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Verification of Macroseismic Methods on Five $M_L > 5$ Instrumental Earthquakes in France

O. Scotti, A. Levret, B. Hernandez

Institut de Protection et de Sûreté Nucléaire, Fontenay-aux-Roses, France

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Abstract. Macroseismic data available for five of the most recent M_L>5 earthquakes that occurred in the Pyrenees and in the Alps, were analyzed using the Sponheuer and the Levret relationship to estimate depth and magnitude respectively. The aim of this paper is to verify if simple and robust macroseismic methods used on recent instrumental earthquakes may provide a good tool to calibrate historical events in France. The excellent agreement found between macroseismic and instrumental estimates shows that macroseismic data of historical events may provide the means to lengthen the instrumental catalogue and better constrain the recurrence rates of earthquakes in moderate seismic rate regions.

1 Introduction

France is a country of moderate intraplate seismicity with long return periods for destructive earthquakes. Therefore, to supplement instrumental data which has only been providing reliable and accurately recorded earthquake data for about the last thirty years, the analysis of the effects of past earthquakes is fundamental for seismic hazard assessment. Consequently, efforts have been made to gather macroseismic observations from original sources (press cuttings, ancient manuscripts, Church or State archives, scientific publications) reporting effects of earthquakes experienced in France and neighboring regions over a period of nearly ten centuries.

These observations estimated in homogeneous intensities (MSK scale) have been interpreted and compiled together with all the documents to constitute the SIRENE database (Godefroy et al., 1990; Godefroy and Levret, 1992; Lambert and Levret-Albaret, 1996). The aim of this paper is twofold: test if simple and robust macroseismic methods already used on different data sets (Ahorner, 1983; Ambraseys, 1985; Haak et al., 1994/1995; Meidow and Ahorner, 1994/1995) may provide a good tool to calibrate historical earthquakes and identify the limits of application of these methods.

2 Description of macroseismic methods

Earthquake intensity, like other empirical evaluations of physical phenomena, when assessed uniformly on a sufficient number of measurement points, may show regular regional patterns which appear to be attributable to the regular variation of intensity with focal distance due to energy absorption. In this context, the distribution of intensities can be used to estimate focal depths and magnitudes of historical earthquakes when these are calibrated with instrumental data.

2.1 Calculation of focal depths

Kovesligethy (1907) showed that intensity decreases regularly with distance, when assessed uniformly on a significantly large number of points. This can be accounted for by a very simple energy radiation model involving a point source. This assumption can be made for the study of medium to small magnitude events of limited source dimensions. The above model was later modified by Sponheuer (1960) as follows:

$$\Delta I = Io - I = k * log(R/h)^m + k * \alpha * log(e) * (R - h) \quad (1)$$

where Io = the epicentral intensity, I = the intensity of the isoseismal at the focal distance R of the isoseismal mean radius (Sponheuer original calculation) or the intensity of the locality at the focal distance R (calculation in this study). The variable k represents the relationship between degrees in the intensity scale and the amplitudes of ground motion (Sponheuer proposed an empirically obtained value of 3); m is the geometrical spreading coefficient of the wave amplitude (1 for body waves, 0.5 for surface waves); α is the absorption coefficient that depends on wave frequency and soil conditions and h is the focal depth. In fact, the law depends strongly on the first term and particularly on the product "k.m" (called intensity factor) which determines the geometrical attenuation. Ambraseys (1985) showed that the quantity "k.m" has values ranging between 1.2 and 4.6 for a set of

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Correspondence to: O. Scotti

