



THE EARTHQUAKES OF THE XIV AND XV CENTURIES IN CATALONIA (NE SPAIN)

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SUMMARY

In 1985 the Geological Survey of Catalonia started a project to compile a comprehensive catalogue of seismic activity in Catalonia in order to provide a correct evaluation of seismic hazard. The project concludes with the publication, in 2006, of a book that gathers the results of the interdisciplinary work carried out on the most important historical earthquakes in Catalonia, which took place in the XIV and XV centuries.

One of the most prominent features of this monograph is that it provides a compilation of all the documentation concerning the earthquakes of the late medieval period. For the first time it has been possible to undertake a joint analysis of all the documentation of the earthquakes of the late medieval period in Catalonia and to evaluate these events using homogeneous criteria. Our evaluation of the earthquakes is a marked improvement on earlier studies in two respects: name and quality of the descriptions, and homogeneity.

A catalogue of the earthquakes of the XIV and XV centuries has been compiled. From this catalogue it can be deduced that the earthquake with the greatest intensity, IX, occurred on 2 February 1428 and that its magnitude corresponds to the highest value M_w of 6.5. The second largest earthquake occurred on 3 March 1373, with a magnitude M_w of 6.2 and epicentral intensity of VIII-IX. Focal parameters of the 8 earthquakes with $I_0 > VI$ are presented. These are the 2 events previously mentioned (1373, 1428), 5 events of the 1427 seismic sequence and another earthquake occurred in 1448.

1. INTRODUCTION

A number of large earthquakes occurred in Catalonia (NE of the Iberian Peninsula) in the XIV and XV centuries. Some of these earthquakes were felt up to a distance of 300 km.

The existence of contemporary sources of the late medieval period in Catalonia allows us to study these earthquakes in more detail. The good state of preservation of old documents and the wealth of description of the events have enabled us to make a relatively reliable reconstruction of these events.

Despite some sporadic attempts to compile reports of earthquakes in the XVII century, it was not until the XIX century that cataloguing of earthquakes began in earnest. Nevertheless, the work of Fontserè and Iglésies [1971] constitutes the first reliable compilation of seismic activity in Catalonia. Their painstaking task provides the basis for any study of historical seismicity in Catalonia.

Using the studies of Fontserè and Iglésies some authors focused their attention on specific earthquakes. This is the case of Cadiot [1979] and Banda and Correig [1984] concerning the earthquake of 1428.

In 1985 the Geological Survey of Catalonia contacted the Department of Medieval History at the University of Barcelona to compile a comprehensive catalogue of seismic activity in Catalonia in order to provide a correct evaluation of seismic hazard. The possibility of finding errors in the existing seismic catalogues prompted us to make a collection of contemporary accounts in order to obtain new data or complete our information on the effects of the earthquakes of the XIV and XV centuries. A critical and in-depth analysis of the contemporary sources of the most significant earthquakes was undertaken.

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As parts of France had also been affected by the earthquakes, collaboration was also established with the *Service d'Aménagement et Risques Naturels de BRGM* in order to carry out a joint analysis and evaluation of all the data. In recent years a macroseismic databank –SISFRANCE (www.sisfrance.net)– has been set up in France in an attempt to better understand historical seismicity.

This interdisciplinary collaboration has yielded partial results since 1987 that have been presented in several journals, books and national and international. This research formed part of the projects funded by the European Economic Community (RHISE: Review of Historical Seismicity in Europe (1989-1993) and BEECD: Basic European Earthquake Catalogue and a Database (1995-1998)), according to which collaborations are established with research workers in different countries in Europe.

The findings of these studies were regarded as incomplete given that the interpretation of each earthquake had been made without considering the other earthquakes of the period. Thus, a monograph [Olivera et al., 2006] compiling all the available information and presenting a joint evaluation of all events in XIV and XV centuries has been published (figure 1). In this paper an outline of the works carried out and the main results achieved are presented.

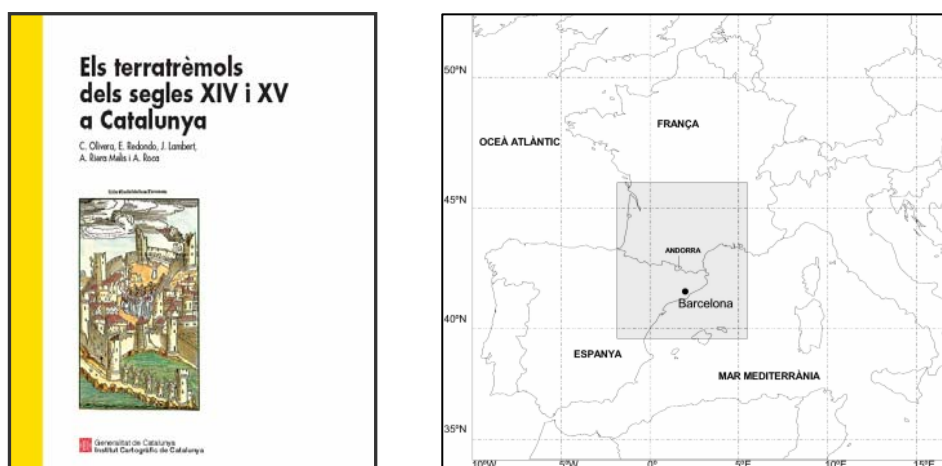


Figure 1: Cover of the monograph (left) and location of area of perception of earthquakes studied in this monograph (right).

