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FRENCH SEISMIC CATALOGUE (FCAT - 17)

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ABSTRACT

When assessing seismic hazard in low-to-moderate seismicity regions such as metropolitan France, the use of the historical seismicity, in addition to the instrumental one, is essential. This work presents the strategy adopted to develop a parametric earthquake catalogue for Metropolitan France, covering both, the instrumental and the historical times. The works carried out in the framework of the SiHex (Cara et al., 2015) and SIGMA projects (EDF-CEA-AREVA-ENEL) are combined to produce the French seismic CATalogue (FCAT-17). The SiHex catalogue includes ~40 000 natural earthquakes, for which hypocentral location (inferred from 1D homogeneous location process and seismological observatory estimates) and Mw magnitude (assessed using either, crustal waves coda ($M_{L,LDG} \geq 4.0$) or magnitudes conversions laws ($M_{L,LDG} < 4.0$) are given. In the framework of the SIGMA research project, the assessment of the seismological parameters of historical earthquakes involved: (i) the calibration of regional Intensity Prediction Equations (IPEs); (ii) the computation of the Mw and depth of earthquakes from the SISFRANCE macroseismic database (BRGM, EDF, IRSN) using Intensity Data Points (IDPs) and the IPEs calibrated above. This computation, performed within an Exploration Tree (ET) approach, allows taking into account the main specificities of the historical earthquake macroseismic field. It also allows to propagate the uncertainties associated to the macroseismic data and to capture the epistemic uncertainties related to the IPE selection. Joint inversion of Mw and depth is performed for earthquakes that exhibit a decay of intensity with distance. On the other hand, for events presenting a poorly constrained macroseismic field (mainly old, cross border or offshore earthquakes), a priori depth needs to be set to compute Mw. Regional a priori depths are defined based on the distribution of depths computed for earthquakes with a well constrained macroseismic field. At the end, for 27% of SISFRANCE earthquakes, seismological parameters are jointly inverted, while for 73% of SISFRANCE earthquakes, Mw are computed assuming a priori depths. Finally FCAT is implemented by combining the SIGMA historical parametric catalogue from 463 to 1965 and the SiHex instrumental catalogue from 1965 to 2009. All magnitudes are expressed in Mw, which makes this catalogue directly exploitable in seismic hazard studies.

Keywords: Historical seismicity, Seismic Catalogue, Macroseismic Intensity

1 INTRODUCTION

Seismic catalogues are one of the key inputs for seismic hazard studies, as they contribute to i) seismotectonic models characterization, ii) earthquake occurrence rates and Mmax estimates and iii) Ground Motion Prediction Equations (GMPE) determination. In low to moderate seismicity regions as France, the earthquake observation time window must be extended beyond the instrumental period to allow for robust estimates of the earthquake occurrence rates. Indeed, in France the instrumental period, which started in 1962 with the deployment of the CEA-LDG seismic network, does not include major earthquakes that occurred in the pre-instrumental period, and that are decisive while performing

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seismic hazard assessment for French critical facilities.
In addition, as recent GMPEs are calibrated using Mw magnitudes, the catalogue should provide moment magnitude estimates, to avoid magnitude scale conversions which contribute to increase the uncertainties in seismic hazard assessment. During these last few years, considerable efforts have been made in France to produce a homogeneous seismic catalogue spanning from about 500 to 2009. The result of these efforts is the French seismic CATalogue (FCAT-17, Manchuel et al., 2017).
For the instrumental part, between 2009 and 2015 the SiHex project (Cara et al., 2015) produced a unified instrumental catalogue for metropolitan France providing accurate hypocenter locations and moment magnitudes for events occurred between 1962 and 2009 in metropolitan France. In general locations are obtained using a 1D velocity model. Nevertheless, more accurate locations provided by regional observatories are preferred in the final SiHex catalog for their respective regions, i.e. the French Alps, the Southernmost Alps and Mediterranean domain including Corsica, the Pyrenees and the Armorican Massif. Magnitude estimates are obtained from i) coda wave analyses for earthquakes with ML-LDG>4 (Denieul, 2014; Denieul et al., 2015) and ii) conversions from local magnitudes (Cara et al., 2017) for smaller events.
Regarding the historical seismicity period, France disposes of the SISFRANCE (EDF-IRSN-BRGM, www.sisfrance.net) macroseismic database, including ~100 000 macroseismic observations from ~6000 earthquakes, from 463 to 2007. In the framework of the SIGMA (EDF-CEA-AREVA-ENEL) research and development program, Mw magnitudes and depths have been estimated for all the events repertoried in the SISFRANCE database. The first step of this work included the calibration of Intensity Prediction Equations (IPEs), based on a set of calibration earthquakes for which we disposed of both, a well described macroseismic field and instrumental estimates of the seismological parameters (Baumont et al., BEE in press). The calibration set includes earthquakes in the French metropolitan territory (or close-by) as well as earthquakes occurred within the Italian peninsula (CPTI11 - Rovida et al., 2011). Including Italian earthquakes in the calibration set allows to overcome the strong limitation/absence of larger earthquakes in France during the instrumental period, and therefore to extend the validity domain of IPEs towards larger magnitudes. This work also takes advantage of a specific study devoted to the estimation of Mw for 15 significant early-instrumental earthquakes occurred in metropolitan France between 1905 and 1972. For these events, paper waveforms were digitized and a waveform inversion process was performed to compute moment magnitudes. The aim of this was to ensure the continuity between instrumental and historical periods and to feed the calibration of IPEs by providing significant earthquakes moment magnitudes. Once IPEs are determined, the estimation of the seismological parameters (magnitude and depth) for historical earthquakes is performed within an exploration tree (ET) framework, allowing both, to explore the epistemic uncertainties related to the choice of the IPEs and to propagate the uncertainties related to the original macroseismic information (Traversa et al., 2017).
Finally, the instrumental parametric catalogue produced by SiHex and the historical one produced by SIGMA are concatenated to produce the French seismic CATalogue –2017 version (FCAT-17) for metropolitan France. The junction between the historical and the instrumental periods is set at the year 1965, because since 1965 the seismic network is homogenously deployed along the French territory. FCAT-17 can be used as direct input for SHA studies due to its homogeneity in magnitude over the whole period. Figure 1 summarizes the interactions between SIGMA and SiHex projects to produce FCAT-17.
In this paper we will describe the procedure applied to retrieve moment magnitudes and associated uncertainties for early instrumental earthquakes. Then the work carried out to determine IPEs and to estimate moment magnitudes and depths for historical earthquakes will be briefly described. Finally FCAT-17 is processed in order to (i) determine completeness periods, (ii) obtain a declustered catalog and (iii) analyze the homogeneity of the catalog over the historical and the instrumental periods in terms of earthquake recurrence rates.