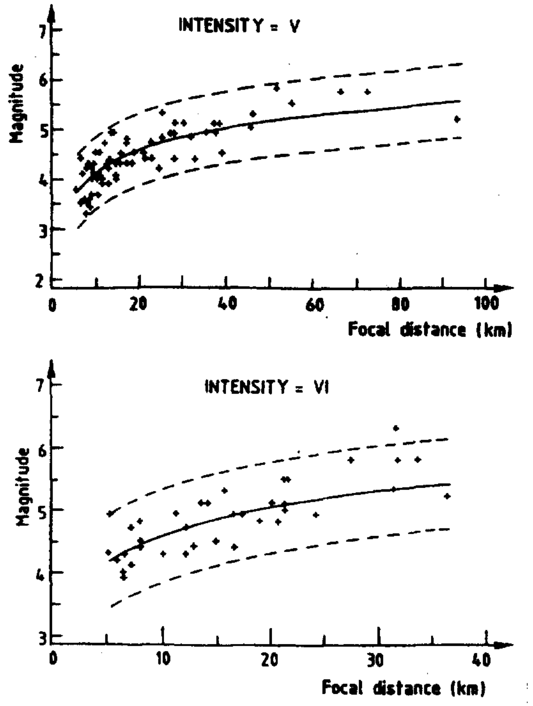

Fig. 1. Magnitude-intensity-distance relationship established on 73 recorded earthquakes (258 isoseismal intensities). Instrumental magnitudes and focal distances of the mean isoseismal radii (crosses) are presented for two isoseismal intensities (VI and V). The inversion curve (line) with its individual confidence interval (dotted) is calculated with the Levret relationship $M = 0.44I + 1.48 * log(R) + 0.48$.

data of northwestern European earthquakes. The derivative of equation (1) shows that the decrease in intensity I varies as a function of the d/h ratio (where d is the epicentral distance). In the far field (large d/h), ΔI varies slowly with depth. In the near field, for the case of a shallow focus event ($d/h \approx 1$ and $1/h >> \alpha$), the variation of I is independent of α and ΔI only varies with depth. For the case of a deep focus event there is no significant variation of ΔI. In the far field and for a deep focus ($d/h \approx 1$ and $1/h << \alpha$), ΔI would depend on α only if $\alpha >> 1/h$, which is not the case in a context of intraplate seismicity where h is less than 30 km. It is therefore shown that the decrease in intensity is much more dependent on the depth of focus than on the absorption by the soil (α), particularly in the near field. A study was carried out on a large set of French earthquakes for which abundant and reliable macroseismic data was available, in order to determine the focal depths (Levret et al., 1994). The results obtained indicate that more than 70% of the foci of the 140 earthquakes studied have a focal depth less than 12 km.

2.2 Determination of magnitude-intensity-distance relationship

In the study mentioned above (Levret et al., 1994), a relationship was established on 73 recorded earthquakes for which macroseismic data as well as instrumental magnitude (M_L between 3.3 to 6.3) were available. Combining the energy radiation model used by Sponheuer (1960) and Karnik (1969) with the Richter (1958) relation between the energy released and the magnitude, a linear regression (least square method) was established on the data set. The basic relation is

$$M = a * I + b * log(R) + c * R + d \qquad (2)$$

where M is the magnitude and I is the intensity of the isoseismal at the focal distance R of the mean radius (in km). Relation (2) is valid at the epicenter where it can be written as

$$M = a * Io * b * log(h) + c * h + d \qquad (3)$$

where h is the focal depth and Io the epicentral intensity. The data set could therefore be supplemented by epicentral data: epicentral intensity and focal distance of the associated isoseismal of maximum intensity. When this value is unknown, it is assumed to be equal to the depth: e.g. 5 km for h = 5 km, 10 km for h = 10 km, etc.). Combining (2) and (3) a new relationship is obtained:

$$Io - I = b/a * log(R/h) + c/a * (R - h) \qquad (4)$$

which corresponds to the Sponheuer relationship (1). In France, effects of earthquake are often of limited extent, indicating that the majority of cases involve only shallow foci ($h \leq 12$ km) events. As a result, the absorption coefficient α in relation (1) is very small (on the order of 10^{-4} km^{-}1). It is therefore possible to write, by way of an approximation, that the coefficient of proportionality between the intensity