2. METODOLOGY ASPECTS FOR ASSESSING EARTHQUAKES PARAMETERS

Our research into contemporary sources has yielded a large volume of documents some of which are new and contain accurate descriptions. A rigorous analysis of the historical sources and context has enabled us to interpret older documents in a different light with respect to earlier studies.

In order to obtain the most reliable evaluation of the earthquakes, only primary sources have been used. Occasionally, secondary sources were considered in accordance with the context and type of source.

The Geological Survey of Catalonia has established an archive collection, which includes microfilms and photocopies of the documentation consulted. The information obtained is stored in a database that allows us to make consultations combining different criteria, and facilitates the incorporation of new reports. This also constitutes an excellent point of departure for subsequent studies.

For the first time it has been possible to undertake a joint analysis of all the documentation of the earthquakes of the late medieval period in Catalonia and to evaluate these events using homogeneous criteria. Our evaluation of the earthquakes is a marked improvement on earlier studies in two respects: name and quality of the descriptions, and homogeneity.

The cataloguing of historical earthquakes is of paramount importance especially in areas where the rate of deformation is low as is the case of Catalonia. European Macroseismic Scale 98 (EMS-98) [Grünthal, G., 1998] has been used to assign intensity at the different sites in order that historical earthquakes can be characterized with parameters that are comparable to those of current earthquakes.

All the destructive earthquakes are assigned a value of point intensity and an index of quality for each locality. Moreover, the macroseismic parameters are associated with an index of quality according to criteria established by Lambert et al., [1996] for the epicenter location (B about 10 km accuracy; C between 10 and 20 km; D between 20 and 50 km) and for the epicentral intensity (decreasing quality from A to E).

Seismic moment M_0 and Moment magnitude M_w are obtained from the isoseismals area and from I_{max} following the empirical relations from Johnston [1996a and 1996b] and Hanks and Kanamori [1979]. In order to estimate focal depth Sponhauer [1960] type attenuation functions are fitted to the observed intensity data points.

It should be mentioned that a special care has been taken in the analysis of earthquake sequences (as is the case of 1427) for which the separation of effects for individual events is a difficult task. Sometimes this problem can be solved analysing together sources in the near field and in the far field [Olivera et al., 1999; Olivera et al., 2006].

3. REVIEW OF THE MOST SIGNIFICANT EARTHQUAKES

3.1 Seismic series of 1373

The first study on the seismic series of 1373 furnished new and valuable data to evaluate seismic hazard [Olivera et al., 1994]. On the one hand, the epicentral zone of this series, which in many catalogues had been erroneously situated in Olot (southern slope of the Eastern Pyrenees) was corrected, and was located 200 km to the west in the county of Ribagorça (southern slope of the Central Pyrenees). On the other hand, two earthquakes catalogued with intensities IX and VIII were considered to be false, suggesting the occurrence of one large earthquake with an epicentral intensity of VIII-IX (MSK).

Once the seismic events of 1373 were studied, contemporary accounts of other earthquakes (1427, 1428 and 1448) were analysed. The joint interpretation of all the large earthquakes in Catalonia presented here provided new information that enabled us to re-evaluate the main earthquake of 3 March 1373. This reappraisal consisted in:

- re-evaluating some intensity values assigned in the earlier study
- assigning intensity to the localities that lacked them
- assigning quality to all the intensity values
- determining the epicentre (not done in the earlier study [Olivera et al., 1994])
- assessing the epicentral intensity
- calculating focal parameters: seismic moment, moment magnitude and depth

The number and geographical distribution of localities where the intensity was known are too low to be able to construct an isoseismal map and to be able to delimit an area with the highest intensities (figure 2).



Figure 2: Intensity map (EMS-98) for the earthquake of 3 March 1373 and epicentre. PD= probable damage and EF= effects on springs.

According to our interpretation, the earthquake could have produced an intensity effect of VIII-IX in the mountains of Ribagorça in the Pyrenees and VIII at Castèth-leon in Val d'Aran 10 km to the north of Ribagorça (figure 3). Moreover, the hydrological effect at Vila suggests the proximity of the epicentre.

