Equation (6) was subsequently rewritten and modified slightly by Jánosi (1907), to reach the better-known formula

$$\mathrm{I}_o - I_i = 3\log(r/h) + 3\alpha \log e(r-h), \tag{7}$$

where r is the radius of the isoseismal of intensity I_i, h is depth, and α is a constant representing anelastic attenuation. In this form the equation has been much used (e.g., Burton *et al.*, 1985). The constant value of 3 represents an equivalence value between the degrees of the intensity scale and ground motion amplitudes. Some workers accept it, others prefer to find their own values by fitting to data (Levret *et al.*, 1996). The attenuation parameter α should usually be determined regionally by group optimisation on an appropriate data set rather than for individual earthquakes, since one assumes that this value, a property of the crust, does not alter from earthquake to earthquake.

This technique is also associated with the name of Blake (1941), whose contribution was essentially a reduction and simplification of Equation (7); Blake's version is still used by some workers today, but Kövesligethy's original equation (in Jánosi's version) is more commonly encountered. Kövesligethy's equation became more widely known, in the form of Equation (7), through a paper by Sponheuer (1960).

$\mathrm{I_o}$ here is properly the barycentral intensity, which has to be solved for as well as solving for h. This is usually done graphically – one can fit the isoseismal data to all possible values of h and $\mathrm{I_o}$ and find a minimum error value consistent with the observed maximum intensity (e.g., Musson, 1996).

A test made by Musson (1993) in comparing macroseismic depths and instrumental depths for modern British earthquakes found that the mean discrepancy between the two depth values was 1.6 km. This does represent working with the most favourable sort of data for the method, that is, from shallow (5–25 km) intraplate events with very small sources and good macroseismic data.

7.5. SOURCE PARAMETERS

It is possible to find on occasion papers that present focal mechanisms for pre-instrumental earthquakes. These are commonly the result of a chain of reasoning which can be summarised as: "this earthquake occurred in such-and-such a place, therefore it must have been produced by such-and-such a fault, therefore it must have had a focal mechanism consistent with the type of faulting on this fault". While the result of this reasoning may sometimes be correct, particularly in cases where the causative fault is obvious from surface rupture, the process cannot be considered as determination of earthquake parameters so much as educated guesswork.

The first attempt to use a processing of macroseismic data to characterise actual fault parameters is to be found in the work of Charles Davison, starting around

1890 in the UK, which is remarkable since this actually predates the use of instrumental data for determining focal parameters. Davison believed that he could use detailed descriptions of perceived ground motion from human observers to derive analytically the strike and dip of the rupturing fault (Davison, 1891). He was unaware, however, of the extent to which perceived direction of motion is distorted by building response (most of his observers being indoors), and his method is overly ambitious and of no practical value.

Modern approaches to the determination of source parameters usually depend on the assumption that the ellipticality of isoseismals is a certain indicator of fault azimuth. The work of Shebalin (1973) seems to be the first attempt to follow this line of approach. While in some cases it is obviously true that elliptical isoseismals are aligned along the fault axis, there is also the possibility that this simple pattern is distorted by radiation patterns and local effects (especially for smaller events). Subsequent studies along these lines are summarised by Gasperini *et al.* (1999), who points out the absence of adequate testing of the various methods against calibrated modern data.

Gasperini *et al.* (1999) present a procedure which runs as follows: (i) locate the epicentre of the earthquake from the highest intensity observations; (ii) assess the seismic moment from an algorithm involving the median distance for the observations of each intensity value; (iii) infer the source dimensions from the moment; (iv) assess the fault azimuth, essentially from the direction of maximum elongation of the highest isoseismals. The authors have tested the method against some recent large Italian earthquakes (5.5 Ms is considered to be the minimum size of earthquake for which the method is reliable) with satisfactory results. It will be an interesting exercise in the future to test this method in other areas.

A study by Parsons *et al.* (2000) applied the method of Bakun and Wentworth (1997) to intensity data for six large earthquakes in the Maramara Sea region of Turkey, and attempted to identify probable causative fault ruptures by comparing contours of epicentre and magnitude goodness-of-fit to the intensity data set with compatible fault segments.

