Supporting Information for

Seismicity patterns in southwestern France

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S1 : situation maps

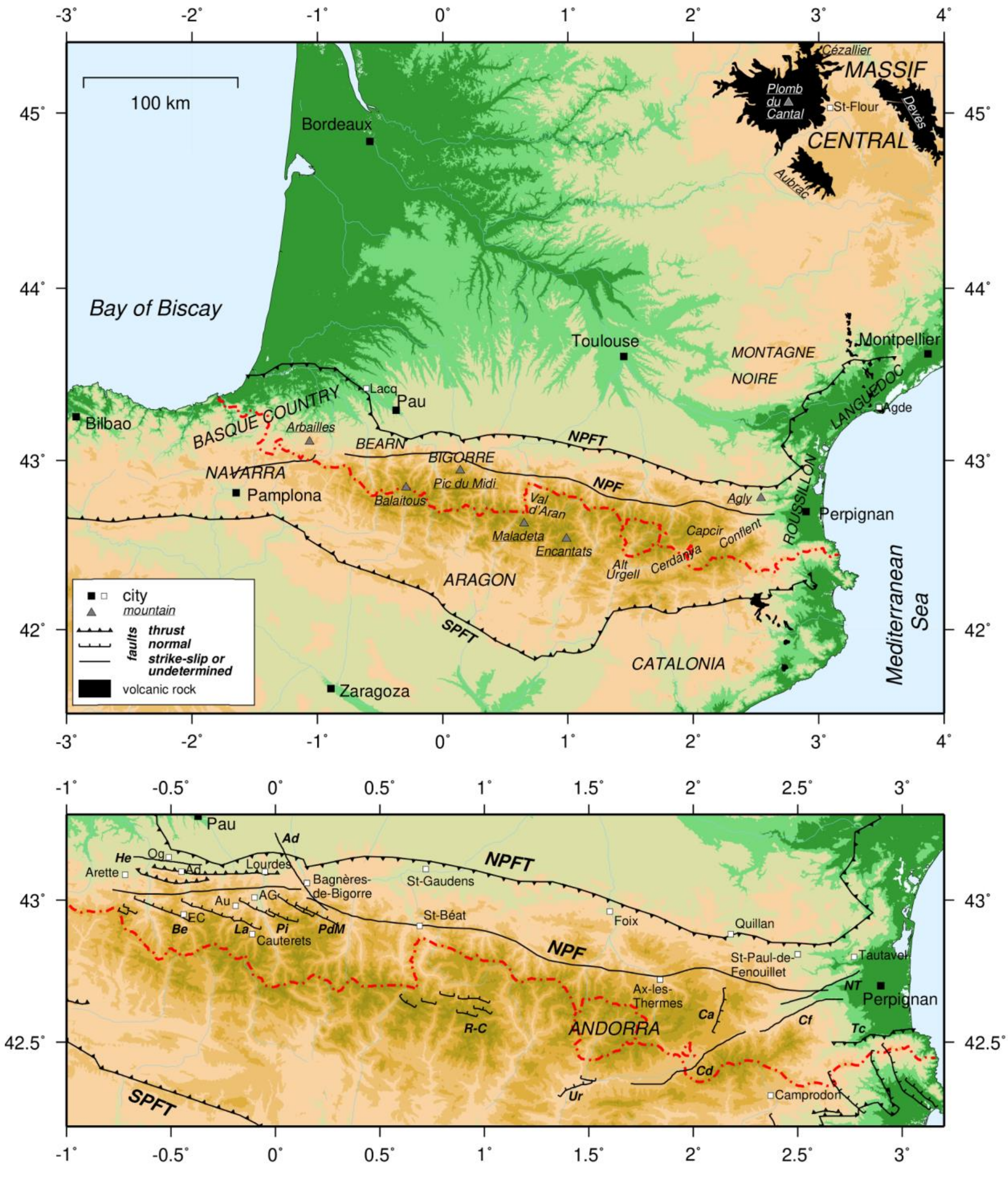

Figure S1. Maps with all the geographic units cited in the paper. Top: whole study area. Bottom: close-up on the Pyrenees. Abbreviations for cities: Ad=Arudy; AG=Argelès-Gazost; Au=Aucun; Og=Ogeu; EC=Eaux-Chaudes. Abbreviations for faults: NPF=North Pyrenean fault; NPFT=North Pyrenean frontal thrust; SPFT=South Pyrenean frontal thrust; Ad=Adour fault; Be=Bedous fault; La=Laruns fault; Pi=Pierrefitte fault; PdM=Pic du Midi fault; He=Herrère fault; R-C=Rius-Cabanes system; Ur=Urgellet graben; Ca=Capcir graben; Cd=Cerdanya fault; Cf=Conflent fault; NT=Northern Têt fault; Tc=Tech fault. Only Tertiary and Quaternary volcanoes are shown.