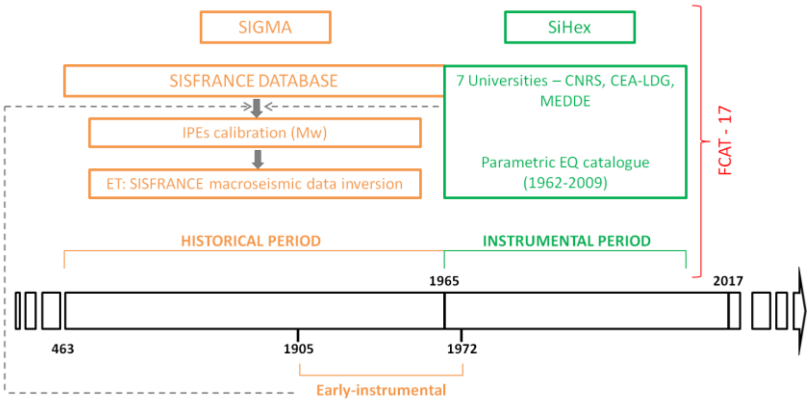

Figure 1 : Interactions between SIGMA and SiHex project to produce the FCAT-17 catalogue. SIGMA project mainly focused on the historical and early instrumental seismicity while SiHex project dealt with the instrumental period seismicity. The Sihex parametric catalogue and the early-instrumental parameter estimates are key inputs for IPEs calibration.

2 M_W OF 15 MAIN EARTHQUAKES IN METROPOLITAN FRANCE BETWEEN 1905 AND 1972

Source parameters of 15 earthquakes strongly felt in metropolitan France between1905 and 1972 have been investigated. We determined moment magnitude Mw, focal depth, and focal mechanism for each event by waveform modeling of early-instrumental seismograms.

The records were originally scanned by ING (Ferrari and Pino, 2003) for the EUROSEISMOS project. We have selected the 1-ton Wiechert records for the period between 1905 to 1964 due to the stability over time of the instrumental constants and polarities, and the WWSSN-LP between 1964 an 1972.

Information on epicenters was collected from multiple sources: (i) bulletin from International Seismological Centre (2014) and Cara et al. (1987, 2008); (ii) macroseismic epicenter locations mainly from Sisfrance (2015) but also from Amorèse (2011) for the 1926 Jersey earthquake and Alasset et al. (2005) for the 1905 Chamonix earthquake. Recent earthquakes recorded on broad-band seismometers located near these early-instrumental events were also used as proxies for checking the methodology.

Two approaches were followed: 1) grid search on the source parameters without any constraints; 2) trial and error approach by selecting a series of focal depths, mechanisms, and seismic moments.

The synthetic seismograms were computed with the version 3.30 of the code of Hermann (2004) and Green's functions corresponding to Crust-2 model averaged along the paths between the epicenters and the seismic stations. Because such a 1-D Green's function is a too simple representation of the elastic structure between the epicenters and the stations we applied a low-pass filter to both the records and the synthetics in order to obtain satisfactory fits. Doing so, crustal Love and Rayleigh waves recorded in Europe become the main source of information for our waveform analysis. As a consequence, the signal to noise ratio of our data is greatly increased but in terms of uniqueness of solutions in the space parameter, the approach gives rather poor results.

A panel of experts of the SIGMA program checked the robustness of the different source parameters issued from the waveform analysis. Together with amplitude cross-comparison with recent events, the conclusion is that the Mw estimations, made from waveform modeling is robust, within ±0.3 uncertainty, but both focal depths and focal mechanisms are poorly determined. The following table gives the acceptable range of Mw for each of the 15 earthquakes according to the conclusion of the expert panel meeting held in Paris on January 7, 2015.

Table 1: Early instrumental earthquakes. Depth and magnitude references are from bibliography. Mw and associated bounds are from this study.

