Magnitude of Historical Earthquakes, from Macroseismic Data to Seismic Waveform Modelling: Application to the Pyrenees and a 1905 Earthquake in the Alps

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Foreword Magnitudes of pre-instrumental moderate-size earthquakes ($M \sim 5.5$) strongly rely on the way macroseismic data are interpreted. In the first part of this paper, after recalling how macroseismic intensity is linearly related to magnitude, we apply a method based on the comparison between historical and recent earthquakes to estimate the moment magnitudes M_W of three earthquakes in the French Pyrenees (Bagneres-de-Bigorre (1660); Juncalas (1750); Arette (1967) and one earthquake in the Alps (Chamonix (1905)). In the second part of the paper we discuss these results in the light of two waveform modelling experiments related to the 1905 Chamonix earthquake, an event well recorded by a Wiechert instrument in Göttingen, and the more recent Arette (1967) earthquake by using WWSSN records. Our instrumental estimate for the Arette (1967) earthquake is 5.1 M_W while we find 5.0 M_W from the macroseismic data. This confirms the rather low magnitude of this most destructive earthquake in continental France since 1909. For the Chamonix (1905) earthquake we find 5.5 M_W, a value close to our macroseismic estimate 5.6 M_W. This good agreement between our macroseismic and instrumental M_W is encouraging for future application of the differential macroseismic method to historical earthquakes, such as the application presented here for the Bigorre (1960) and the Juncalas (1750) Pyrenean earthquakes.

1 Introduction

Macroseismic observations are the only information available for estimating the magnitude of pre-instrumental earthquakes when no fault rupture is observable at the surface, as it is the case for most moderate-size earthquakes in Europe (magnitude ∼5.5). Macroseismic scales currently in use are twelve-degree scales that were formerly based on the Mercalli Cancani Sieberg scale (MCS) (Sieberg 1932). It is important to recall that the suggestion to extend the former ten-degree European scales to twelve degrees is due to Cancani who suggested a quantitative approach

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based on ground acceleration measurements. In the proceedings of a meeting held in Strasbourg in 1903, he wrote (Cancani 1904): *collecting these data* [on macroseismic intensity]*, and performing some interpolations, I think I have found, with enough accuracy, the accelerations corresponding to the ten degrees of the Forel-Mercalli scale. These accelerations increase following a geometrical rule with a common ratio of two. According to the seismologist's judgment, the tenth degree of the Forel-Mercalli scale corresponds to an acceleration which is not larger than 2 500 mm* (sic), *while there are some earthquakes in Japan or South America (...) where acceleration reaches 10 000 mm per second* (sic)*; this is why it was necessary to add two degrees to the above scale.* Because this 1903s note linking degree XII to 10 m/s^2 is not easily accessible, we reproduce it in its original French language in the appendix. One can find in (Sieberg 1912) a detailed description of the twelve-degree scale of what became later on the MCS scale.

The Cancani 1903s factor 2 in ground acceleration between two degrees of intensity may be compared with the factor 2.15 that can be inferred from a relationship published by Richter (1958). It is not far either from the factor which can be expected from the study of Alkinson and Sonley (2000) who established a more sophisticated relationship taking implicitly into account the shift in frequency with epicentral distance. Alkinson and Sonley's formula is established for 29 California earthquakes in the moment magnitude range 4.9–7.4. It links intensity I, peak ground acceleration Y, epicentral distance D, and magnitude M through the relationship:

$$\mathrm{I} = -9.32 + 6.08(\log \mathrm{Y} + 0.46\mathrm{D} - 0.03\mathrm{M}). \tag{1}$$

The correction by the factor 0.03 M being negligible, one can infer from (1) that one degree of intensity at a fixed epicentral distance D roughly corresponds to a multiplicative factor 1.5 in peak ground acceleration.

The logarithmic relationship between ground acceleration and macroseismic intensity has been thus known for more than a century. As the Richter magnitude M is defined from the logarithm of the output of the short period Wood Anderson seismometer with a flat response to acceleration up to 1.25 Hz (Richter 1935), it corresponds to frequencies which are relevant for macroseismic effects and M may be linearly related to intensity I. This is what many empirical relationships show, such as the following general equation adapted from Musson and Cecic (2002):

$$\mathrm{I} = \mathrm{a} + \mathrm{b}\,\mathrm{M} + \mathrm{c}\log \mathrm{R} + \mathrm{d}\,\mathrm{R}, \tag{2}$$

where "a" and "b" are constants, R is the hypocentral distance, and c and d depend on geometrical spreading and anelastic attenuation, respectively.

Most estimations of magnitude of historical earthquake rely on (2). Focal depth h and magnitude M of small and moderate-size earthquakes are commonly estimated from I versus D observations, taking in mind that $\mathrm{R}^2 = \mathrm{D}^2 + \mathrm{h}^2$. Most often, a magnitude is estimated directly from the epicentral intensity I_0 after correction is made from the focal depth h. By doing so, site effect at the epicentre and/or error in the focal depth may strongly bias an estimation of magnitude made from macroseismic observations as we will see for the 1967 Arette earthquake in the French Pyrenees. Furthermore, I_0 may differ from the maximum intensity I_{max} when the epicentre is outside a zone of observation, making I_0 estimate difficult. The situation is not much better when using the whole set of macroseismic areas A(I) due to the strong dependence of the macroseismic attenuation law on the focal depth.