S2 : Example of annual magnitude regressions for year 2014

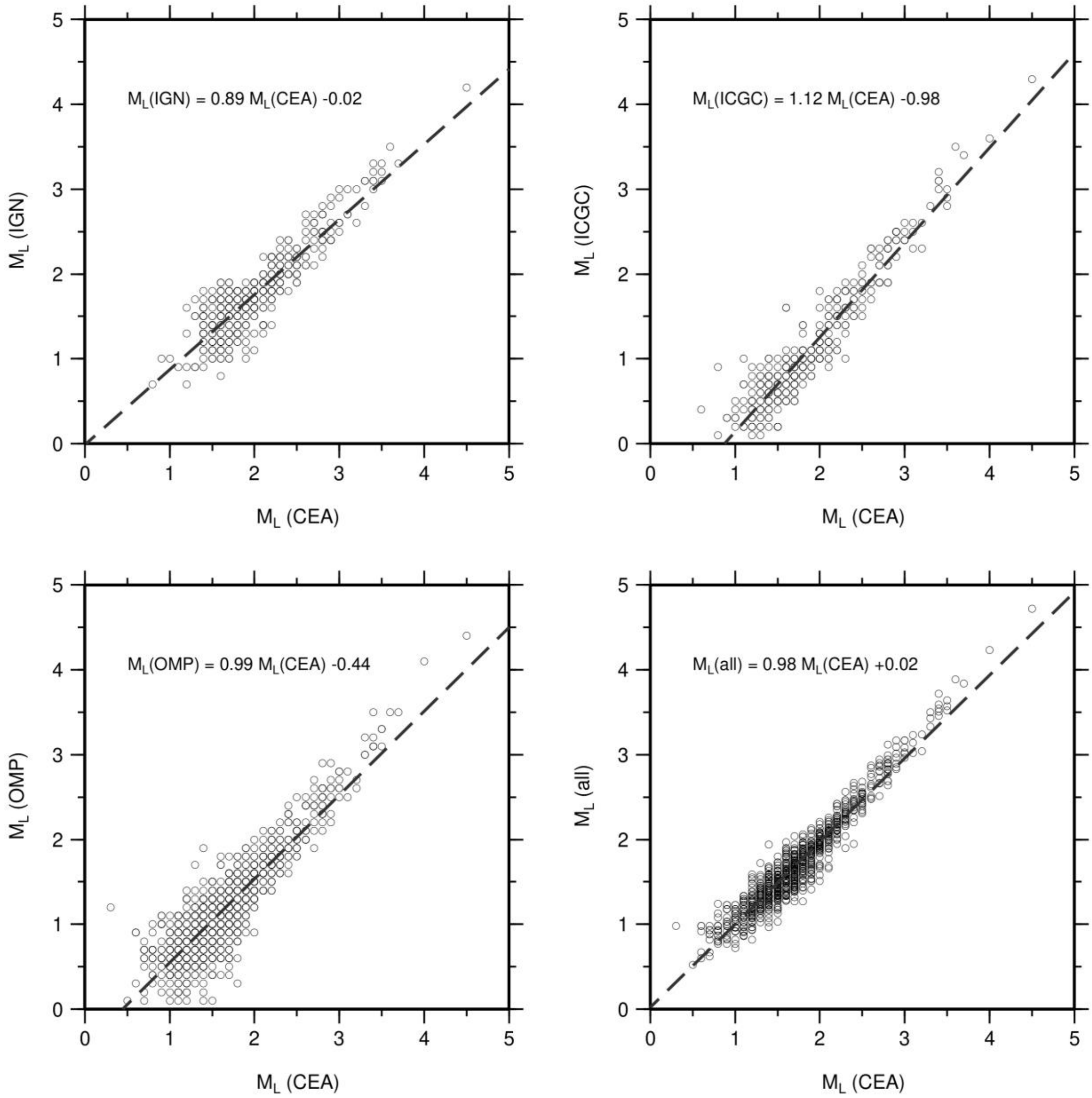

Figure S2. Annual linear regressions between individual magnitudes calculated by various institutes (IGN, ICGC, OMP) and CEA for year 2014. Bottom right : linear regression between composite magnitudes resulting from the averaging of all CEA-aligned magnitudes and genuine CEA magnitudes. All magnitudes are of the ML kind.