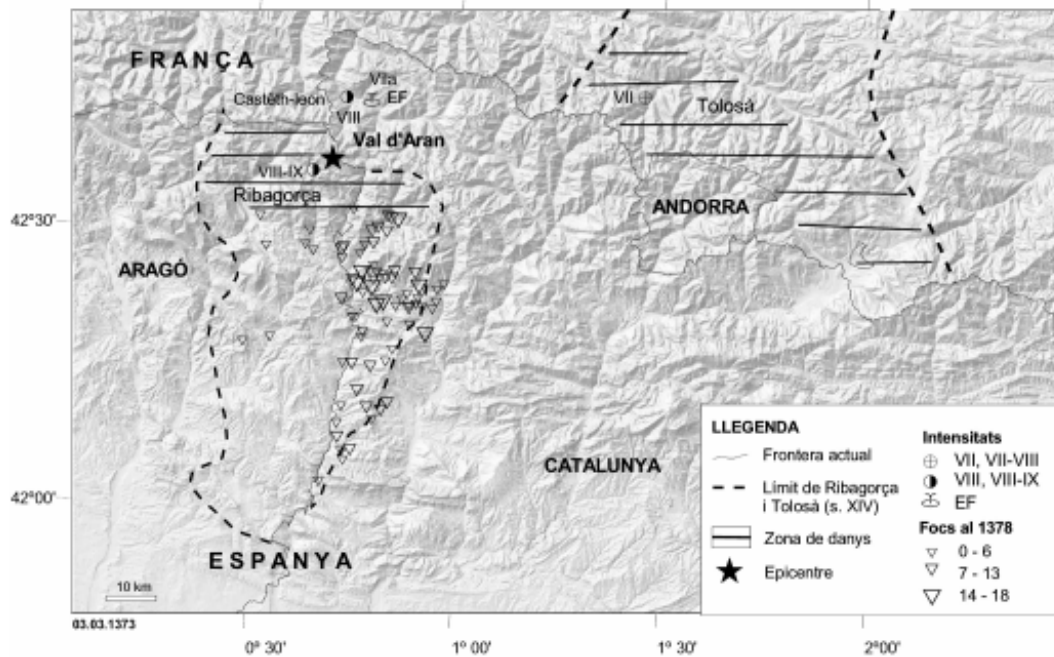


Figure 3: Epicentral area of the earthquake of 3 March 1373. Probable zone of damage (shaded area) corresponding to Ribagorça and Toulosain. Households in Ribagorça (triangles).

The earthquake on 3 March 1373 attained an epicentral intensity of VIII-IX (EMS-98), with quality C. The epicentral area lies between the county of Ribagorça and the Val d'Aran, 42° 38'N and 0°41'E and has quality D (uncertainty of 20-50 km). The analysis of the attenuation curve obtained from the intensity data points for this earthquake and the comparison with another earthquake of $I_0 = VIII$ occurred in 1923 in the same area [Susagna et al., 1994] indicates that the focus of the earthquake would be within the crust at a depth of about 16 km. The energy released by this earthquake corresponds to a seismic moment M_0 of 2.56×10^{18} N.m and a moment magnitude M_w of 6.2.

3.2. Seismic sequence of 1427

The sequence of earthquakes in 1427 is less well known, probably because it has been overshadowed by the earthquake on 2 February 1428, which was more destructive.

Given that all the available documentation had not been used in earlier studies, the evaluation of the earthquakes presented here is more complete and more reliable since it provides epicentre and epicentral intensity, with a quality index for each earthquake of the sequence (table 1). The analysis of the descriptions indicates that the chronology is reliable. The epicentres proposed have an uncertainty of up to a maximum of 20 km.

Hence, all previous doubts concerning the duplication of the earthquake of 15 March and 15 May are dispelled. The records allow us to obtain the date and time of the two events. On 15 March an earthquake damaged the Amer monastery. This became the focus of considerable attention because of its symbolic significance although the earthquake was less intense (VI, EMS-98) than the others of the sequence.

The most important earthquakes of the sequence occurred on 19 March with an epicentre in the area between Osor and Amer (figure 4) and on 15 May, located between vall d'en Bas and Olot (figure 5), the two locations with quality B (uncertainty around 10 km). Both earthquakes reached an epicentral intensity of VIII, with quality C. The energy released by the 19 March earthquake corresponds to a seismic moment M_0 of 8.43×10^{17} N.m and a moment magnitude M_w of 5.9 and the energy released by the 15 May earthquake corresponds to a seismic moment M_0 of 6.31×10^{17} N.m and a moment magnitude M_w of 5.8.

Table 1: Catalogue for the seismic sequence of 1427. The table gives date and time of the earthquake, epicentre (name of the epicentral area, latitude, longitude), quality of epicentre, epicentral intensity (Io) (EMS-98) and quality assigned.