EV#	Location	Origin Time	Lat. [°]	Lon. [°]	h ref. [km]	[1]I_{EPC}	Ref. Mag.	[15]M_S	This study		
									Mw min	Mw	Mw max
1	Chamonix, France	[1]1905/04/29 01:49:15	[1]46.00	7.00	[2]11	7.5	[9]5.5M_W	5.7	**5.1**	**5.4**	**5.7**
2	Lambesc, France	[1]1909/06/11 21:05:00	[1]43.65	5.32	[5]6	8.5	[5]6.1M_W	6.2	**5.5**	**5.8**	**6.1**
3	Jura, Germany	[1]1911/11/16 21:26:00	[1]48.28	8.93	-	8.5	[10]6.1M_L	6.1	**5.2**	**5.5**	**5.8**
4	Viella, Spain	[3]1923/11/19 03:54:05	[1]42.50	1.00	-	8.0	[11]5.4M_L	5.4	**5.2**	**5.4**	**5.7**
5	Jersey, France/UK	[1]1926/07/30 13:19:52	[1]49.12	-2.12	-	5.5	[11]5.4M_L	5.6	**5.2**	**5.5**	**5.8**
6	Vannes, France	[3]1930/01/09 19:38:38	[4]47.61	-2.88	[4]25	7.0	[11]5.5M_L	5.5	**4.8**	**5.1**	**5.3**
7	Queyras, France	[3]1935/03/19 07:27:21	[3]44.70	6.50	-	7.0	[11]4.9M_L	5.0	**4.5**	**4.9**	**5.3**
8	Nukerke, Belgium	[3]1938/06/11 10:57:33	[3]50.77	3.63	[6]19	7.0	[12]5.6mb_{Lg}	5.8	**4.5**	**5.0**	**5.5**
9	Sion, Switzerland	[3]1946/01/25 17:31:45	[3]46.28	7.55	-	7.5	[13]5.8M_W	6.1	**5.1**	**5.6**	**5.9**
10	Quimper, France	[3]1959/01/02 05:19:39	[3]48.01	-3.93	-	7.0	[11]5.4M_L	-	**5.0**	**5.4**	**5.7**
11	Guillestre, France	[3]1959/04/05 10:47:01	[3]44.62	6.85	-	7.5	[11]5.5M_L	-	**5.0**	**5.2**	**5.5**
12	Vercors, France	[3]1962/04/25 04:44:58	[3]45.61	5.72	-	7.5	[11]5.3M_L	-	**5.1**	**5.4**	**5.7**
13	Ligurian, France/Italy	[3]1963/07/19 05:45:24	[3]43.42	8.12	[3]8	-	[14]6.2M	-	**5.8**	**6.0**	**6.3**
14	Arette, France	[1]1967/08/13 22:08:00	[1]43.08	-0.78	[7]3-20	8.0	[2]5.1M_W	-	**4.9**	**5.2**	**5.5**
15	Oleron, France	[1]1972/09/06 22:26:54	[1]45.75	-1.22	[8]10	7.0	[11]5.2M_L	-	**5.0**	**5.2**	**5.5**

[1]Macroseismic data from SisFrance (2014), [2]Alasset (2005), [3]ISS Catalogue (Villaseñor et al., 1997); [4]IPGS Annual Report 1930 by Rothe (1931); [5]Baroux et al. (2003); [6]Earthquake report from ORB (2006); [7]Rothe (1967); [8]Mazabraud et al. (2013); [9]Cara et al. 2008 after Alasset (2005); [10] cited by Grüntal and Wahlström (2003); [11]Massinon B. (1979); [12]Camelbeeck (1993); [13]ECOS-09 (2014) Catalogue; [14]Bossolasco et al. (1965); [15]Karnik (1969).

3 INTENSITY PREDICTIVE EQUATIONS (IPEs)

3.1 Calibration earthquakes

As described in Baumont et al. (BEE, in press), the calibration events were selected among the earthquakes for which we dispose of both, a well described macroseismic field and reliable magnitude estimates. The calibration dataset includes 30 events well distributed among the main seismic areas in France or in immediately neighboring zones, with Mw ranging from 3.6 to 5.8. Note that epicentral locations are defined according to the SisFrance database.

Given that this calibration set only includes moderate size earthquakes, Baumont et al (BEE, in press) expanded the dataset with Italian earthquakes of larger magnitude. 11 earthquakes with Mw ≥ 6 occurred within the Italian territory since 1900 were added to the initial set. The macroseismic data are from the DBIM11 database (Locati et al., 2011) and the parametric information from the CPTI11 (Rovida et al., 2011). A comparison with the isoseismal radii derived from the new DBMI15 was performed a posteriori, showing that the calibration results are not affected by the original database. In order, to avoid introducing biases related to the differences in terms of intensity scales (MSK versus MCS), only intensities smaller than or equal to VII were considered (Traversa et al., 2014).

Mw and depth metadata were defined according to the available information in published literature, catalogues and specific works as the one described above on early instrumental earthquakes. A technical committee composed of 5 experts was then charged to assign preferred magnitude values, as well as min and max values. The preferred magnitude value finally retained for the IPE calibration phase is the median of the preferred individual expert opinions. The minimum (maximum) value also corresponds to the median value of the individual minimum (maximum) estimates. Depth estimates (preferred, min and max values) were defined based on the review of the instrumental estimates (when available) as well as on the comparison of these values with the estimates obtained applying a

Kövesligethy (1907) and Sponheuer (1960) models on the macroseismic data, similarly to the approach of Ambraseys (1985) or Levret et al. (1994).
To better capture the epistemic uncertainties related to the selection of the set of earthquakes to be used in the IPE calibration phase, several regressions were run using different subsets of the full original calibration set, satisfying different levels of exigency on the selection criteria. The calibration datasets tested in this way include between 27 and 41 events depending on the selection criteria applied, with Mw from 3.6 to 7.1 (Baumont et al., BEE in press and Figure 2).