8. Practical Application

8.1. EXAMPLE 1: 23 SEPTEMBER 2000 WARWICK (UK) EARTHQUAKE

The earthquake of the 23 September 2000 occurred at 04:23 UTC, 05:23 local time, with an epicentre just west of Royal Leamington Spa, near Warwick. The instrumental magnitude was determined at 4.2 ML, and initial reports suggested that the earthquake had been felt over a wide part of the Midlands and surrounding area, and into Wales. A questionnaire survey was launched. In the UK, there are no suitable local government officials who can be charged with the task of reporting on local earthquake effects; therefore it is necessary to address questionnaires to the general public. This also affects the design of the questionnaire. It is not possible to phrase questions chiefly about the general local experience; the focus needs to be on the respondent's own experience, as this is all that the respondent can be relied upon to know about. The question is then one of distribution. Since the 1970s, when macroseismic data collection by the BGS was first started, it has been found that placing questionnaires in newspapers is the most efficient way to collect a large number of responses (Musson and Henni, 1999). This method was also used historically in the UK by Charles Davison, who conducted systematic macroseismic surveys between 1889 and 1916 and collected data in this fashion (Davison, 1924). Davison was able to insert his very short questionnaire in the correspondence column of newspapers; today it is necessary to insert the BGS questionnaire as a paid advertisement, which can incur a significant bill in the case of a large earthquake where a large number of newspapers need to be used for good area coverage.

In the present case, questionnaires were placed in the following newspapers, giving extensive coverage over the felt area:

> Birmingham Evening Mail, Birmingham Post, Bristol Evening Post and Western Daily Press, Cambridge Evening News, Coventry Evening Telegraph, Bucks Herald (Central Counties Newspaper Group Series), Derby Evening Telegraph, Nottingham Evening Post, Leicester Mercury, Leicester Mail Series, Lincolnshire Echo and Sister Papers, Northcliffe Newspapers, Nottingham and Trent Valley Journal, Oxford Mail and Sister Papers, Oxfordshire Courier, Newsquest, Shropshire Star, The Daily Telegraph, The Sentinel, (Staffs).

Additionally, an electronic questionnaire was made available from the BGS "Earthquakes" website.* The design of the questionnaire is essentially the same as that used in the newspapers, so the data collected from one is in the same format as the other. The online questionnaire was promoted on the main BGS website, BBC news site and, also, in the above newspapers as part of editorials and with the web address given at the bottom of the published questionnaires.

The total number of usable replies received was 2,460, of which 2,299 were positive and 161 were negative. About 400 were received by email from the online questionnaire, and it is clear that this method of collecting data in the UK is increasing rapidly in its usefulness as more and more people have access to the internet and turn to it as a main source of information.

From the larger settlements sufficient replies were received to allow the assignment of intensities, but many small hamlets and isolated farms contributed single questionnaires, from which it is more difficult to establish reliable values, and which were given "F" to denote "felt". The total number of places from which replies were received was 283 (after amalgamating replies from very close settlements less than 2 km apart). The large number of replies received is partly a function of the strength of shaking in the most affected area, but is also influenced

* http://www.earthquakes.bgs.ac.uk/bgs_quest.html.

by the fact that the shock occurred in the heart of the English Midlands, in a quite well-populated area.

The highest intensity experienced was 5 EMS, which was observed quite widely over an area around and south of Coventry, and east of Stratford-on-Avon. In this area there was a certain amount of mingling of places where the intensity was 4 and where it was 5, and borderline cases. Intensity 5 was generally distinguished by an increased number of reports of objects thrown down, a greater level of alarm, and a greater tendency for the shaking to be described as strong. Objects thrown down included a large vase of flowers, books thrown from shelves, tools from hooks, a clock thrown off a wall, and so on. In a number of cases alarms were set off, and in one case at Claybrooke the automatic fuel cut-out in a car (designed to operate in case of a collision to stop engine fires) was triggered. This last occurrence is something of a novelty in macroseismics (such devices being quite recent in manufacture) but evidently denoting of quite strong shaking. In some places (e.g., Daventry) the shock was perceptible out of doors, though the time of day that the event occurred meant that there were not many potential observers who were up and about at the time. There were no reports of people running out in fright, though some people did go and investigate. Animals (pets, cage birds, horses) were alarmed in many cases. A very common report was the creaking of house joists.