Date	Time	Epicentre			Q_Ep	Io	Q_Io
		Region	Latitude N	Longitude E			
1427.02.F		Amer	42° 02'	2° 35'	C	<IV	C
1427.03.02	21h	Amer	42° 02'	2° 35'	C	V	C
1427.03.03	1-2h	Amer	42° 02'	2° 35'	C	V	C
1427.03.13	11h	Amer	42° 02'	2° 35'	C	VI-VII	C
1427.03.14	12h	Amer	42° 02'	2° 35'	C	VI	C
1427.03.15	23h	Amer	42° 02'	2° 35'	B	VI	C
1427.03.19	21h	Amer- Osor	41° 59'	2° 35'	B	VIII	C
1427.03.21	12h	Amer- Osor	41° 59'	2° 35'	C	IV-V	C
1427.03.22	13h	Amer- Osor	41° 59'	2° 35'	C	IV-V	C
1427.04.13	1-24h	Lloret Salvatge	41° 59'	2° 35'	C	<IV	C
1427.04.22	22h	Lloret Salvatge	41° 59'	2° 35'	B	VI-VII	C
1427.04.23	11h	Lloret Salvatge	41° 59'	2° 35'	B	IV	C
1427.05.15	15-16h	Vall d'en Bas - Olot	42° 10'	2° 26'	B	VIII	C
05.15 - 06.04	1-24h	Vall d'en Bas - Olot	42° 10'	2° 26'	C	<IV	C
1427.06.08		Caldes de Malavella	41° 51'	2° 49'	C	V	C
1427.06.12	1-24h	Caldes de Malavella	41° 51'	2° 49'	C	<VI	C
1427.06.14	8h	Caldes de Malavella	41° 51'	2° 49'	C	VII	C
06.15 - 08.31		Caldes de Malavella	41° 51'	2° 49'	C	<V	C
1427.12.25		?	?	?		?	

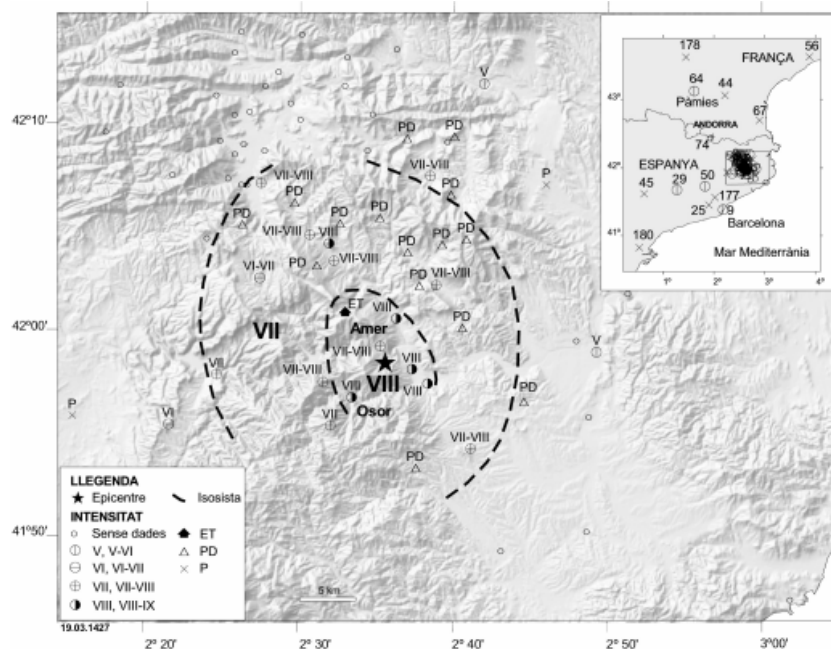


Figure 4: Intensity map (EMS-98), epicentre and isoseimal lines for the earthquake of 19 March 1427 (left) and for the earthquake of 15 May 1427 (right). Open circles depict the localities lacking in data for the seismic sequence of 1427. P= perception, PD= probable damage, ET= effects on terrain (landslides, mass movements, fissures, etc....).