3.2 Taking into account spatial variability of attenuation properties

Previous studies already highlighted the existence of significant laterally varying attenuation properties in the French and Italian crust (Bakun and Scotti, 2006; Gasperini, 2010). Recently, Mayor et al. (2017) obtained high resolution maps of attenuation of the seismic coda waves at the scale of the French metropolitan territory. According to the Mayor et al. (2017) seismic attenuation map at 1 Hz (which well correlates with intensity, e.g. Lesueur, 2011), the North-Western part of France is characterized by low attenuation of seismic waves, whereas the South and Eastern part exhibit moderate to high attenuation patterns. Bounded to the compromise between the want to take into account the lateral variability of attenuation and the need to dispose of a sufficient number of calibration earthquakes to perform robust intensity attenuation model calibration, for France we delimited two regions with different attenuation properties.
Regarding the Italian peninsula, Gasperini (2010) indicates that the crustal attenuation properties are significantly different between the region north of 43.5°, where the Po plain area is characterized by relatively low attenuation, and the region south of 43.5° where the Apennines chain and Tyrrhenian Sea are characterized by relatively high attenuation. These two regions were therefore distinguished when dealing with the Italian earthquake calibration dataset.

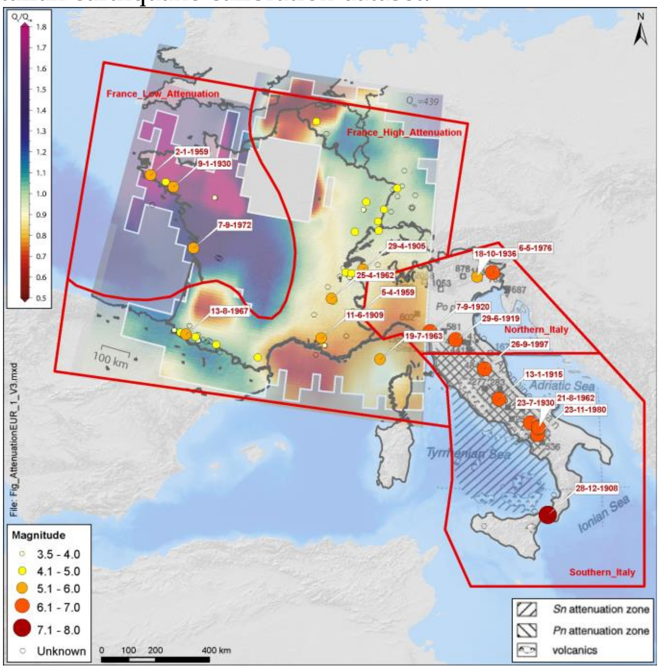

Figure 2 Regional zonation based on attenuation wave characteristics. For France, we use the Mayor et al. (2017) attenuation map at 1 Hz. For Italy, we rely on the Gasperini (2010) seismic attenuation map and apply a limit along the latitude 43.5°N. The calibration events are shown in colored symbols. The events shown as open circles correspond to events that were analyzed but not kept due to the lack of good metadata or macroseismic data.

3.3 Intensity Prediction Equations (IPE)

The attenuation of macroseismic intensity as function of the hypocentral distance and the magnitude is described according to the following formulation:

$$I_j = c_1 + c_2 \cdot M_W + \beta \cdot \log_{10}(R_j) + \gamma_{region} \cdot R_j \quad (1)$$

where I_j and $R_j = \sqrt{D_j^2 + H^2}$ are the intensity and the hypocentral radius of the j^th^ isoseismal. D_j are j^{th} the epicentral radii and H the focal depth. M_W is the moment magnitude of the earthquake and c_1, c_2, β and γ_{region} are the IPE coefficients determined by Baumont et al. (BEE, in press). As it will be explained later, the isoseismals are defined according to several complementary metrics or indicators (i.e. R_{AVG}, R_{OBS}, R_{P50}, R_{P84}, R_{F50} or R_{F84}).
As shown by Baumont et al. (BEE, in press), the IPEs resulting from the regression on the macroseismic data is pretty sensitive to both, the chosen parametrization and the calibration dataset. As a consequence, choosing a single (best) IPE to be used in the estimate of the seismological parameters for historical earthquakes clearly appears not reasonable. On the other hand, the use of a set of models looks as a rational way to overcome this limitation. The results of both, residual analysis and goodness of fit evaluation procedures performed by Baumont et al. (BEE, in press) on the whole set of IPEs they propose, guided Traversa et al. (2017) in the selection of the subset of IPEs that are the most appropriate to be used in the estimation of the seismological parameters of historical earthquakes in metropolitan France.