There was practically no damage to speak of. A number of reports of extremely minor damage were received, not all of which can be authenticated (it is common that after an earthquake householders believe their pre-existing cracks have widened, but unless measurements before and after have been made, this could be put down to imagination much of the time). In the absence of any reports of damage in the period immediately following the earthquake, it was decided that sending anyone in person to the affected area was not necessary. This is usually the case for British earthquakes, which seldom cause notable damage. The last occasion when it was necessary to send a seismologist into the field to look at damage in the UK was in 1990.

The most distant reports were from the following places: in the west, the earthquake was felt near Hay-on-Wye and Builth Wells. In the east, the earthquake was reported from Ely and near Cambridge. In the north, the limit of observation was marked by Wakefield. In the south, the shock was felt as far as Warminster and Winchester, with also a very dubious observation from Taunton. The total felt area is over 51,300 km^2.

Isoseismals can be drawn for intensity 5, 4, 3 and 2 EMS. As is usual, not many places can be assigned an unqualified intensity 2 observation. But the scarcity of reports from heavily populated areas such as South Yorkshire and the Thames Valley indicates that the intensity was generally 2 in these areas. The isoseismals show an elongation in the NE-SW azimuth, especially those for intensity 3 and 4. The distribution of intensity points and isoseismals in the epicentral area is shown in Figure 1, and the full extent of the isoseismals is shown in Figure 2.

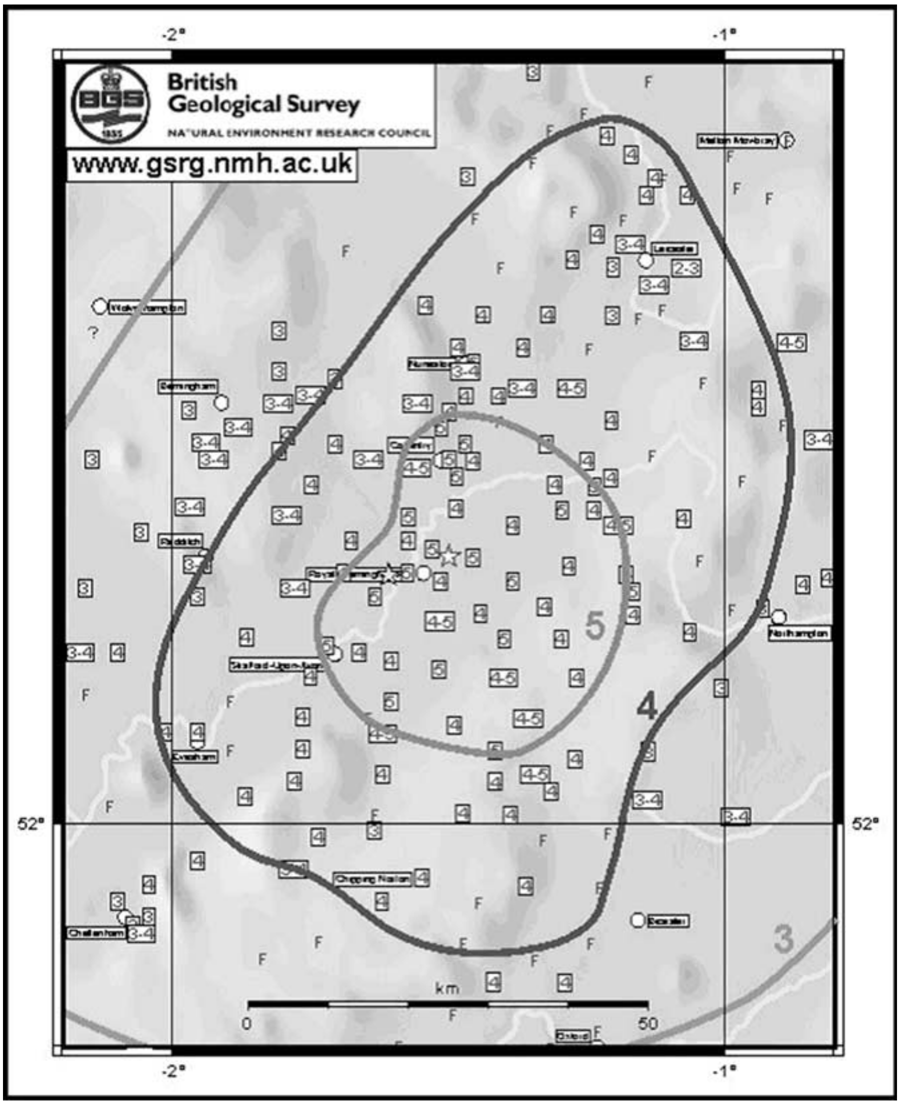

Figure 1. Intensities and isoseismals (EMS) for the epicentral area of the 23 September 2000 Warwick earthquake. The two stars indicate (left to right) the instrumental and macroseismic epicentres.