S3 : Monitoring history

This supplementary section aims to give a comprehensive overview of the different stages of seismic monitoring in south-western France.

Period 1: before 1970

The general beginnings of instrumental seismology date back to the end of the 19th century, with the development of the first seismometers. Near our study area, two stations were set up early in the 20th century, in Tortosa, not far from the Ebro Delta (1905), and in Barcelona (1907). To the north, the Puy de Dôme was equipped in 1906 (station moved to Clermont-Ferrand in 1913).

Seismic monitoring of south-western France did not become operational until the second half of the 20th century, with the deployment by the Commissariat à l'Energie Atomique (CEA) of a network of seismological stations on the French territory (Duverger et al., 2020). Although it was originally designed to monitor worldwide nuclear tests, the presence of several of these stations in and near the Aquitaine basin in the early 1960s made it possible to locate the strongest earthquakes with a precision of about twenty kilometers. At the same time, the Observatoire du Pic du Midi et de Toulouse (OPMT), ancestor of the current Observatoire Midi-Pyrénées (OMP), set up a station at Bagnères de Bigorre (Hautes-Pyrénées, 1960), and the Institut de Physique du Globe de Paris (IPGP) another one at Moulis (Ariège, 1963).

On the Spanish side, the Instituto Geografico Nacional (IGN), in charge of seismic monitoring at the federal level, installed half a dozen stations on its territory, including one not far from the Pyrenees, in Logroño (1963).

Period 2: 1970-1985

At the end of the 1970s, the CEA launched 4 new stations covering the whole of south-western France. The IPGP, for its part, set up between 1978 and 1984 a very localized network of 9 stations in Béarn, around the region of Arette, the site of a destructive earthquake in 1967. This network passed under the responsibility of the OMP in 1992, then was progressively dismantled. The Arette network provided high-quality recordings throughout its period of operation (1978-1998), recording in particular the Arudy seismic crisis of February 1980 (Gagnepain et al., 1980; Gagnepain-Beyneix, 1985; Gagnepain-Beyneix et al., 1982).

In the Massif Central, a monitoring network with hertzian transmissions was deployed in the 1980s by the Observatoire de Physique du Globe de Clermont-Ferrand (OPGC). In 1986, it was made up of 7 stations, integrated into the National Seismic Monitoring Network (RéNaSS).

Period 3: 1985 - 2000

From the second half of the 1980s, with the progress of digital recording technologies, network deployments accelerated:

- In Catalonia, the Servei Geologic de Catalunya (SGC, now part of the Institut Cartografic i Geologic de Catalunya, or ICGC) deployed a network of 11 stations between 1985 and 1995; other Catalonian institutions set up 4 more ;
- in Spain, the IGN densified its federal network, with 6 additional stations in and around the Pyrenean area between 1986 and 1992 ;
- In France, the CEA installed three new stations in the Pyrenees in 1996;
- In the eastern half of the French Pyrenees, the OMP deployed between 1988 and 1991 a network of 10 stations (including one in Andorra), affiliated to the RéNaSS. The OMP also took over responsibility for the Arette network.

  Part of the SGC and OMP stations then used a common data transmission technology via the Meteosat satellite. Exchanges of parametric data (locations, magnitudes, seismic wave arrival times) also began to emerge between SGC and OMP. A common seismicity bulletin was thus set up for a few years, on the eastern part of the Pyrenees. This common bulletin stopped when the OMP was entrusted with the monitoring of the whole French Pyrenees, at the end of the 1990s.

Period 4: 2000-2010

The two networks managed by OMP/RéNaSS in the Pyrenees (Arette and East-Pyrenees) were merged and redeployed between 1997 and 2002 to form a homogeneous mesh on the entire French side of the chain. These stations were equipped with three-component short-period velocimetric sensors, operated in triggered mode. This network is also known as Réseau de Surveillance Sismique des Pyrénées (RSSP).