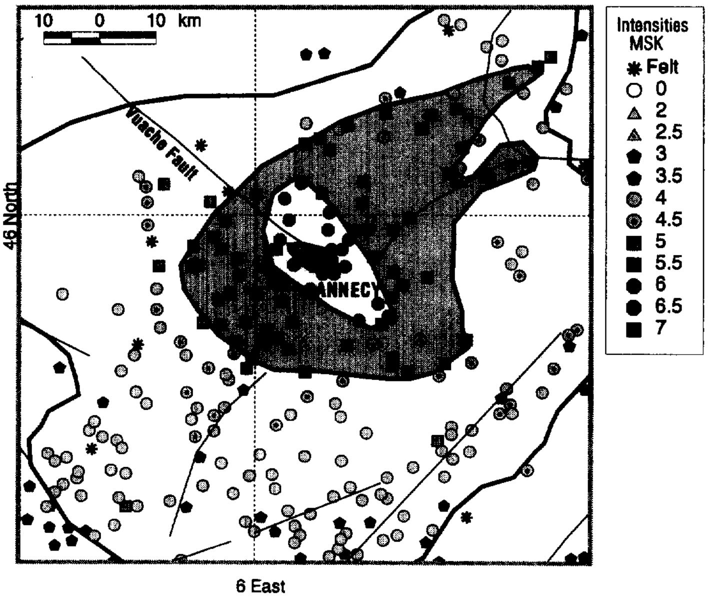

Fig. 2. Macroseismic map of the Annecy earthquake (07/15/1996). The isoseismals are drawn according to the intensity observed in the localities: near field isoseismal shapes for intensities VII and VI are controlled by the NW-SE Vuache fault on which the earthquake occurred; far field isoseismal shapes (V is drawn in grey) are mainly controlled by geological conditions of superficial layers.

and the amplitude of motion is (in the case of body waves): $k = b/a$. The results of the regression calculations for 258 values of I (VIII to III) and R (from 7 to 380 km) show that the term c.R in equation (2) is not significantly different from zero, so the results were obtained on the simplified form (Fig. 1)

$$M = 0.44 * I + 1.48 * log(R) + 0.48 \qquad (5)$$

with a $\sigma = 0.4$.

3 Verification of macroseismic methods on recent instrumental earthquakes

The macroseismic methods described above have been verified on recent earthquakes of magnitude greater than 5 that occurred in two regions: the French Alps and the French Pyrenees.

3.1 Source and geological influences on isoseismal shapes

The July 15, 1996 Annecy earthquake occurred in the French Alps along the Vuache fault. The instrumental depth estimate indicates a shallow hypocenter. The question raised by this event is whether the Vuache fault, a conspicuous NW-SE trending left-lateral strike-slip fault, is a superficial or a crustal feature (Thouvenot et al., 1998). According to a preliminary study (Scotti, 1998) at least two earlier events, Frangy (1936) and Faverges (1980), can be attributed to the Vuache fault and are shallow focus events. Isoseismal shapes drawn for the most recent Annecy earthquake show in the near field a geometry controlled by the source (Fig. 2) and in the far field, isoseismals shapes controlled by the superficial geological formations.

The distribution of the intensities for the recent Pyrenean earthquake of Saint-Paul-de-Fenouillet (1996) shows extended effects indicating a deeper focus, presumably on a ramp structure of the North Pyrenean Frontal Thrust (Rigo et al., 1997). In the far field, in Spain, the strong orientation of the isoseismals in the direction SW beyond the Pyrenean mountains may be due to geological conditions but also to a different data set and intensity evaluation. Similar shapes are observed for the two large earthquakes that occured in the western part of the Pyrenees mountains: Arudy, 1980 and Arette, 1967.