4 COMPUTING M_W AND H FOR FRENCH HISTORICAL EARTHQUAKES

4.1 Macroseismic Data and Processing

In France, the SisFrance database is jointly implemented by BRGM, EDF and IRSN (www.sisfrance.net) since the sixties. For each earthquake, the database provides information on the epicentral location, the epicentral intensity as well as the estimates of the effects induced by the earthquake at various localities (IDPs – Intensity Data Points), expressed in steps of half intensity values according to the MSK 1964 intensity scale. Each IDP is associated to a quality factor that is representative of the level of confidence associated with the numerical estimate (quality A: certain intensity, quality B: fairly certain intensity, quality C: uncertain intensity). A quality factor is also associated to the epicentral intensity value (quality A: certain epicentral intensity; quality B: fairly certain epicentral intensity; quality C: uncertain epicentral intensity, quality E: arbitrary epicentral intensity; quality K: fairly certain epicentral intensity, resulting from a calculation based on an attenuation law). Finally, the SisFrance database provides quality factors associated to the epicentral location (quality A: exact location (a few km); quality B: fairly certain location (around 10 km); quality C: imprecise location (between 10 and 20 km); quality D: strongly assumed location (from a few km to 50 km); quality E: arbitrary location).
With the aim of computing the seismological parameters for historical earthquakes in France, the macroseismic data undergoes the processing chain described in the following sections.

4.1.1 Processing of SisFrance macroseismic intensity data

Consistently to the procedure adopted in Baumont et al. (BEE, accepted), six different intensity binning strategies are applied to obtain isoseismal radii. The aim of this is to obtain six different representations of the available data. The following six metrics are defined:
(i) R_{AVG}, corresponding to the weighted barycenter of the IDPs within a given class of intensity (i.e. for the considered intensity class, the isoseismal radius is taken as the weighted mean of the $\log_{10}$ IDP hypocentral distances, and the corresponding intensity is the weighted mean of IDP intensity values). The width of the intensity class is fixed to 1.0 MSK. In the mean computation, the weight assigned to each IDP is function of the SisFrance quality factor associated to it ($W_{QA} = 4$, $W_{QB} = 3$ and $W_{QC} = 2$ for A, B and C qualities, respectively. When used, a weight $W_{QD} = 1$ is assigned to quantified felt testimonies). The uncertainty associated to each R_{AVG} isoseismal radius is defined as the weighted standard deviation of the considered IDPs;
(ii) The R_{OBS} metric is identical to the R_{AVG} but using an intensity bin width equal to zero;
(iii) The R_{P50} metric is analogue to R_{OBS} metric, but the weighted 50^th^ percentile (using an intensity bin width equal to zero) is considered. The uncertainties on the R_{P50} isoseismal radii are defined as the half of the difference between the percentiles 84^th^ and 16^th^ of the IDPs hypocentral distances (expressed in the $\log_{10}$ scale);
(iv) The R_{P84} metric is analogue to the R_{OBS} metric, but the weighted 84^th^ percentile (using an intensity bin width equal to zero) is considered. The uncertainties on the RP_{84} isoseismal radii are defined as the

half of the difference of the percentiles 98th and 50th of the hypocentral distances (expressed in the log scale);
(v) The R_{F50} metric (to be intended as a kind of "felt radius") is equivalent to the R_{P50} metric but, rather than describing the decay of the macroseismic intensity with respect to the distance, only the intensity bin being representative of far field reliable information is considered. To obtain this isoseismal, the W parameter is defined, as follows:

$$\boldsymbol{W_j = W_{n_j} \cdot W_{q_j} \cdot R_{P50_j}} \quad (3)$$

where j represents the j^{th} isoseismal, $W_{n_j}$is the square root of the number of IDPs in the isoseismal j, W_{q_j} is the sum of the weights associated to IDPs of isoseismal j (defined as function of the quality index assigned by SisFrance to each IDP) and R_{P50_j} is the j^{th} isoseismal radius. The isoseismal presenting the largest value of parameter W is selected as R_{F50}.
(vi) The R_{F84} metric is equivalent to the R_{F50} metric, but the 84th percentile is considered.
Finally, for all these metrics, the uncertainties associated to the isoseismals intensity values are deduced from the uncertainties on the hypocentral radii using the apparent slope β of the intensity decay with the log distance ($I = I_0 - \beta \log_{10} R/H$), measured on the isoseismal radii above completeness for each event.

4.1.2 Intensity of completeness

Basing the estimate of the earthquake seismological parameters on the decay of macroseismic data with distance relies on the hypothesis that the macroseismic dataset is complete. If such hypothesis holds for recent events down to very weak intensities, it may fail for historical events, for which weakest intensity information either has not been passed down to these days or is particularly difficult to collect. If not taken into account, these cutoffs in the data collection may introduce a bias in the inversion scheme. The following procedure has therefore been set up to identify the intensity of completeness in the macroseismic dataset of a given event, value below which the intensity data has been discarded from the inversion procedure. The lack of completeness is detected using the R_{AVG} metric by identifying the inflection point in the cumulative number of observations per intensity bin, defined as the point where the second derivative of the cumulative number of observations as function of the intensity bin value changes sign. The intensity of completeness (IC) is therefore the intensity value corresponding to the inflection point.

4.1.3 Treatment of felt testimonies

In case of either, earthquakes disposing of less than 50 intensity data points, or earthquakes for which the proportion of felt testimonies is larger than 10% of the total number of observations, we assign a quantitative intensity value to the available "felt" testimonies depending on the epoch they derive from. Following the statistical analysis described by Traversa et al (2017) we apply:

- Earthquakes occurred starting from 1980: I_{felt} = II MSK;
- Earthquakes occurred during the period [1875 – 1980[: I_{felt} = III MSK;
- Earthquakes occurred before 1875: I_{felt} = IV MSK.