To avoid the uncertainties due to the attenuation law, site effects, or shift in frequency with epicentral distance, Cara et al. (2005) have proposed to compare directly the intensities of a recent instrumentally-known earthquake with the historical-earthquake intensities at large distances from the epicentre. Looking at (2), it is clear that for two earthquakes located at the same hypocentral distance R, the difference of intensity ΔI is proportional to the difference of their magnitude ΔM:

$$\Delta I = b\Delta M, \tag{3}$$

where the constant factor "b" is determined experimentally in the region of interest. For two earthquakes located at the same epicentral distance, R may be confounded with D far from the observation point. As a rule of thumb, we propose to work at distances D larger than three times the standard 10–15 km focal depths of crustal earthquakes in continents, a difference between D and R of a few kilometres being negligible for a macroseismic investigation.

Using the isoseismal areas A(I) to estimate D(I), as in Cara et al. (2005), furthermore acts as a smoothing filter on the azimuthal radiation pattern at the source and on the possible site effects. The investigated zone may then be broad enough to cover densely-populated regions, making the average intensity observations more robust and reliable than the epicentral intensity I_0 for estimating an earthquake magnitude.

The main source of uncertainty comes from the parameter "b" of relationship (3). As the linearity of this relationship probably fails when it is applied to a too broad magnitude range, it is safe to estimate "b" from a set of events with magnitudes not too far from those under study. In France, Levret et al. (1994) found $b = 2.27$ for a large set of data based on a homogeneous set of local magnitudes (4–5.8 M_L) issued by the Laboratoire de Détection Géophysique (LDG) of the French commission of atomic energy, while Souriau (2006) found $b = 2.17$ from a smaller set of recent earthquakes and magnitudes issued by the Réseau National de Surveillance Sismique (ReNaSS) (3.0–5.4 M_L). Accordingly, a value $b = 2.2$ will be used in the present paper for application to France in the moderate-size magnitude range 4.5–6 M_w. The fact that we use a factor "b" determined from M_L catalogues to compute M_w should not be a problem if we refer to Braunmiller et al. (2005). These authors have shown that the slope of the M_w versus M_L relationship is close to 1 for the different European catalogues they have investigated in the neighbouring countries of Switzerland. Only the intercept differs, M_w being smaller than M_L. The difference reaches 0.2 for both the Swiss Seismological Service (SED) and the Karlsruhe catalogues and 0.6 for the LDG catalogue. Note also that in the differential macroseismic method proposed here, an error on "b" will only affect the difference of magnitude ΔM. Taking a difference of macroseismic intensity $\Delta I = 2.2$, a typical value in the application made in this paper, an error of 0.1 on "b" would for example cause an error of 0.05 on ΔM. In addition to the error on "b", the uncertainty of the magnitude of a historical earthquake computed from (3) also depends on the errors on ΔI and on the magnitude of the reference event.

2 Application to Historical Earthquakes in the Pyrenees

The Pyrenees is one of the most active seismic zones of France (Souriau et al. 2001). In the present paper, we focus our attention on the western part of the mountain range. Since the Lambesc (1909) earthquake in the South of France ($M_w = 5.7$–6.1 (Baroux et al. 2003)), this region of the Pyrenees has been visited by the most damaging French earthquake, with a maximum intensity of VIII near the locality of Arette. This is also where two large historical earthquakes occurred (Bigorre (1660) $I_{max} =$ VIII–IX, Juncalas (1750) $I_{max} =$ VIII). In order to apply the differential technique described above, we choose two events as reference earthquakes, one located near Lourdes (Argelès-Gazost (2006) $M_L = 4.9$ ReNaSS, $m_b = 4.6$ NEIC, $M_w = 4.5$ from several independent sources) and another one near Arudy (Arudy (1980) $m_b = 5.1$ (Gagnepain-Beyneix et al. 1982)). The epicentre of the Arudy earthquake is located about 35 km from both the macroseismic epicentres of the Arette (1967) and Bigorre (1660) earthquakes (Fig. 1). The epicentre of the Argelès-Gazost earthquake is located around 10 km from the Bigorre (1660) macroseismic epicentre.