On the Catalan side (ICGC), a rejuvenation was completely carried out between 1999 and 2007, resulting in a very dense and modern network of 20 stations, all equipped with broadband velocimetric sensors, continuous record and real-time satellite transmissions. The CEA and IGN stations followed a similar path to the ICGC, with the majority of their stations moving to continuous recording/real-time satellite transmission in the early 2000s. However, the density of stations remained low in the Pyrenean massif, outside Catalonia.

From the beginning of the 2000s, a network of permanent accelerometric stations (RAP) was gradually set up in all seismically active zones in France. In the Pyrenees, about twenty stations were installed, half of them entrusted to BRGM and half to OMP. In the Massif Central, OPGC installed 8 stations between 2003 and 2006. In parallel with the deployment of the RAP, accelerometric stations were also being installed in Spain, at the instigation of IGN and ICGC. All in all, about fifteen stations were set up between 1995 and 2008, most of them in Catalonia. If they were much less sensitive than the velocimetric stations, their contribution could be very interesting in some areas.

Period 5: 2010-2020

In 2008, at the initiative of OMP and ICGC, a project to improve cross-border seismic monitoring was launched on both sides of the Pyrenees (SISPyr: http://www.sispyr.eu). Between 2008 and 2013, it initiated the modernization of the French seismological stations (velocimetric and accelerometric), as well as the deployment of new stations on the French side. Short-period velocimeters were replaced by broadband sensors, and digitizers were upgraded to continuously record and transmit their signals in real time.

Several stations were thus created, mainly in the Pyrenees, but also in the north of the Aquitaine basin. This evolution prefigured the generalization on the French territory of the modernization and densification of the seismological observation device, within the framework of the RESIF Research Infrastructure (Réseau Sismologique et Géodésique Français, www.resif.fr), decided in 2012, and whose construction spread over the 2014-2021 period (Vergne et al., this issue).

The Lacq gas field

At the end of the 1960s several earthquakes were felt in the vicinity of the Lacq gas field (south of Aquitaine Basin). Starting in 1974 with 4 stations, a local network was progressively deployed by IPGS (Strasbourg), and from 1979 to 1997 a total of 10 stations have been dedicated to the study of this supposed induced seismicity. In 1991, this network was extended with 5 other stations, set up by the Observatoire de Grenoble. All the stations (from Strasbourg and from Grenoble) were stopped in 1997 and for some years the local Lacq seismicity was only recorded by the regional RSSP network. Finally, from 2001 to 2006 a third local network of seven 3-component stations was deployed by the Université de Pau et des Pays de l’Adour in order to better understand the relationship between the gas field late exploitation and the observed local seismicity.