The IDPs "created" in this way are assigned a quality factor D.

4.2 Exploration Tree (ET) approach

For detailed description of the earthquake datasets used to calibrate the IPEs, as well as their associated uncertainties and regional dependencies, the reader can refer to the Baumont et al. (BEE, in press) paper, and to the Traversa et al. (2017) paper for the final selection of the models used to retrieve magnitude and depth of the historical earthquakes.
In summary, a maximum of N = 4×6×6 = 144 different IPEs are retained in the calculations. As explained by Traversa et al. (2017), the Exploration Tree (ET) approach allows to deal with such a number of alternative models and to characterize the epistemic uncertainty related to the model selection process (i.e. the variability in the magnitude and depth estimates resulting from the fact that we do not know the "true" model that can explain the data exactly).

As mentioned before, all SisFrance earthquake macroseismic field configurations are treated following this same philosophy. However, depending on the macroseismic information we dispose of for a given earthquake, two main cases can be identified.

4.2.1 Case of several IDPs available

When several IDPs are available for a given earthquake, it is possible to build isoseismal radii according to the six metrics described above. In this case, magnitude and depth are simultaneously computed through a maximum likelihood inversion scheme based on a weighted least squares (WLSQ) criterion (Tarantola, 2005). The following subcases are identified:

- Earthquakes located within the French territory. In this case, the macroseismic data is generally sufficiently well distributed in both, the near and the far field. In this case, a simultaneous inversion of magnitude and depth is performed for each selected IPE (i.e. 144 models), resulting in 144 individual couples (Mi, Hi) allowing the different models to explain the decay of the intensity with distance, as well as the epicentral intensity value;
- Earthquakes located either, offshore or outside the French boundaries. In these cases, the macroseismic field provided by SisFrance is generally poorly described in the near field, with very few (if any) IDPs in the epicentral area. In these cases all selected IPEs are still used, but only the RF50 and RF84 metrics are retained. Indeed, since the near field information for these types of earthquakes is either, nonexistent or strongly incomplete, we believe that restricting the inversion scheme to metrics representative of the earthquake effects in the far field allows keeping only unbiased isoseismals in the computation. Again, simultaneous inversion of individual magnitude and depth couples is performed, resulting in 48 individual couples (Mi, Hi) allowing the different models to explain the far-field macroseismic information, as well as the epicentral intensity value;

4.2.2 Case of single/sporadic (if any) intensity observations available

Case of single/sporadic (if any) intensity observations available. This is unfortunately the case for the majority of SisFrance earthquakes. Two subcases can still be distinguished:

- When the epicentral intensity value is known, but isolated or sporadic IDPs available, the depth is fixed a priori (following the Manchuel et al., 2017 zonation for depth) and 144 individual magnitudes (Mi) are computed for the considered earthquake using the selected IPEs, the a priori depth and the epicentral intensity value.
- Unknown epicentral intensity value. This is generally the case of extremely poorly known earthquakes, for which we dispose of several felt testimonies, but the associated information and the descriptions of the effects induced by the earthquake are not sufficient to assign a quantitative value to any data point (i.e. absence of quantified IDP). Nonetheless, based on expert judgment, SisFrance provides an epicenter location for these earthquakes. Following the methodology illustrated in section 4.1.3, an intensity value is assigned to "felt" testimonies, based on the year they derive from. We therefore dispose of a "felt intensity value" and a "felt radius", this latter being defined as the mean hypocentral distance of felt testimony locations. The depth is fixed a priori similarly to the previous case and 144 individual magnitudes (Mi) are computed using the selected IPEs.

4.2.3 Treatment of uncertainties

In addition to the M_W and depth uncertainties related to the macroseismic data and modelization uncertainties, dealt with within individual joint inversions of these parameters, the ET approach also allows to take into account the epistemic uncertainty related to the choice of the IPE(s) to be used in the computations. Indeed, an operator can consider several different IPEs, each of them representing a branch of the ET.
Finally, for 27% of SISFRANCE earthquakes, seismological parameters are jointly inverted, while for 73% of SISFRANCE earthquakes, the depth is fixed a priori and the magnitude computed accordingly (Manchuel et al., 2017).

5 FCAT-17 CATALOGUE

As described above, FCAT-17 combines the historical parametric catalogue implemented following

the strategy described above (Baumont et al., BEE in press; Traversa et al., 2017; Manchuel et al., 2017) with the instrumental parametric catalogue implemented by SiHex (Cara et al., 2015). The junction between the two periods is set at the year 1965, because since 1965 the seismic network is homogenously deployed along the French territory, and therefore earthquake location and parameter estimates can be considered stable.
The final catalog includes 41658 earthquakes from 463 to 2009 and is represented on Figure 3.