3.2 Focal depth calculation

The parameters of the Sponheuer relationship (equation 1) are estimated by a least-squares inversion using, both the isoseismal radii (square) and all the macroseismic observations (star). The depth as well as α and k parameters are adjusted to fit the curve representing the data. A grid search is used to explore the solution space globally. Each parameter is allowed to vary between two limit values $\alpha \epsilon [10^{-5}, 10^{-3}]$ km^{-1}; k $\epsilon [1, 5]$ and h $\epsilon [0, 30]$ km. The misfit function used in this inversion is the L2 norm between the intensity calculated with the Sponheuer law for a given triplet (α, k, h) and the corresponding data, either isoseismal parameters or all the macroseismic data. Inversion in the least-squares sense leads to the optimum solution. The solution is shown in Fig. 3 only for the value of α corresponding to the least square solution on the data points. The grid search offers the possibility to define the shape of the solution domain in the

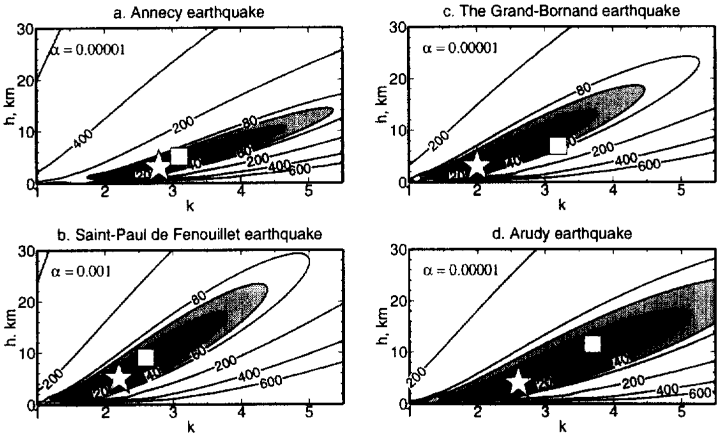

Fig. 3. Solutions are shown for the α [km^{-1}] given by the best solution on the data points. In the grey region each contour line represents a 20% increase in the standard deviation on all the macroseismic data compared to the best solution. The star and the square represent the best solutions deduced from the data points and the isoseismals respectively. a) Annecy with data 695 points (star): k=2.8, h=3.1 km, SD (standard deviation) on ΔI=0.45; using 5 isoseismals (square): k=3.1, h=5.1 km, SD on ΔI = 0.07; b) Saint-Paul-de-Fenouillet with data 748 points (star): k=2.2, h=5.1 km, SD on ΔI=0.43; using 6 isoseismals (square): k=2.6, h=9.1 km, SD on ΔI=0.22; c) Grand-Bornand with 476 data points (star): k=2.0, h=3.1 km, SD on ΔI=0.45; using 4 isoseismals (square): k=3.2, h=7 km, SD on ΔI=0.05; d) Arudy with 1020 data points (star): k=2.6, h=4.1 km, SD on ΔI=0.69; using 5 isoseismals (square): k=3.7, h=11.5 km, SD on ΔI=0.65.

Table 1. Comparison of the instrumental and macroseismic values on focal depth and magnitude of earthquakes

Earthquake	Date	Macroseismic depth	Instrumental depth	M_I (macro)	M_L (instrum)	Ref.
St P.de Fenouillet	02/18/1996	5 to 9 km	6 to 11 km	4.9 to 5	5 to 5.6	Rigo et al. (1997)
Arudy	02/29/1980	4 to 11 km	4 to 6 km	5.1 to 5.3	5.1 to 5.7	Gagnepain-Beyneix et al. (1982)
Arette	08/13/1967	3 to 4 km	5 to 7 km	5.2	5.5	Hoang Trong and Rouland (1971)
Annecy	15/07/1996	3 to 5 km	3 to 4 km	4.6 to 4.7	4.5 to 5.5	Thouvenot et al. (1998)
Grand- Bornand	12/14/1994	3 to 7 km	10.4 ± 1 km	4.6	5.1	Frechet et al. (1996)

parameter space. The black to grey regions represent 20%, 40% and 60% increase in the misfit to all macroseismic data points when compared to the misfit of the best solution σ_{best} (star in Fig. 3) :

$$increase\ of\ misfit\ (\%) = \frac{\sigma - \sigma_{best}}{\sigma_{best}} * 100. \qquad (6)$$