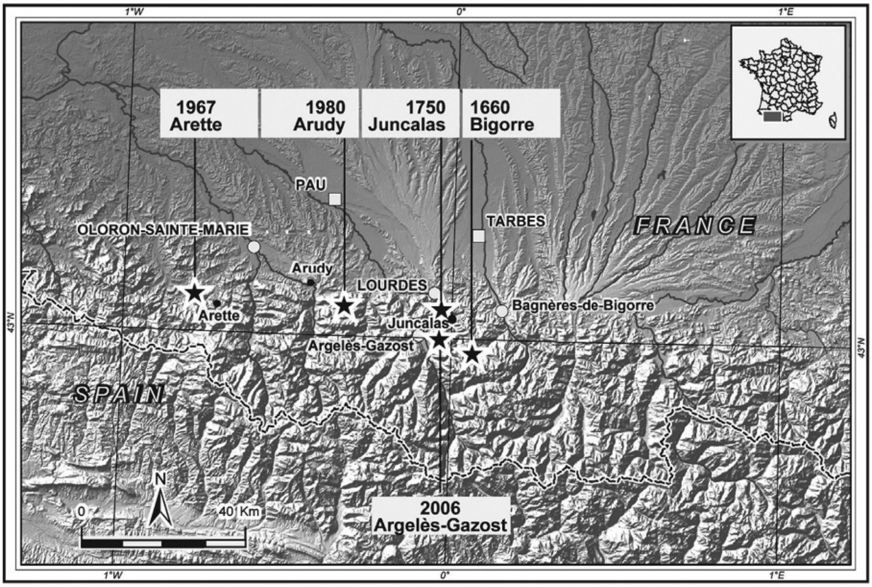

Fig. 1 Epicentres of the Pyrenean earthquakes investigated in this paper

To guarantee a similar spatial sampling for the pairs of historical and recent events, we have clustered the recent localities inside circles of 10 km radius around each historical site, and took the average intensity within each circle. For example, intensities of the Argelès-Gazost (2006) earthquake is known in several localities around the city of Bordeaux while we have only one value of intensity in Bordeaux for the Bigorre (1660) earthquake. With this procedure we can draw the isoseismals of the recent and historical earthquakes from the same geographical sampling. Historical intensities (MSK scale) are taken from the SisFrance data base (www.sisfrance.net). The MSK scale (Medvedev et al. 1964), which was in use in France until 2000, is now replaced by the EMS-98 (Grünthal 1998). The differences between MCS, MSK and EMS are negligible at degrees smaller than or equal to V, and are less than half a degree for larger degrees of intensity (Molin 1995). Working with small intensities, we may thus confound the two scales. Figure 2 shows the isoseismals drawn for the pair of events Argelès-Gazost (2006) – Bigorre (1660). When the isoseismals are not complete, such as those cutting the Atlantic coast or the Franco-Spanish border, we have linearly extrapolated each isoseismal area to a full 360° azimuthal range.

Once the macroseismic areas A(I) are known within each isoseismal, we convert them into distance-intensity curves $D(I) = \sqrt{A(I)/\pi}$ for both the reference and the historical earthquakes, such as in Fig. 3. For the Argelès-Gazost (2006) earthquake, we have completed the D(I) curve down to intensity II by setting its macroseismic

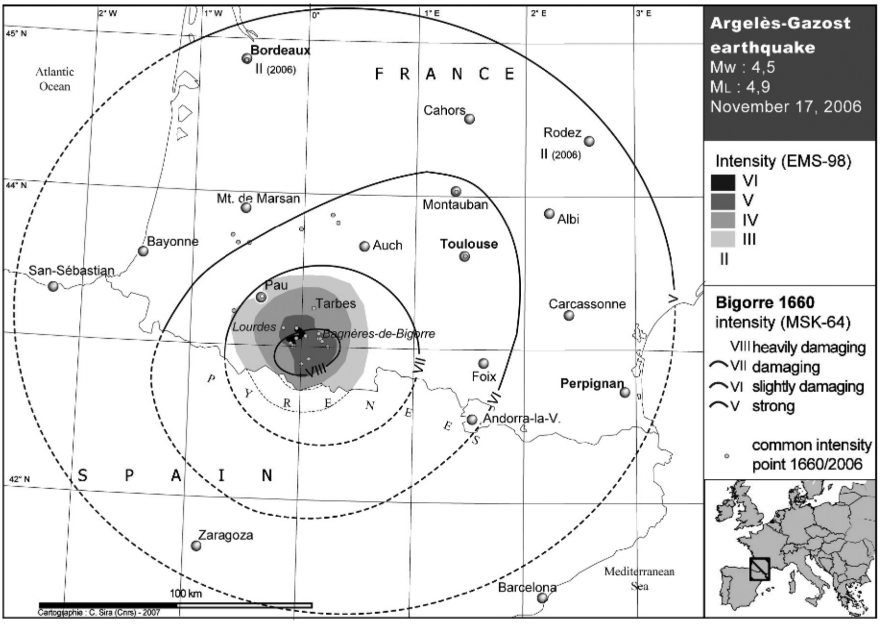

Fig. 2 Isoseismals and macroseismic areas for the Bigorre (1660, MSK-64) and Argelès-Gazost (2006, EMS-98) earthquakes

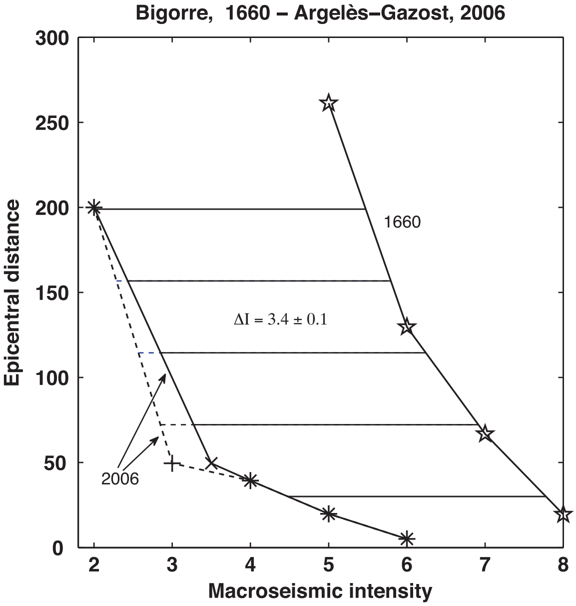

Fig. 3 Epicentral distance D versus intensity I inferred from Fig. 2 for the pair of earthquakes Bigorre (1660) – Argelès-Gazost (2006). Dotted line for the uncorrected intensity

radius to D = 200 km according to the farthest unambiguous macroseismic observations in France (Rodez, D = 255 km; Bordeaux and its vicinity, D = 200 km).