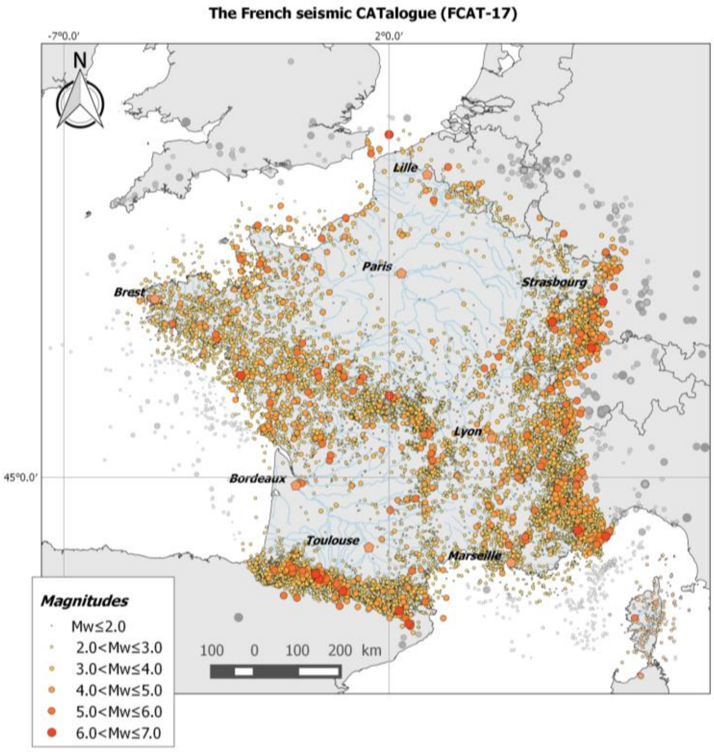

Figure 3 The French seismic CATalogue (FCAT-17). Size and color of circles are defined according to magnitude values. Grey circles are earthquakes located outside France plus a buffer of 40 km, which are not included in the provided FCAT-17 catalogue (Manchuel et al., 2017).

6 CATALOG PROCESSING

The main objective of FCAT-17 is to be used in seismic hazard assessment studies, whose basic step is the determination of earthquake occurrence rates. To compute activity rates, one needs to estimate completeness periods which correspond to dates after which all events of a given magnitude range are detected and included in the seismic catalogue. Keeping in mind that the basic hypothesis of a classic PSHA rely on the time independency of the seismic activity (i.e. earthquake occurrence should follow a Poisson process), the catalog has to be declustered before being used.

6.1 Earthquake completeness analysis

The exhaustiveness periods of a catalogue (as function of magnitude) can be determined following different approaches. For the historical period, earthquakes are identified in written reports (newspaper, church archives…) which compile testimonies of observed effects of earthquakes on people and buildings. Then, for the historical period, the catalog completeness is likely to be related to population density, literacy rate, archive preservation etc. On the other hand, for the instrumental period, completeness is related to the deployment of seismic networks, but spatial variations also exist since offshore events have less probability of being recorded on seismographic stations, especially for small events. Due to these spatial and temporal heterogeneities, the completeness analysis should be carried out individually in each seismotectonic zone. However, the moderate character of the seismic activity in metropolitan France and the scarcity of earthquakes in a large portion of the territory prevent us from performing such an analysis. Completeness periods are then determined for two large domains: one assembling together the zones that were traditionally scarcely populated and consequently have short completeness (i.e. the mountainous and marine zones) and the other representative of more populated zones (i.e. the continental areas). Figure 4 (left panel) illustrates these domains for the French territory, with FCAT earthquakes associated: in red continental France domain earthquakes and in blue mountain-marine domain earthquakes.

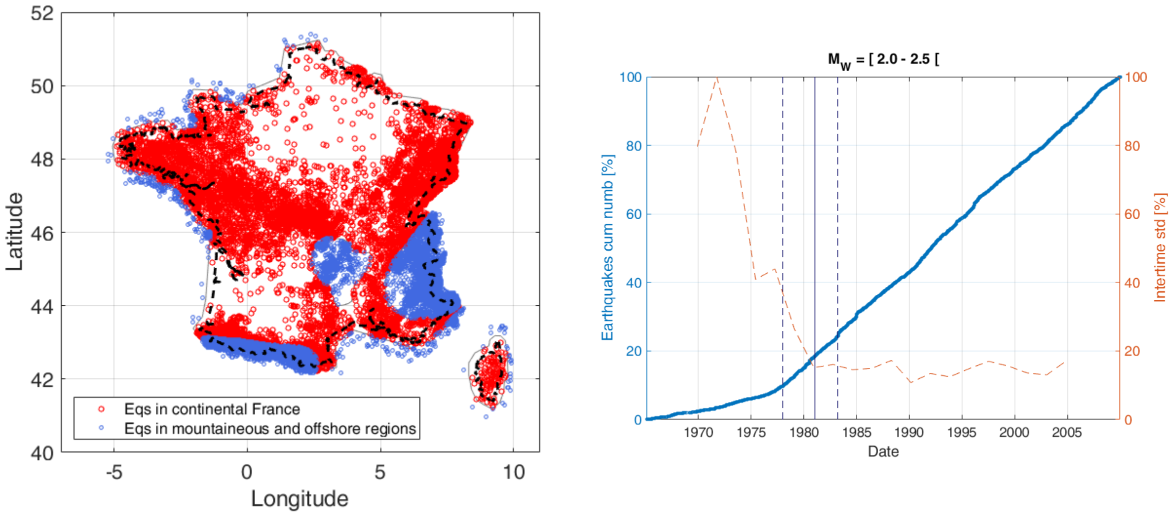

Figure 4. Left : Earthquakes in FCAT catalogue as function of the domains described in the text for the completeness analysis; Right: example of completeness period determination for the magnitude bin Mw 2 to 2.5 in the continental France domain.