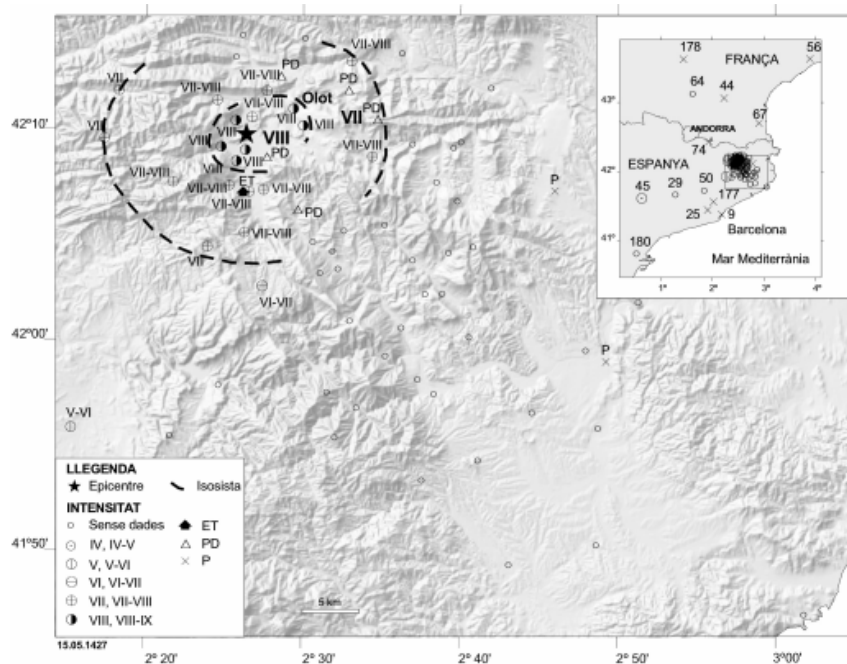


Figure 5: Intensity map (EMS-98), epicentre and isoseimal for the earthquake of 15 May 1427. Open circles depict the localities lacking in data for the seismic sequence of 1427. P=perception, PD=probable damage, ET= effects on terrain (landslides, mass movements, fissures, etc...)

3.3. Earthquake of 2 February 1428

The earthquake of 2 February 1428 wrought heavy destruction in Catalonia and France. Taking into account the households for 1378 [Redondo, 2002] considering that inhabitants = households x 4) and the available descriptions (sometimes qualitative) the number of deaths caused by the earthquake has been estimated around 1000.

Although the results of our study do not differ greatly from those of Banda and Correig, new factors should be borne in mind when interpreting this earthquake:

- Data from some French localities were incorporated (figure 6). A review and analysis of the records from the French archives [Lambert, 1993] led to the exclusion of some towns, i.e. Bordeaux, Clayra, Libourne, Montpellier and Le Puy, which had been included in earlier studies. This is an important finding when evaluating the extension of the area of perception, which did not affect more than 300 km. Cadiot [1979], proposed an epicentral intensity of X-XI, basing himself on a larger area of perception.
- The previous destructive effects caused by the earthquake of 1427 in some localities were considered. Given that the epicentral zones of the earthquake of 1427 and that of 1428 do not coincide, it is possible to evaluate the epicentral intensities independently. By contrast, for certain localities devastated in March 1427 (vall d'Amer and vall d'en Bas) and those affected by the earthquake on 15 May 1427 (vall d'en Bas, Olot ...) the descriptions record the accumulated effects of the earthquakes of 1427 and 1428. Some of these localities have not assigned intensity values because of the impossibility of discriminating between the effects of the different earthquakes. Only destruction or probable damage is indicated in such cases.

This is the first time that a rigorous review of an important set of the contemporary accounts of the earthquake of 1428 has been carried out. It is also the first time that an interpretation of this earthquake has been made, bearing in mind the reappraisal of the seismic sequence of 1427 and that of the earthquake of 1448.

The studies of Cadiot [1979] and Banda and Correig [1984] propose an epicentral area for the 1428 earthquake between Puigcerdà and Camprodon. The two localities were assigned the same intensity value, X-XI according to Cadiot, and IX-X according to Banda and Correig. An accurate analysis of the records shows that the destruction was more widespread at Camprodon (I=IX) than at Puigcerdà (I=VIII) (figure 7). Accordingly, we assign an epicentral intensity of IX (EMS-98) with quality C to the earthquake of 2 February 1428. The epicentral zone is located in the vicinity of Camprodon, 42°18'N and 2°20'E with quality B (uncertainty around 10 km). The focus of the earthquake is in the crust at a depth of about 9 km and the energy released corresponds to a seismic moment M_0 of 5.95×10^{18} N.m and a moment magnitude M_w of 6.5.