As explained in the previous section, at a fixed epicentral distance D, we expect that the differences of intensities depend on the differences of magnitudes ΔM only. The curves D(I) should thus be parallel. From this respect, the recent Argelès-Gazost curve is abnormal at intensity III. Unreliable answers to the macroseismic questionnaires received at BCSF for distances between 50 and 100 km is the most likely reason for this anomaly. Within this distance range, the answer "not felt" is often quoted by local city officers while reliable reports of intensity II (felt) are sent by individuals. This lack of information from local city officers could explain the abnormally too small area of intensity III in Fig. 2. In order to check the effect of this possible underestimation of intensity III area we test below what is the consequence of increasing the intensity by half a degree at a distance of 50 km from the epicentre.

The average difference of intensity between the pair of earthquakes Argelès-Gazost (2006) – Bigorre (1660) is estimated to $\Delta I = 3.59 \pm 0.29$ from a set of five epicentral distances D in the range 30–200 km (Fig. 3). From the relationship (3) we found that the difference between their magnitudes is $\Delta M = 1.63 \pm 0.13$ (rms deviation). Starting from the 4.5 M_W Argelès-Gazost (2006) earthquake, we thus find a magnitude $M_W = 6.13 \pm 0.13$ (rms deviation) for the Bigorre (1660) earthquake. Following the same procedure with the corrected intensity III $^1/_2$ we get $\Delta M = 1.56 \pm 0.06$ and $M_W = 6.06 \pm 0.06$. Within an rms deviation around 0.1, one can thus conclude with a quite good confidence that a magnitude 6.1 M_w is expected for the Bigorre (1660) earthquake. If one adds an uncertainty around 0.1 for both the reference magnitude and "b", the total error on the macroseismic M_w may be estimated to ±0.2.

The same differential technique can be applied to the pair of earthquakes Arudy (1980) – Bigorre (1660). An average difference of intensity $\Delta I = 1.9 \pm 0.2$ is observed in the distance range 30–200 km (Fig. 4). It corresponds to $\Delta M = 0.86 \pm 0.09$. As no M_W is available for the Arudy (1980) event, we start from the teleseismic body wave magnitude $m_b = 5.1$ (Gagnepain-Beyneix et al. 1982) and we get $m_b = 5.96 \pm 0.09$ for the Bigorre (1660) earthquake, a value close to the 6.1 M_W estimated from the Argelès-Gazost (1980) reference event.

When comparing the Juncalas (1750) to the Arudy (1980) earthquakes in the distance range 30–200 km, we find $\Delta I = 1.3 \pm 0.3$ and $\Delta M = 0.60 \pm 0.12$. Starting again from $m_b = 5.1$ we get a magnitude $m_b = 5.7 \pm 0.1$ for this second largest historical earthquake of the region ($M_W = 5.8$ based on the 4.5 M_W Argelès-Gazost (2006) earthquake). Table 1 gives the different magnitudes reported here and our final preferred solution for M_w.

Similarly, we can compute a magnitude for the Arette (1967) earthquake from the Arudy (1980) event. We get $m_b = 4.9 \pm 0.1$ from $\Delta I = -0.4 \pm 0.2$ and $\Delta M = -0.17 \pm 0.10$. Starting from the magnitude $m_b = 4.6$ ($M_w = 4.5$) of the Argelès-Gazost (2006) event, we get the slightly larger value $m_b = 5.1$ ($M_w = 5.0$). The Arette (1967) earthquake thus has m_b and M_w magnitudes close to 5. Such a magnitude is much smaller than the macroseismic magnitude MM = 5.8 found by Rothé (1972) from macroseismic data (I_0 = VIII, h = 15 km). It is closer to the value MM = 5.2 proposed by Levret et al. (1994). Following the procedure used by Rothé (1972), it is easy to fit both I_0 = VIII and MM = 5 by changing the focal depth to 2.5 km, a depth also shallower than that found by Levret et al. (1994) (h = 5 km). It is thus likely that the hypocentre of the second largest damaging

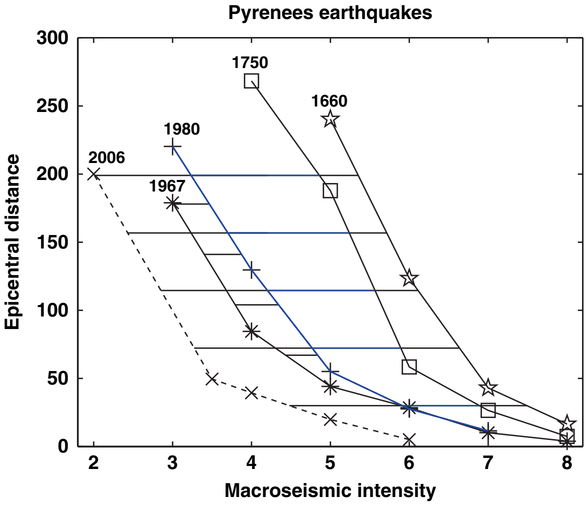

Fig. 4 The same as Fig. 3, but for the Bigorre (1660), Juncalas (1750), Arudy (1980), Arette (1967) and Argelès-Gazost (2006) earthquakes