The most common approach is to determine completeness periods visually by representing the number of earthquakes as function of the time. In this paper completeness periods are manually selected based on the following criteria:

- The cumulative number of earthquakes should monotonically increase with time following the completeness year;
- Following the Hakimhashemi and Grünthal (2012) method, the inter-event time standard deviation is used as completeness parameter: the complete part of the data set starts when the deviation parameter remains;
- Completeness years are forced to increase with increasing magnitude.

Figure 4 (right panel) shows an example of completeness year determination for the magnitude bin Mw = 2.0 to 2.5. In future works, alternative approaches will be tested, such as the Muggeo (2003) or the Albarello et al. (2001) methods.
Table 2 shows the completeness periods for continental France issued from the analysis.

Table 2 Completeness periods for continental France.

LowerMw	UpperMw	Year	Min Year	Max year
1.5	2.0	2003	2000	2005
2.0	2.5	1980	1978	1983
2.5	3.0	1970	1972	1976
3.0	3.5	1965	1965	1973
3.5	4.0	1850	1800	1875
4.0	4.5	1825	1750	1850
4.5	5.0	1750	1650	1800
5.0	5.5	1634	1500	1700
5.5	7.5	1500	1400	1600

6.2 Declustering

Available declustering methods are based on different hypothesis and models of earthquake interaction in space and time. Two methods are used here: (i) the Gardner and Knopoff (1974), window-based method; and (ii) the Reasenberg (1985) cluster-based method.

Following the Gardner and Knopoff (1974) method, an earthquake close to a larger previous one in space and time is considered as the aftershock of the previous one. The distance in space and time is function of the magnitude of the mainshock.

However this method is strongly dependent on the chosen size for the spatial and temporal windows, which should be suitable for the considered catalog.

In the Reasenberg (1985) declustering approach, on the other hand, the definition of the time and space interaction zone is based on an earthquake interaction model. In a seismic sequence, the largest event is defined as the mainshock, i.e. the independent event. Although the latter method seems to carry less subjectivity than the previous one, the result is dependent on the choice on computational parameters, with a sensitivity that should be tested (e.g. van Stiphout et al., 2012).

The two approaches give different results in terms of mainshock and aftershock rates and these differences should be explored in sensitivity studies when performing seismic hazard assessment studies.

6.3 Consistency between the historical and the instrumental periods

Once the completeness has been estimated over the whole catalogue and the declustering has been performed, we can compare the earthquake recurrence rates for different zones of the French metropolitan territory.

Looking at earthquake recurrence rates within low attenuation regions such as the Armorican massive (according to the attenuation zonation presented in Figure 1), we observe some slope discontinuity/difference on the magnitude frequency distributions (Figure 5). This could be related to the fact that, for magnitudes lower than Mw 3.4, in the SiHex catalogue Mw have been obtained from local magnitudes $M_{L,LDG}$ by applying ad hoc magnitude conversion relations (Cara et al., 2015). However, contrary to the historical part of the catalogue, for which at least an approximate attenuation zoning is considered, in the instrumental part the 2D variability of attenuation is not taken into account, which could explain such differences. As already shown by Mayor et al. (2017), it could be of interest to incorporate lateral variations of attenuation when parameterizing local magnitude relations to dispose of more robust small event magnitude estimates.

7 CONCLUSIONS

In this paper we presented the overall approach set up to obtain a homogenous seismicity catalogue for metropolitan France, covering both the instrumental and the historical periods and providing Mw and depth estimates. Uncertainties associated to the seismological parameters are also provided in the catalogue. Then the catalog undergoes the necessary processing prior to any probabilistic seismic hazard assessment study, i.e. exhaustivity period determination, declustering and recurrence rate estimation. When retrieving recurrence rates, however, we observe some discontinuities/inconsistencies at smaller magnitudes when comparing magnitude frequency distributions for the historical and the instrumental period earthquakes. These might be related to the difference in account for spatial variability of seismic attenuation between the historical and instrumental parts of the catalogue. Indeed for the historical part, a compromise zoning distinguishing a lower attenuation zone in the North-Western part of the French territory from a higher attenuation zone in the rest of the territory has been used for the whole catalogue. On the other hand, for the instrumental part, the smaller magnitudes are computed by applying magnitude conversion equations from $M_{L,LDG}$ to Mw.

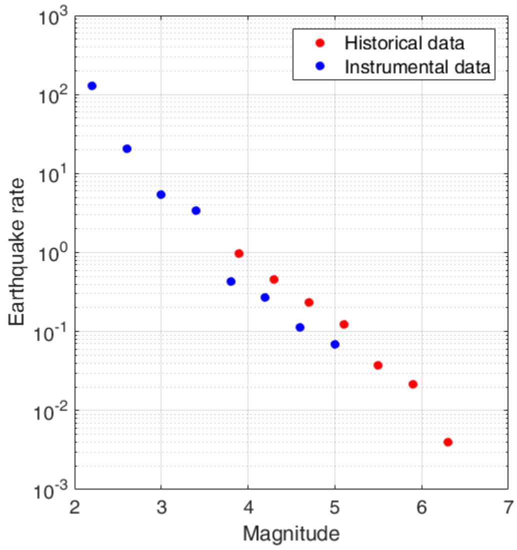

Figure 5 Recurrences for historical (red dots) and instrumental (blue dots) earthquakes

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