Macroseismic parameters were calculated according to the procedures described in Musson (1996). The magnitude was consistently calculated to be 4.1 ML from either the 3 or 4 isoseismal. The macroseismic depth is around 12–13 km. These values (for both magnitude and depth) are within the error margins of the instrumental determinations, showing that both methods of calculation are in good agreement.

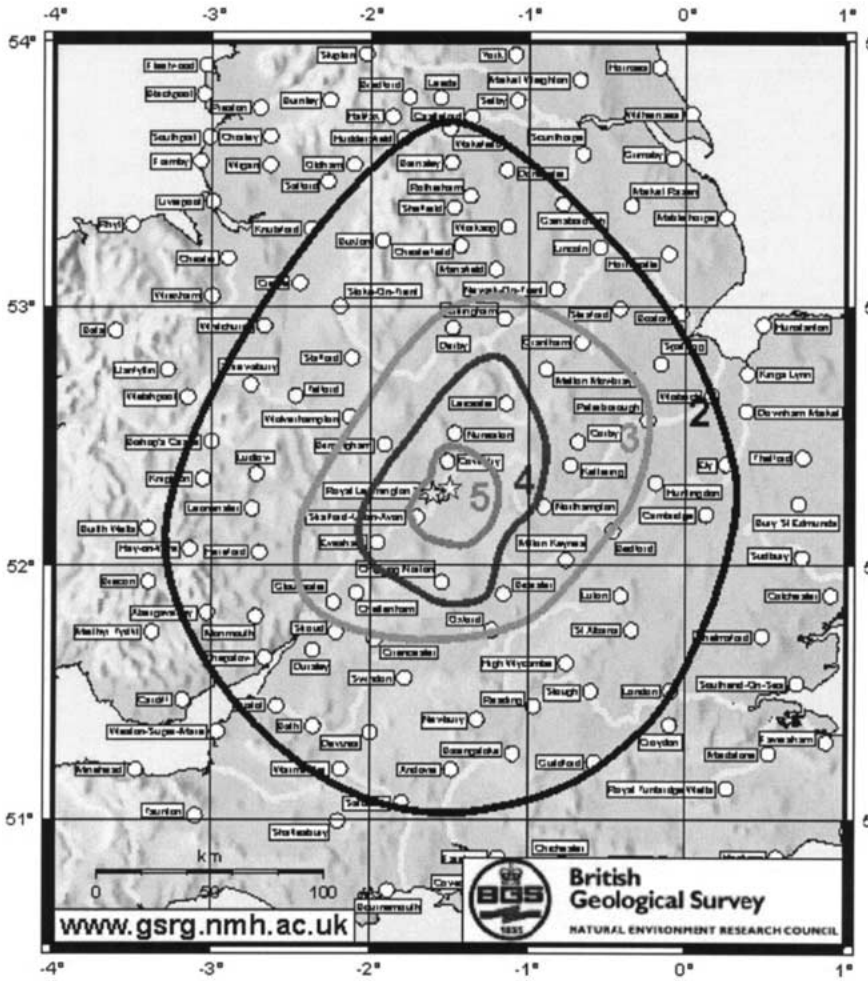

Figure 2. Isoseismals (EMS) for the whole of the felt area of the 23 September 2000 Warwick earthquake. The stars are as in the previous figure.

8.2. EXAMPLE 2: 16 APRIL 2000 RAKA (SLOVENIA) EARTHQUAKE

The earthquake of the 16 April 2000 occurred at 20:29 UTC, 22:29 local time, with an epicentre a few kilometres SW of Raka, near Veliki Koren (Cecić *et al.*, 2001). The instrumental magnitude was determined at 3.2 ML. Initial reports suggested that the earthquake had been felt over a wide part of eastern Slovenia, and possibly in Croatia as well.