Table 1 Summary of the different magnitudes investigated in this study

Event	date	m_b	Instrumental M_w	Macroseismic M_w	Proposed M_W
Argelès-Gazost	17-11-2006	*4.6*(a)	*4.5*(1)	–	*4.5*
Arudy	29-02-1980	*5.1*(b)	–	**5.2**(1)	**5.2**
Arette	13-08-1967	**5.1**(a), **4.9**(b)	*5.1*(2)	**5.0**(1)	**5.0**
Juncalas	24-05-1750	**5.9**(a), **5.7**(b)	–	**5.8**(1)	**5.8**
Bigorre	21-06-1660	**6.2**(a), **6.0**(b)	–	**6.1**(1)	**6.1**
Vallorcine	08-09-2005	–	*4.5*(3)	–	*4.5*
Epagny	15-07-1996	*4.5*(c)	*4.6*(4)	**4.9**(3)	**4.8**
Grand-Bornand	14-12-1994	–	*4.3*(5)	**4.4**(3)	**4.4**
Chamonix	29-04-1905	–	*5.5*(2)	**5.7**(3), **5.6**(4), **5.5**(5)	**5.6**

– *italic*: instrumental magnitudes m_b and M_w from different agencies and authors ((a) and (c) USGS’s PED catalogue; (b) Gagnepain-Beyneix et al. (1982); (1) INGV and Géoscience Azur, (2) this study; (3) SED, Géoscience Azur and INGV; (4) and (5) Braunmiller et al. 2005).
– **bold**: macroseismic magnitude computed from the reference event magnitude (n).
Right column: final M_w proposed in this study. The cumulative errors in ΔI, Δb and the reference-event M_w cause an uncertainty on the macroseismic M_w is estimated to ±0.2.

earthquake that occurred in France in the XX century is much shallower than what was previously thought.

There is another conclusion we can draw from Fig. 4 by comparing the two recent Arudy (1980) and Argelès-Gazost (2006) earthquakes. Our macroseismic investigation favoured a rather large magnitude difference $\Delta M = 0.7$ between the two earthquakes, similar to the difference between their teleseismic body wave magnitude ($\Delta m_b = 0.5$), while the French catalogues published by BCSF show similar values (4.9 M_L for Argelès-Gazost (2006) according to ReNaSS and 5.0 M_L for Arudy (1980) according to Schlich and Hoang Trong (1987)). In addition to the well known systematic discrepancy between M_L and M_w when looking at the catalogues of several agencies in Europe (Braunmiller et al. 2005), this example shows that there is no simple rule to convert M_L into M_w when using the BCSF catalogues covering the last 25 years.

3 Application to the Chamonix April 29th, 1905 Earthquake in the Alps

The northwestern part of the Alps is another seismically active region of France (e.g. Thouvenot et al. 1998) where we can test the differential macroseismic method. The Chamonix earthquake of April 29th, 1905 is one of the poorly known earthquakes of this region. Located near the triple border between France, Italy and Switzerland, it is close to several $M \sim 6$ earthquakes of the Swiss Alps. The catalogue issued by the Swiss Seismological Service ECOS (Fäh et al. 2003) contains four historical $M_w > 6$ events at distances less than 60 km from the city of Chamonix. On September 8, 2005, an earthquake of magnitude 4.9 M_L (4.5 Mw) occurred at proximity of the macroseismic epicentre of the 1905 Chamonix event, near the locality of

Vallorcine. As this later earthquake has been well investigated from both local and regional broad-band seismic networks, it provides an excellent opportunity to apply our differential technique.

Intensities of the 1905 earthquake are taken in three catalogues: BCIS (Bureau Central International de Sismologie (Christensen and Ziemendorff (1909)), BSSI (Bollettino della Societa Sismologica Italiana (Palazzo 1907)), and ECOS. Intensities issued by BCIS and BSSI are given in the Rossi-Forel scale (De Rossi 1883), while ECOS intensities are converted into the EMS-98. We have checked the description of the macroseismic effects published by BCIS with both the Rossi-Forel scale and the EMS-98. Doing so, we conclude that for this event, intensities V of the Rossi-Forel scale was intermediate between IV and V of the EMS-98, while VI and VII are equivalent to V and VI of the EMS-98, respectively. Figure 5 shows the isoseismals of the 1905 Chamonix earthquake where intensities are converted into the EMS-98 with two possible interpretations for intensity V. Superimposed on the 1905 map, we have drawn the isoseismals of the Vallorcine (2005) earthquake by using, as previously, the same spatial grid for both the historical and the recent events.