S4 : detailed statistics for the seismicity clusters

Cl	Area	lat	lon	Nt	Nt/area	<Z>	stdZ	Mmax	<N>	stdN	skewN	n1	n2	n3	nbin1	nbin2	%bin1	%bin2	nb75%	n>30
01	10.69	43.129	-1.133	137	12.8	12.6	21.3	3.0	0.34	0.95	5.52	29	12	6	11	7	8.0	5.1	46	1
02	6.72	43.145	-1.072	121	18.0	15.2	13.1	3.1	0.30	1.99	14.06	7	2	2	34	18	28.1	14.9	20	2
03	4.15	43.058	-0.826	61	14.7	6.3	6.7	3.4	0.15	0.90	10.49	10	10	4	12	11	19.7	18.0	14	2
04	76.86	43.083	-0.655	1432	18.6	8.5	17.5	4.1	3.58	2.94	1.94	49	16	8	20	19	1.4	1.3	184	0
05	128.28	43.065	-0.424	2149	16.8	6.2	11.0	4.5	5.37	5.79	3.78	34	17	8	51	44	2.4	2.0	173	0
05a	21.20	43.076	-0.454	484	22.8	6.6	14.9	3.7	1.21	1.85	3.73	34	15	9	17	15	3.5	3.1	108	0
05b	23.79	43.059	-0.352	549	23.1	6.0	6.2	4.0	1.37	2.73	8.72	15	6	2	37	30	6.7	5.5	115	0
06	34.02	43.027	-0.207	926	27.2	5.3	7.7	4.9	2.32	10.24	13.41	12	4	3	174	87	18.8	9.4	62	2
07	57.15	43.015	-0.043	1192	20.9	6.4	7.1	5.5	2.98	11.30	13.43	9	5	5	196	66	16.4	5.5	79	1
07a	17.89	43.010	-0.004	682	38.1	6.3	5.4	5.5	1.71	10.28	15.18	6	4	4	186	60	27.3	8.8	38	2
07b	5.74	43.005	-0.055	127	22.1	4.7	5.4	3.8	0.32	2.25	15.35	7	6	3	41	10	32.3	7.9	15	2
08	45.14	42.999	0.173	686	15.2	9.1	10.0	4.0	1.72	2.03	4.01	48	10	4	22	16	3.2	2.3	147	0
09	67.73	42.829	-1.399	1396	20.6	5.2	12.7	5.4	3.49	14.82	10.48	19	9	6	232	84	16.6	6.0	27	1
09a	8.01	42.853	-1.462	343	42.8	6.6	7.4	3.5	0.86	9.48	18.15	4	4	1	184	29	53.6	8.5	4	3
09b	11.57	42.829	-1.416	404	34.9	4.9	12.2	4.1	1.01	3.44	5.70	30	17	11	38	26	9.4	6.4	27	1
10	5.88	42.846	-0.267	88	15.0	4.6	0.7	3.3	0.22	1.16	10.55	16	9	5	18	7	20.5	8.0	16	3
11	5.12	42.609	0.834	84	16.4	7.5	5.6	3.9	0.21	1.50	12.18	9	4	3	23	16	27.4	19.0	11	3
12	16.58	42.592	0.890	280	16.9	6.3	9.2	3.2	0.70	2.20	11.90	25	5	4	37	11	13.2	3.9	65	1
13	6.14	42.591	1.027	103	16.8	5.8	9.2	2.7	0.26	1.01	9.27	19	7	6	15	7	14.6	6.8	32	1
14	5.01	42.545	0.983	73	14.6	7.5	6.1	3.0	0.18	0.53	3.60	54	13	13	4	3	5.5	4.1	36	0
15	24.34	42.333	1.327	1176	48.3	1.9	5.5	4.4	2.94	38.84	15.70	2	2	2	688	362	58.5	30.8	2	2
16	8.74	42.392	1.452	174	19.9	4.2	6.8	2.7	0.44	8.40	19.84	1	1	1	168	3	96.6	1.7	1	1
17	2.71	42.362	1.527	55	20.3	5.1	2.7	3.2	0.14	2.21	19.52	2	1	1	44	4	80.0	7.3	1	1
18	3.45	42.286	1.558	75	21.7	2.6	4.9	3.3	0.19	2.17	14.70	3	3	2	37	22	49.3	29.3	2	3
19	4.28	42.590	2.110	77	18.0	7.5	5.6	3.5	0.19	0.76	6.49	43	15	6	8	7	10.4	9.1	24	3
20	7.02	42.340	2.148	129	18.4	2.7	2.3	4.9	0.32	1.95	10.42	8	5	4	25	24	19.4	18.6	14	4
21	4.03	42.301	2.223	83	20.6	7.0	1.6	4.5	0.21	1.38	9.34	13	8	4	16	15	19.3	18.1	8	4
22	6.66	42.419	2.300	145	21.8	5.8	8.0	3.0	0.36	1.60	7.28	25	15	9	20	13	13.8	9.0	17	2
23	8.14	42.794	2.536	136	16.7	5.4	7.5	5.2	0.34	1.98	11.63	11	5	3	31	16	22.8	11.8	19	3

Table S4. Detailed statistics for the seismicity clusters (see main text); Cl = cluster identity; area = surface area of cluster (km²); lat, lon = position of the cluster barycenter; Nt = total number of events in the cluster; Nt/area = number of events per unit area (km^{-2}); <Z> = average (mean) depth of the events in the cluster; <stdZ> = standard deviation of depth; <Mmax> = maximum magnitude (of ML_{CEA} kind) in the cluster (1989-2019); <N> = average number of events per time window; stdN = standard deviation of this distribution; skewN = skewness of this distribution; n1 = number of bins above <N>+stdN; n2 = number of bins above <N>+2stdN; n3 = number of bins above <N>+3stdN; nbin1 = number of events in the most populated bin; nbin2 = number of events in the second most populated bin; %bin1 = proportion of events in the most populated bin; %bin1 =

proportion of events in the second most populated bin; nb75% = number of bins necessary to reach 75% of Nt; n>30 = number of bins above 30<N>