A questionnaire survey was launched. When an earthquake is felt in Slovenia, the seismologist decides to which area the questionnaires are to be sent. There exists a network of permanent voluntary observers (at present, July 2002, there are approx. 5800). The observers' addresses can be chosen according to geographical co-ordinates and two different marks. The quality mark denotes the average quality

5

4 4

3 3 3

2 2 2 2

1 1 1 1 1

Figure 3. The density mark (between 1 and 5) makes it possible to choose a number of people living in the same town or village (inside the same post code); the mark for each observer is based on the quality of answers and demographic conditions in the area.

of the expected answer (1 for the worst and 9 for the best). The density mark decides how many people inside the same postcode will receive the questionnaire. There are five density levels for each postcode area, and the basic unit is a pyramid of 15 addresses (Figure 3). After selecting a suitable number of addresses, they are printed on the questionnaires and sent out. On average more than 70% of questionnaires are returned.

In the present case, questionnaires were sent to 389 observers, and 281 questionnaires (72%) returned. All the observers within 14 km from the instrumental epicentre with quality mark 7 or better received the questionnaires; in the outer area (14–32 km from the epicentre) the questionnaires were sent to observers with quality mark 7 or better and density level 3. It was not expected that the earthquake would be felt more than 30 km away from the epicentre.

Additionally, an electronic questionnaire was made available from the ARSO (at that time URSG) website.* The design of the questionnaire is essentially the same as that used by mail, so the data collected from one is in the same format as the other. Only one report was received by email. It is still more natural to Slovene citizens to make a phone call (to the police, radio stations or seismological observatory) than to search for information online.

Two days after the earthquake a one-day field survey was conducted by two seismologists (Cecić and Jesenko, 2000). The aim of the field survey was to check for possible damage, and to collect as many data as possible in the epicentral area. The latter was especially important due to the fact that the only NPP in Slovenia is situated approx. 10 km from the instrumental epicentre. However, according to a telephone conversation with the NPP immediately after the earthquake, the shaking was not felt in the offices of on-duty engineers.

The field survey was divided into two parts: first the secondary school in Krško was visited. This particular school was selected because it is the only secondary school in the town, but also because the students live in the wider region and it is therefore relatively easy to get an overview of earthquake effects for many

* http://www.sigov.si/cgi-bin/wpl/ugf/slo/vprasalnik.htm?language=winee.

localities. The questionnaires were distributed to the students in two classes, and their answers were filled in with the assistance of the seismologist. Out of 46 interviewed students, 23 of them did not feel the earthquake. During the second part of the survey, 19 localities in the epicentral area were visited. In each locality several inhabitants, preferably living in different parts of town/village, were interviewed; all the answers were recorded on questionnaires as well as in free written form. Every person was asked about existence of damage, and in some cases we were either told exactly where to find it, or taken into the house and shown the pieces of fallen plaster and cracks in the walls.

The total number of usable replies received was therefore 365, of which 260 were positive and 105 were negative. From the questionnaires 281 answers were received, 21 from the field survey and 46 from the school in Krško. One answer each was received by fax, phone and email. There were in fact many phone conversations, but only one person gave complete enough data to assign intensity from; the rest were made immediately after the earthquake and only the names of localities were recorded, as the number of calls was very high and seismologist on duty did not have time to make long conversations and take notes. On 11 questionnaires there were additional data for another locality. Three data points (all with intensity 1 EMS-98) were supplied from Croatia.

In the affected area there are no large towns. The largest settlements are Krško and Brežice (approx. 7,000 inhabitants each), which were treated as a single locality when the intensities were assessed. Also, in this part of Slovenia isolated farms are rare, and the vast majority of people lives in villages and small towns.

The highest intensity (5 EMS-98) was experienced in 26 localities. The inhabitants left their houses, but mainly because they were interested what was going on. There were reports of smaller objects overturned or fallen off the shelves or walls. People stressed the fact that the shaking was short but strong, so that the whole houses shook. Some were frightened to go back to sleep; one person went to bed wearing a motorcycle helmet – but it is important to stress that the main concern of the local population is the NPP, and the level of fright in case of an earthquake is in general much higher than elsewhere in Slovenia. Animals were frightened as well, as there are many reports on dogs barking loudly and excitedly. It is possible that part of the fright can be attributed to the loud noise that accompanied the shaking. There is some incomplete information about light damage in the locality Brezje pri Raki, which should probably be included in the list of places of intensity 5 EMS-98, but with the limited information available, the intensity was simply expressed as D (damage). In 19 cases it was not possible to decide whether the intensity was 4 or 5 EMS-98.