Figure 6 displays the distance-intensity curves D(I) for the pair of earthquakes 1905-2005, together with the curves corresponding to two recent magnitude $M_L \sim 5$ earthquakes located at distances less than 80 km from Chamonix. The moment magnitude of the Vallorcine (2005) earthquake is well constrained to 4.5 from three independent sources (SED in Zurich, INGV in Rome, and Géosciences Azur in

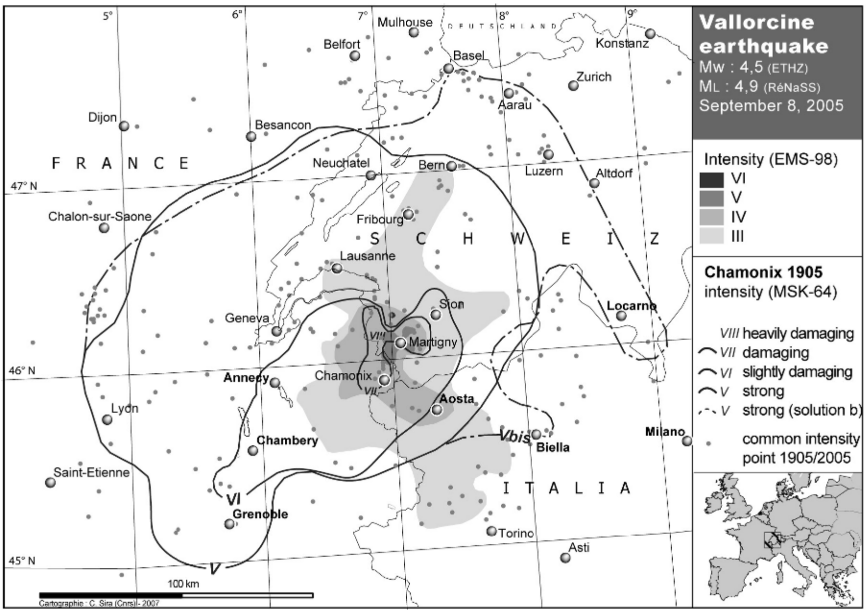

Fig. 5 Isoseismals and macroseismic areas for the Vallorcine (2005) and Chamonix (1905) earthquakes (EMS-98 converted)

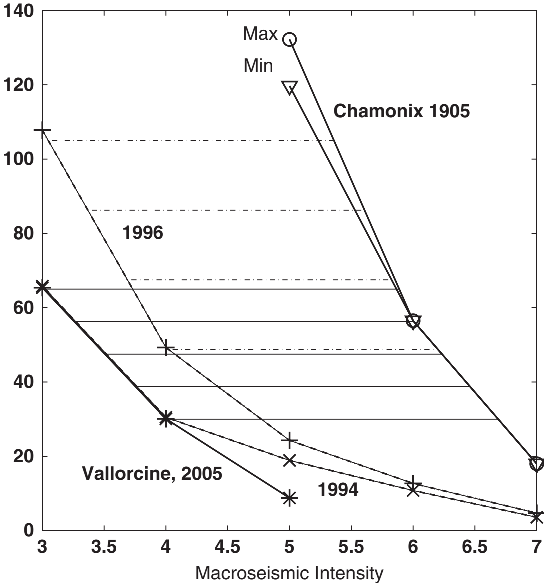

Fig. 6 The same as Fig. 3 but for the Chamonix (1905), Epagny (1996), Grand-Bornand (1994), and Vallorcine (2005) earthquakes

Nice). For the Epagny (1996) event near Annecy and the Grand-Bornand (1994) event, at mid path between Annecy and Chamonix, we use the values M_w computed from several broad-band stations by Braunmiller et al. (2005): 4.6 and 4.3 M_w, respectively. Note that the local magnitude M_L issued by ReNaSS for these three reference events are higher by 0.4–0.6 units (4.9, 5.2 and 4.7, respectively). Using as previously ΔI for the reference earthquakes at a set of five epicentral distances, we obtain an average magnitude $M_w = 5.6 \pm 0.1$ for the Chamonix (1905) earthquake while it would be 6.1 M_L if we start from the short period ReNaSS magnitudes. It is also interesting to note that the macroseismic magnitude $MM = 5.7$ given by Karnik (1969) for the main shock of the April 29th 1905 Chamonix earthquake is in better agreement with our 5.6 M_w macroseismic estimate than what is excepted from the ReNaSS M_L.

4 Instrumental Magnitude and Discussion

The above magnitude estimates can be compared with the instrumental seismic moment magnitudes M_w for both the Arette (1967) and Chamonix (1905) events, although very few reliable records are available for the latter.

In 1967, the WWSSN stations provide many long-period records so that a reliable measurement of the seismic moment can be performed from the surface-wave records. Fitting by trials and errors the observed Rayleigh waves in the distance range 463–2656 km, we find that the best fit is obtained with the following source parameters: strike of the fault = 100°, dip = 75°, rake = −160° and $M_W = 5.1$ (Alasset 2005). The instrumental magnitude $M_W = 5.1$ we find from the long period WWSSN records is very close to that computed from the reference events with macroseismic data ($M_w = 5.0$ or $m_b = 4.9$–5.1). Note also that teleseismic m_b of $M \sim 5$ earthquakes provide a good reference for computing the seismic moment magnitude of this moderate-size Arette (1967) earthquake, while starting from local magnitudes we find a significantly larger value $M_L = 5.4$.