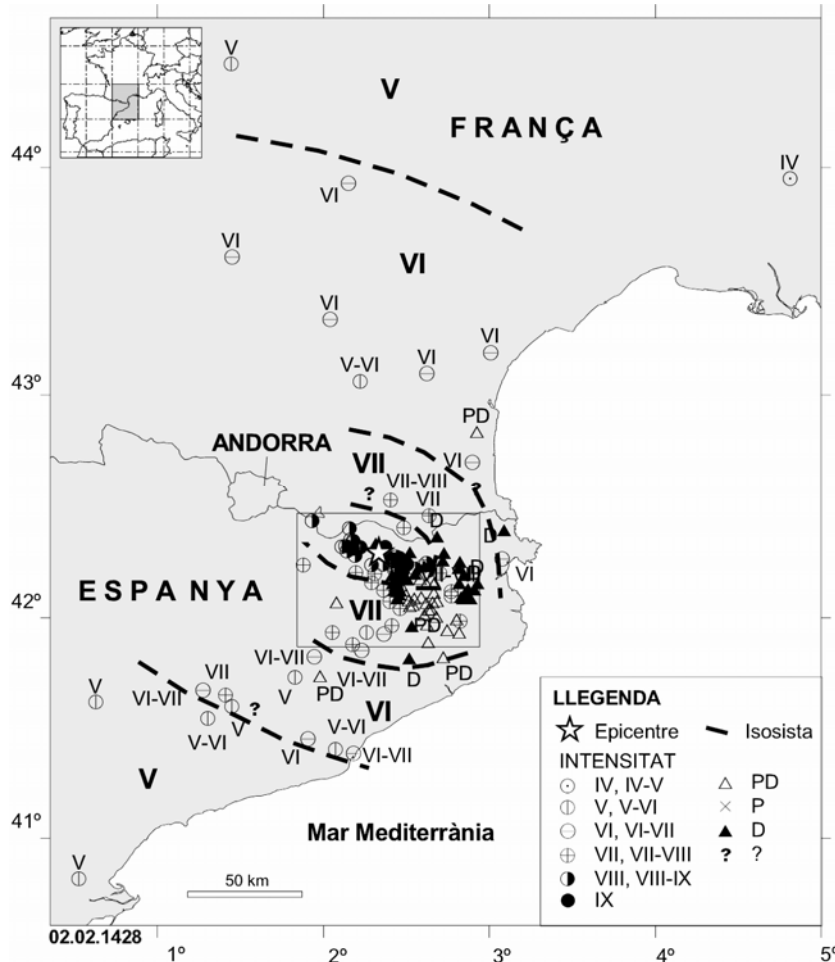


Figure 6: Intensity map (EMS-98), epicentre and isoseismal lines for the earthquake of 2 February 1428. P= perception, PD= probable damage, D= damage, ET= effects on terrain (landslides, mass movements, fissures, etc....). The dots in the rectangle are shown in figure 7

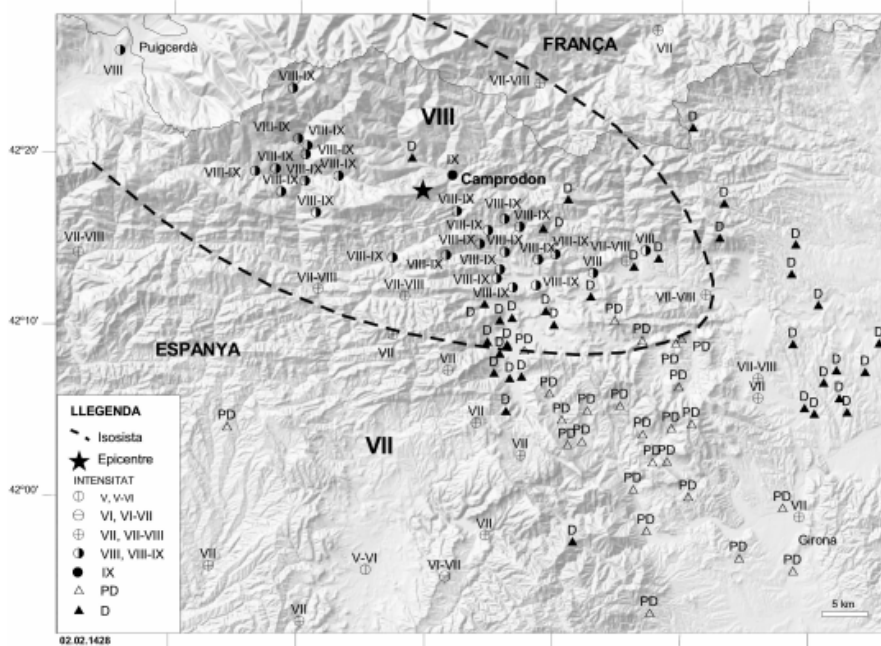


Figure 7: Epicentral area of the 2 February 1428 earthquake (rectangle in figure 6). Intensity map (EMS-98) and isoseismal line for intensity VIII. PD=probable damage, D= damage.

3.4 Earthquake of 25 May 1448

The proximity of the earthquake of 2 February 1428 to that of the event of 1448 (only 20 years earlier) probably coloured the accounts that we have of the 1448 earthquake.

This study is significant with respect to earlier ones [Salicrú, 1995] for the following reasons:

- this is the first work to assess the effects of this earthquake in terms of point intensity.
- this is the first study to take into account the destruction of earlier earthquakes (1373, 1427, 1428).
- for the first time, the assessment of the 1448 earthquake considers the extreme meteorological episodes that occurred in the months prior to the earthquake in the epicentral zone [Olivera et al., 1994].

Figure 8 gives the point intensity values. Many localities are not assigned a point intensity value because of the lack of reliable information and because of the possible effects of accumulation in the descriptions of the earthquake of 1428. The earthquake claimed 7 lives in 4 separate localities, which increases the uncertainty when evaluating the macroseismic parameters.