This means that all solution within the black region, for exemple, have only a 20% incresase in the misfit compared to the best solution. The variability in the shape of the solution implies a variable degree of sensitivity of the parameters to changes in the fit to the Sponheuer relationship. It seems clear that for all shapes, a correlation exists between the estimation of the k and h parameters. This reduces somewhat the physical meaning that Sponheuer attributed to k. Nevertheless, we can observe that reasonable (20% contour lines) values of k (between 2 and 4) lead to physically reasonable values of h ($\leq$ 10 km). The solution domain is better constrained for Annecy because it is a shallow event (h $\leq$ 5 km) and there are a sufficient number of data points in the epicentral area to better constrain k. For deeper events (greater than 5 km), the Sponheuer relation cannot distinguish between an event at a depth of 5 or one at 10 km. This can be seen at Grand Bornand, Arudy and St Paul de Fenouillet, where depth values can vary between 2 and 10 km in the 20% contour line. This uncertainty is also reflected in the solution obtained with the isoseismal parameters (squares in Fig. 3). For the Grand Bornand and Arudy events, the squares give quite different values of h and k compared to the stars. Nevertheless, with the exception of Grand Bornand, they fall in the black region corresponding to a 20% increase in the standard deviation compared to the best solution. We propose therefore to use these two methods to estimate the "error" on the evaluation of the depth h and expansion coefficient k (Table 1). The α coefficient, on the other hand, cannot be constrained accurately because the studied earthquakes occurred at a very shallow depth and, as mentioned above, the intensity decrease is practically independent of α.

3.3 Magnitude calculation

The magnitude is calculated according to the Levret relationship (equation 5) by using the isoseismal surfaces and assigned intensities for each earthquake. The mean radius for each isoseismal is therefore estimated and according to the focal depth range evaluated above, the focal distance is then calculated. The magnitude of the earthquake is the mean value of the magnitudes obtained on the various isoseismals. These macroseismic magnitudes are compared with the instrumental values obtained by different laboratories and show an excellent agreement as presented in the Table 1.

4 Discussion and conclusions

At each processing step in the analysis of historical data, uncertainties cumulate (punctual and epicentral intensity evaluation, epicentral location) due in particular to the discrete nature of the intensity scale and to personal judgements. Nevertheless, in this study, uncertainties in the intensities are reduced as all observations are estimated in a homogeneous manner in the MSK scale. It has to be emphasized that these substantial uncertainties would affect the final estimate of the parameters much more than the model or methods of calculation used. In this study, we wanted to differentiate between the uncertainties due to the qualitative nature of the intensity data, from those due to the Sponheuer simplified relationship. Firstly, the relationship has been used on mean radii of isoseismals more in agreement with the energy model developed by Sponheuer. Except in the epicentral area, the uncertainty on the isoseismal radii has very little influence on the determination of focal depth and magnitude as the relationship uses the logarithm of the distance. Secondly, the relationship has been used on all the intensity data points with their scattering reflecting in the near field an extended source (Sponheuer assumes a punctual source model). In the far field it is shown that the geological conditions of the surface layers increase the scattering. It seems obvious that considering all the uncertainties, the greater challenge does not lie in finding a unique solution but rather in estimating the reliability of the parameters obtained through the inversion procedure. This is attempted by using a grid search method that allows to define the shape of the solution domain in the parameter space. Comparison of this solution to that obtained using the isoseismal parameters it is possible to obtain an estimate on the "error" on the evaluation of the depth h. This study points out that for shallow moderate earthquakes :

1. the α parameter cannot be constrained for shallow foci events; this result is consistent with the development of the Sponheuer relation
2. the k value, can vary over a wide range (2 to 3.7) and no regional value appears in this limited data set
3. the k and h parameters do not appear to be independent
4. nevertheless the macroseismic focal depth obtained with the Sponheuer relation using both individual data points and isoseismals allow an estimation of the "error" and consequently an evaluation of the correct macroseismic magnitude range (Levret relation)
5. macroseismic estimates of magnitude are consistent with instrumental values and show comparable uncertainties (Table 1).

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