Classical estimates of both the surface-wave magnitude M_{SZ} and duration magnitude M_D can also be made for the Arette (1967) earthquake. By using the long-period WWSSN records and a short-period record from a Mainka seismometer in Bagnères-de-Bigorre, we find $M_{sz} = 5.1 \pm 0.3$ and $M_D = 5.2$ (Alasset 2005). This confirms the rather small magnitude we find above for the Arette earthquake. One can thus conclude from these very different approaches that a magnitude 5.1 (M_w, m_b, M_{sz}) is a quite well constrained value for the most damaging earthquake that occurred in metropolitan France since the Lambesc (1909) earthquake. This also confirms that the hypocentre of this earthquake should have been closer to the surface than proposed by Rothé (1972) from his interpretation of macroseismic data.

Estimating an instrumental magnitude for the Chamonix (1905) is much more difficult. Quite many short period instruments recorded this earthquake in Europe but very few long-period instruments were functioning at that time. Three horizontal 1-ton Wiechert seismometers recorded the April 29, 1905 earthquake (Strasbourg, Göttingen and Uppsala). The records in Strasbourg have been lost and those in Uppsala are of very small amplitude and clearly distorted by the solid friction of the pen on the smoke paper drum. The two horizontal records made in Göttingen are of high quality and the amplitudes of the seismograms are large enough so that comparison with synthetics can be made. Another record is available from a Rebeur-Ehlert long-period instrument in Uccle, Belgium, but the drum speed was so small that no signal can be extracted from the record.

The only records we can rely on for the Chamonix (1905) are thus the two horizontal Wiechert records from Goettingen observatory. Taking several plausible focal mechanisms for this event based on tectonics hypotheses, we find a seismic moment magnitude around 5.5 M_w when modelling both the Love and Rayleigh waves signals (Fig. 7). This result is in very good agreement with the magnitude

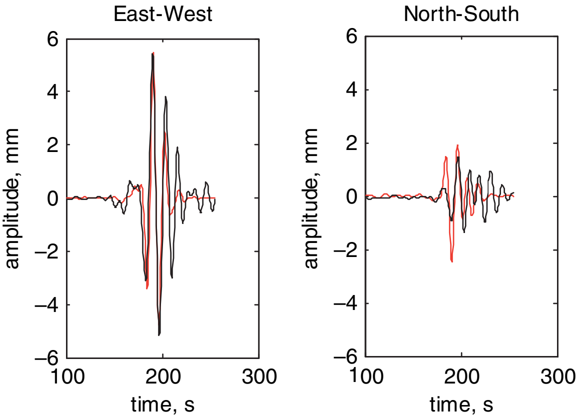

Fig. 7 Fit of the two horizontal component of the Chamonix (1905) records made in Goettingen with synthetics. The observed signals (*black line*) and synthetics (*red line*) are low pass-filtered (cut-off frequency 0.03 Hz). The focal mechanisms used for computing the synthetics corresponds to a normal left-lateral fault (strike 20°, dip 70°, rake –70°, Alasset 2005)

Table 2 Instrumental and macroseismic moment magnitudes computed in this paper (bold characters) or reported from publications (normal characters). MM are published macroseismic magnitudes

		MM	Instrumental M_W	Macroseismic M_W
Arudy	29-02-1980	5.3$^{(1)}$	–	5.2
Arette	13-08-1967	5.2$^{(1)}$	5.1	5.0
Juncalas	24-05-1750	–	–	5.8
Bigorre	21-06-1660	–	–	6.1
Epagny	15-07-1996	–	4.6$^{(3)}$	4.9
Grand-Bornand	14-12-1994	–	4.3$^{(3)}$	4.4
Chamonix	29-04-1905	5.7$^{(2)}$	5.5	5.6

References: [1]Levret et al. (1994), [2]Karnik (1969), [3]Braunmiller et al. (2005).

5.6 M_w obtained in this paper by applying our differential macroseismic method to three recent earthquakes. Table 2 gives a summary of the M_w inferred from both macroseismic and instrumental data together with published macroseismic magnitudes MM.

5 Conclusion

The two XX century damaging earthquakes studied in this paper, Arette (1967) in the Pyrenees and Chamonix (1905) in the Alps, show that the magnitudes M_w of moderate-size earthquakes inferred from our differential macroseismic method are in reasonable agreement with those directly computed from the low-frequency instrumental observations. They are also in close agreement with the macroseismic magnitudes MM published for these two events by Levret et al. (1994) and Karnik (1969), respectively. For the Arette (1967) earthquake, we find a macroseismic value $M_w = 5.0$, while our instrumental estimate is 5.1. For the Chamonix (1905) earthquake, the macroseismic value $M_w = 5.6$ is close to our instrumental estimate 5.5 M_w. The macroseismic magnitude MM = 5.8 issued by Rothé (1972) for the Arette (1967) event is much larger than the value 5.0 M_w reported here. As a consequence the focal depth of this I_0 = VIII latter earthquake must have been much shallower than previously thought.

Present-day macroseismic investigations performed on earthquakes of magnitude $\sim$4.5 M_w thus appear to be extremely useful for calibrating moderate size historical earthquakes when working in the low intensity range [II–V] at some distances from the epicentre. As an application, we have computed seismic moment magnitude of two historical earthquakes in the Pyrenees (Bigorre (1660) 6.1 M_w, and Juncalas (1750) 5.8 M_w). The accuracy of these latter magnitudes is estimated around ± 0.2.