The earthquake took place in the proximity of Granollers with an epicentre of 41°38'N and 2°17'E with quality C (10-20 km). The epicentral intensity is assigned a value of VII-VIII (EMS-98) with quality C. The expected magnitude M_w for this earthquake is within the interval 5.3-5.8.

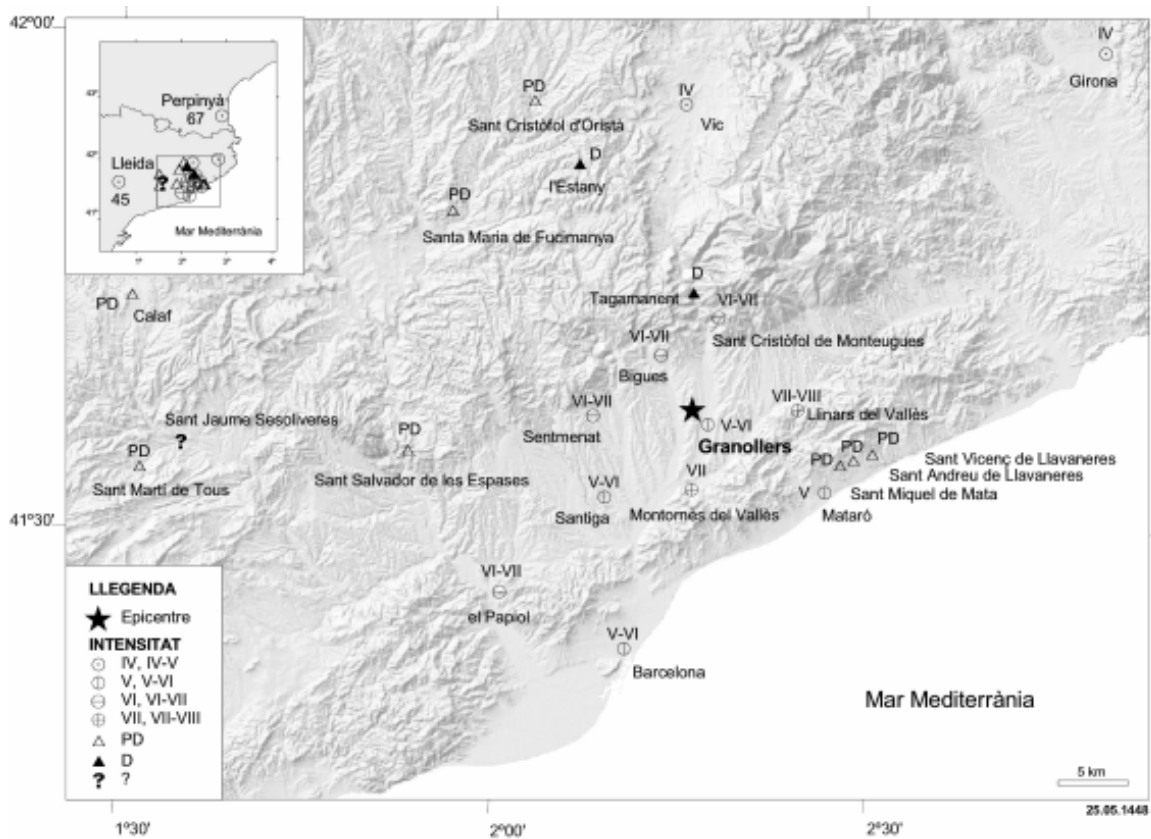


Figure 8: Intensity values (EMS-98) assigned to localities affected by the earthquake of 25 May 1448 and epicentre. PD=probable damage, D= damage

4. CONCLUSIONS

Of the earthquakes in the XIV and XV centuries, only the 8 events shown in figure 9 have epicentral intensity $I_0 > VI$ (EMS-98). The values of their parameters are given in table 2.