The seismologists in the field were able to find only few cases of light damage. In most cases there were the typical effects described for intensity 5 EMS-98: hairline cracks in walls and fall of small pieces of plaster; all the damage that was surveyed during the field work was found on buildings of low vulnerability levels (A and B in bad state of disrepair).

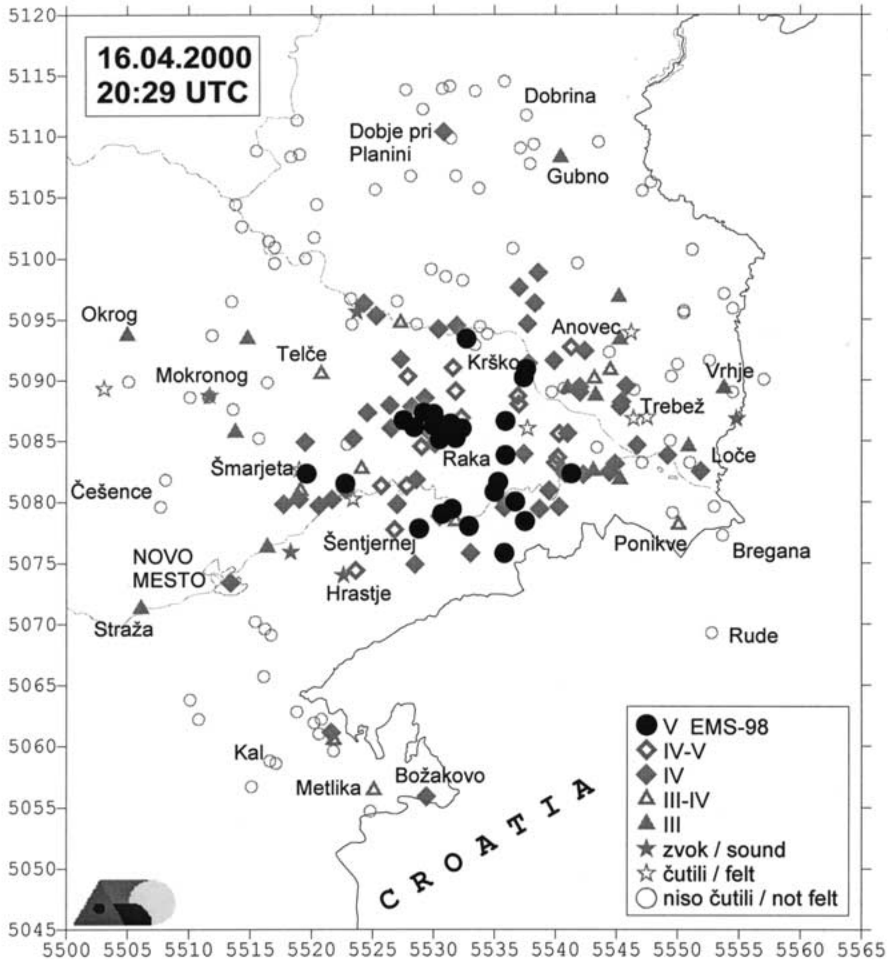

Figure 4. Observed intensities (EMS-98) for the 16 April 2000 Raka earthquake.

The most distant reports were from the following places: in the west, the earthquake was felt in Gorenja vas (near Mirna). In the north, the limit of observation was marked by Dobje pri Planini. In the east, the earthquake was reported from localities next to the Croatian border, but not from Croatia. In the south, the shock was felt as far as Božakovo and Metlika. The total felt area is over 2,400 km^2.

Beside the reports about the main shock, the observers reported several smaller foreshocks and aftershocks. The strongest aftershock happened at 21:27 UTC and its maximum observed intensity was 4 EMS-98.

The intensity map is shown as Figure 4.

9. Conclusions

Although seismology has entered an age of automation, with instrumental data being acquired, transmitted, interpreted and distributed rapidly and automatically, it would be wrong to neglect traditional methods of study of the effects of earthquakes by questionnaire and field survey. The ultimate practical aim of seismology is to help protect communities against earthquakes, and for this it is important to understand the patterns of effects of earthquakes as a function of magnitude, distance, local conditions and other factors. Studying the effects of past earthquakes is an important component of preparing for the effects of future earthquakes. Macroseismic surveys will continue to play a significant role in seismological practice for the foreseeable future.

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