Appendix

Sur l’emploi d’une double échelle sismique des intensités, empirique et absolue. *On the use of a double seismic intensity scale, empirical and absolute* (Cancani, 1904)

Les avantages que présente l’emploi d’une échelle sismique des intensités sont bien connus et c’est pourquoi je n’entretiens pas la Conférence sur cet argument.

Je me permets au contraire d’appeler son attention sur l’utilité que retirerait la sismologie de la diffusion universelle d’une échelle unique, qui servirait également bien à évaluer empiriquement le degré d’intensité comme à l’évaluer rationnellement et mathématiquement.

Pour l’évaluation empirique, presque tous les sismologues, en Italie et à l’étranger, ont accepté l’échelle De Rossi-Forel qui a été sensiblement améliorée par M. le prof. Mercalli.

L’échelle Mercalli, aussi bien pour la valeur des degrés que pour les critériums qui président à leur définition nous offre une différence remarquable par rapport à celle qui, sous le nom De Rossi-Forel, a été adoptée, particulièrement en Italie, depuis 1883 jusqu’à 1899, mais elle ressemble au contraire beaucoup à l’échelle proposée par M. le prof. Forel en 1881. Voilà pourquoi, selon le désir que m’a manifesté tout dernièrement M. Mercalli, nous donnerons dès à présent à la nouvelle échelle le nom de Forel-Mercalli.

Elle apporte une utilité incontestée dans la formation des catalogues sismiques, comme j’ai pu moi-même le constater par l’expérience de l’application que j’en ai faite depuis quatre ans.

L’emploi d’une bonne échelle sismique est aussi nécessaire à donner une valeur conventionnelle, mais précise et invariable aux adjectifs léger, médiocre etc. qu’on a introduits dans la sismologie.

Cependant, tandis que l’échelle susdite est bien appropriée à une classification des effets de la secousse dans une description détaillée d’un tremblement de terre, ou dans une monographie de caractère narratif, certainement elle ne se prête pas bien à une étude mécanique à une recherche de caractère scientifique sur le même tremblement de terre.

Dans ce dernier cas il est évident qu’on doit nécessairement adopter une échelle absolue, c’est à dire une échelle dans laquelle les degrés représentent un élément mécanique bien défini de la secousse, par exemple, l’accélération du mouvement.

Toutefois, au lieu de généraliser et recommander l’emploi d’une échelle absolue des intensités, isolée, qui réponde par elle seule aux exigences de la science, il me semble plus rationnel, et de facile réalisation, réunir (sic) aux degrés de la susdite échelle Forel-Mercalli, les valeurs absolues correspondantes.

MM. les professeurs Omori et Milne et d’autres sismologues illustres, ont pu exécuter en plusieurs occasions, des mesures absolues d’intensité nous fournissant ainsi du matériel qui contribue largement à trouver les accélérations correspondantes aux différents degrés de l’échelle empirique.

En recueillant çà et là ce matériel, et en faisant les nécessaires interpolations, je crois avoir réussi à trouver, avec une exactitude suffisante, les accélérations correspondantes aux dix degrés de l'échelle Forel-Mercalli. Ces accélérations augmentent suivant une progression géométrique qui a pour raison deux.

Selon le jugement très concordant des sismologues déjà nommés, le dixième degré de l'échelle Forel-Mercalli correspond à une accélération qui n'est pas supérieure à 2500 mm (sic), tandis qu'il y a des tremblements de terre, qui ont lieu bien des fois au Japon, dans l'Amérique du Sud, et en d'autres pays terriblement éprouvés par ce fléau, dans lesquels l'accélération arrive jusqu'à 10 000 mm par seconde (sic); c'est pour cela qu'il était nécessaire d'ajouter deux degrés à l'échelle susdite.

Les professeurs Forel et Mercalli convaincus de cette nécessité ont bien voulu m'autoriser à prolonger leur échelle par les deux degrés XI et XII, et former ainsi une échelle sismique qui puisse être adoptée non seulement en Italie mais dans tous les pays du monde.

J'ai donc l'honneur de présenter à la Conférence l'échelle sismique Forel-Mercalli, avec les deux degrés ajoutés et avec les accélérations qui correspondent à chaque degré.

Je prie la Conférence de procéder à la nomination d'une Commission chargée de discuter la double échelle que j'ai l'honneur de présenter avec la faculté de la modifier, si elle le juge nécessaire, et d'en proposer ensuite l'emploi universel.

A. Cancani

Echelle sismique Forel-Mercalli, empirique et absolue

Degrés	Dénominations	Accélérations correspondantes (mm. par seconde)*
I	Secousse instrumentale	<2,5
II	Bien légère	2,5–5,0
III	Légère	5–10
IV	Sensible ou médiocre	10–25
V	Assez forte 1)	25–50
VI	Forte	50–100
VII	Très forte	100–250
VIII	Ruineuse	250–500
IX	Désastreuse	500–1000
X	Très désastreuse	1000–2500
XI	Catastrophe	2500–5000
XII	Grande catastrophe	5000–10000

1)Les dénominations Assez forte et forte en correspondance aux degrés V et VI, sont préférables, selon l'opinion de M. Mercalli, aux dénominations forte et beaucoup forte, déjà introduites.
*mm/s^2, the original error is corrected in the different publications of Sieberg (1932, 2005 (translation of a 1943 publication)).

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