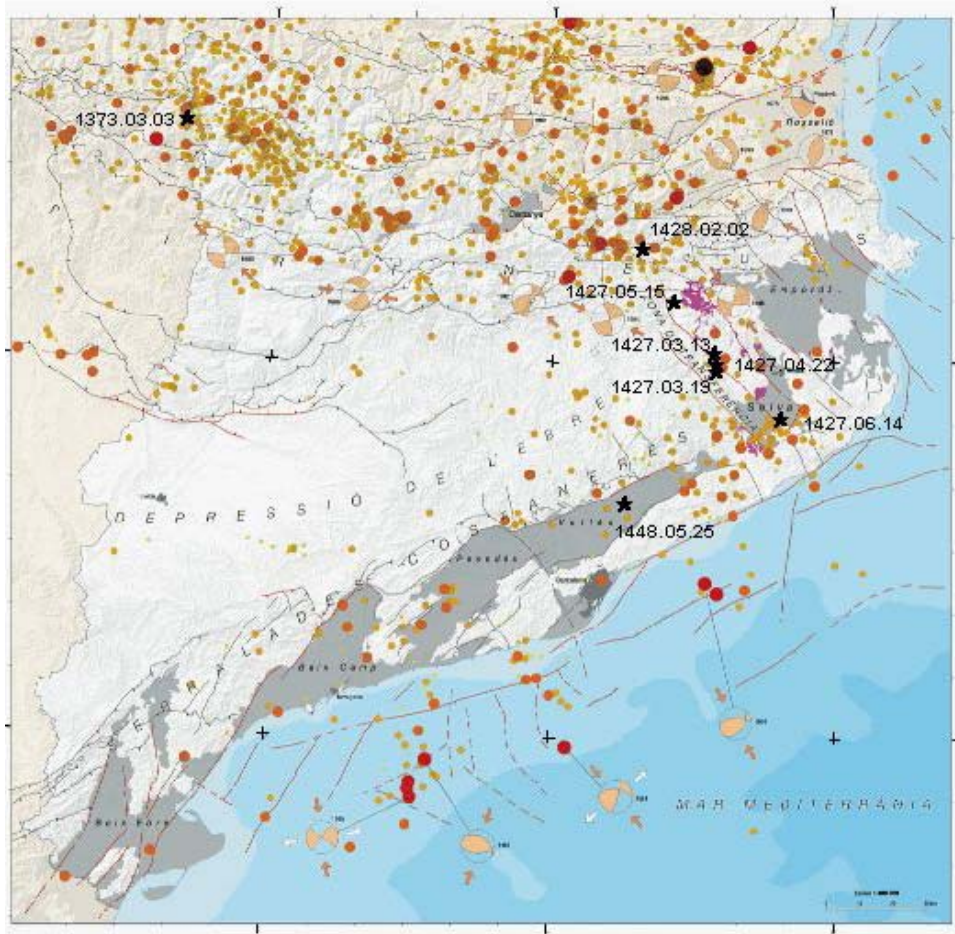


Figure 9: Epicentres for the earthquakes of the XIV and XV centuries, with $I_0 > VI$, in accordance with the results of our study. These historical events are plotted on a seismicity map for the period 1977-1997, which includes structural features of the region [ICC, 1999].

Table 2: Late medieval earthquakes with $I_0 > VI$ (EMS-98) obtained as a result of the review. Lat N= latitude north, Long E= Longitude east, Q_e = quality of epicentre, I_0 = epicentral intensity, Q_i = quality of I_0 , h = depth in km, M_w = moment magnitude, M_0 = seismic moment in N.m.

Data	Hora	Lat N	Lon E	Q_e	I_0	Q_i	h	M_w	M_0
1373.03.03	1-2	42° 38'	0° 41'	D	VIII-IX	C	15	6.2	2.56×10^{18}
1427.03.13	11	42° 02'	2° 35'	C	VI-VII	C		5.0	
1427.03.19	21	41° 59'	2° 35'	B	VIII	C	6	5.9	8.45×10^{17}
1427.04.22	22	41° 59'	2° 35'	B	VI-VII	C		5.0	
1427.05.15	15-16	42° 10'	2° 26'	B	VIII	C	<5	5.8	6.90×10^{17}
1427.06.14	12	41° 51'	2° 49'	C	VII	C		5.3	
1428.02.02	8-9	42° 18'	2° 20'	B	IX	C	9	6.5	5.50×10^{18}
1448.05.25	1	41° 38'	2° 17'	C	VII-VIII	C		5.6	

Quality C is assigned to epicentral intensity for all the earthquakes although the events of 15 May 1427 and 2 February 1428 have some less uncertainty than the others. As regards the quality of the epicentre, the most uncertain is the one of 1373. Despite the uncertainty of many aspects of the seismic sequence of 1427, the area of maximum destruction is well defined and therefore quality B is assigned to some epicentres.

Only for some earthquakes it is possible to estimate the isoseismal area and calculate the values of M_0 and M_w . In the remaining cases, the value expected for M_w is given, which is obtained from the value of maximum intensity.

The most important earthquakes of the period studied are those of 1428 and 1373 in terms of magnitude 6.5 and 6.2, and epicentral intensity IX and VIII-IX, respectively.

The two most destructive earthquakes of the sequence of 1427 are those of 19 March and 15 May; both have the same value of epicentral intensity VIII, and similar magnitudes close to 6. It should be pointed out that the accumulation of effects of all the earthquakes that occurred would be equivalent to the area of maximum destruction intensity IX.

Although the earthquake of 1428 is the most intense, its area of perception of 300 km is less than that of the earthquake of 1373, for which we have reports of 360 km. This corroborates the result that we obtained in relation to the depth: the earthquake of 1373 occurred at a depth of 16 km whereas that of 1428 took place at a depth of 9 km. It may be assumed that all the earthquakes occurred within the crust at depths of less than 20 km.

As a final remark, it can be stated that, in the area under study, there is very little likelihood of other late medieval earthquakes with $I_0 > VII$ not being included in this review.

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