INSTITUT DE FRANCE
Académie des sciences

Comptes Rendus

Géoscience

Sciences de la Planète

Laurent Bollinger, Kristell Le Dortz, Clara Duverger, Amaury Vallage, Sylvie Marin and Yves M. Leroy

Seismic swarms in Tricastin, lower Rhône Valley (France): review of historical and instrumental seismicity and models

Supplementary material to the article available at:
<https://doi.org/10.5802/crgeos.93>

Comptes Rendus
Géoscience — Sciences de la Planète
Supplementary material to the article available at:
`https://doi.org/10.5802/crgeos.93`

Supplementary material: Seismic swarms in Tricastin, lower Rhône Valley (France): review of historical and instrumental seismicity and models

Laurent Bollinger *, [a], **Kristell Le Dortz** [a, b], **Clara Duverger** [a], **Amaury Vallage** [a], **Sylvie Marin** [a] and **Yves M. Leroy** [b]

[a] CEA, DAM, DIF, F-91297 Arpajon, France

[b] Ecole normale supérieure, Department of Geosciences, PSL Research University, Paris, France

Current address: Seister, 40 Avenue de Lascours 13400 Aubagne, France (K. Le Dortz)

E-mails: laurent.bollinger@cea.fr, laurent.bollinger@gmail.com (L. Bollinger), kristell.ledortz@seister.fr (K. Le Dortz), clara.duverger@cea.fr (C. Duverger), amaury.vallage@cea.fr (A. Vallage), sylvie.marin@cea.fr (S. Marin), leroyy@biotite.ens.fr (Y. M. Leroy)

The supplementary data material comprises 3 Tables (Table S1, S2, S3) and 3 Figures (Figures S1, S2 and S3), as well as a supplementary text illustrating the statistical test of the correlation between the seismicity and the folds.

We tested the hypothesis of a spatial correlation between the main tectonic region, affected by two distinct folds and the regional historical and instrumental seismicity. In order to base the test on the whole set of 156 historical events, even if all the epicentres cannot be determined, we decide to characterize the information on their geographical origin by their epicentral area. This area is defined as the set of observations which differ of less than 1 degree from the epicentral intensity. 57% of these epicentral areas observations are represented by a single observation for a total of 348 maximum observations. We select the observations extending from Rochemaure to Sainte-Cécile-les-Vignes from North to South, and from Saint-Montan to Vaison-la-Romaine from West to East. 90% of the maximum intensities are located at less than 12 km from the nearest fold. In order to test if the set of maximum intensities representing an earthquake can be jointly associated to one of the two folds, we define a correlation index as the number of nearest observations from one fold normalized by the total number of maximum observations for the event. The earthquake origin is then supposed associated to the fold with maximum correlation and remains undetermined when the two indexes are equal. Because every event is always associated with one fold whatever the distance, it is necessary to combine it with a distance criterion. We use the mean distance of the maximum intensities representing the earthquake. the correlation rate between the seismicity and a fold is assessed by the number of earthquakes for which the individual index suggests an association. Table S1 details the time repartition

* Corresponding author.

Supplementary Table S1. Correlation between the historical seismicity and the two folds for a distance of 10 km. Beyond the threshold r99 the hypothesis that the correlation rate is due to chance is rejected

Beginning	End	Localization	Number of events	Number of correlations	$\rho_{0.99}$	Structure
1549-01-16	1549-05-04	BASSIN DE MONTELIMAR (MONTELIMAR)	2	2	2	Donzère-Est
1610-01-02	1610-01-03	BASSIN DE MONTELIMAR (MONTELIMAR)	2	2	2	Donzère-Est
1772-06-08	1773-11-26	TRICASTIN (CLANSAYES)	27	27	23	Echavarelles
1790-01-24		TRICASTIN (TULETTE)	1	0	—	—
1852-11-20	1853-02-09	TRICASTIN (DIEULEFIT)	7	0	—	—
1859-12-06		TRICASTIN (DONZERE)	1	1	1	Donzère-Est
1872-06-20		TRICASTIN (LA GARDE-ADHEMAR)	1	1	1	Echavarelles
1873-07-14	1876-00-00	TRICASTIN (CHATEAUNEUF-DU-RHONE)	29	28	16	Donzère-Est
1897-01-27	1897-01-27	TRICASTIN (LA GARDE-ADHEMAR)	2	2	2	Echavarelles
1905-04-10		BARONNIES (VAISON-LA-ROMAINE)	1	0	—	—
1907-12-09	1907-12-09	TRICASTIN (DIEULEFIT)	2	0	—	—
1907-12-26	1908-01-10	TRICASTIN (ROUSSAS)	4	4	4	Echavarelles
1910-10-00		TRICASTIN (GRANGES-GONTARDES)	1	1	1	Echavarelles
1911-12-14		TRICASTIN (TULETTE)	1	0	—	—
1933-10-00	1936-08-02	TRICASTIN (GRANGES-GONTARDES)	71	63	57	Echavarelles
1938-04-29		TRICASTIN (LA GARDE-ADHEMAR)	1	1	1	Echavarelles
1974-05-10	1974-05-10	TRICASTIN (GRIGNAN)	2	2	2	Echavarelles
1975-02-19		BAS-VIVARAIS (BOURG-SAINT-ANDEOL)	1	0	—	—

of the correlation for the distance of 10 km accounting for the geometry of the folds and for the uncertainty on the location of the observations due to the fact that they represent intensities at the scale of the French smallest administrative unit, i.e. about 5 km. Except for the earthquakes that are not associated to the folds because they are far from them, almost all events of a same crisis have a consistent correlation with a single fold: the Echavarelles fold for the 1772–1773 and 1933–1936 crises and the Donzère fold for the 1873–1876 crisis. Despite the poor number of events in the more isolated clusters, they also seem associated with a single fold: the Donzère fold for the 1549 and 1610 earthquakes and the Echavarelles fold for the 1897, 1907 to 1910 and 1974 earthquakes.

These results suggest that each crisis could be spatially and temporally associated with a seismic activity in the vicinity of either one fold or the other. In order to test if this spatial and time correlation rate is particular, we test the hypothesis that it would be in agreement with a spatial repartition of events due to chance. This hypothesis is simulated by 10,000

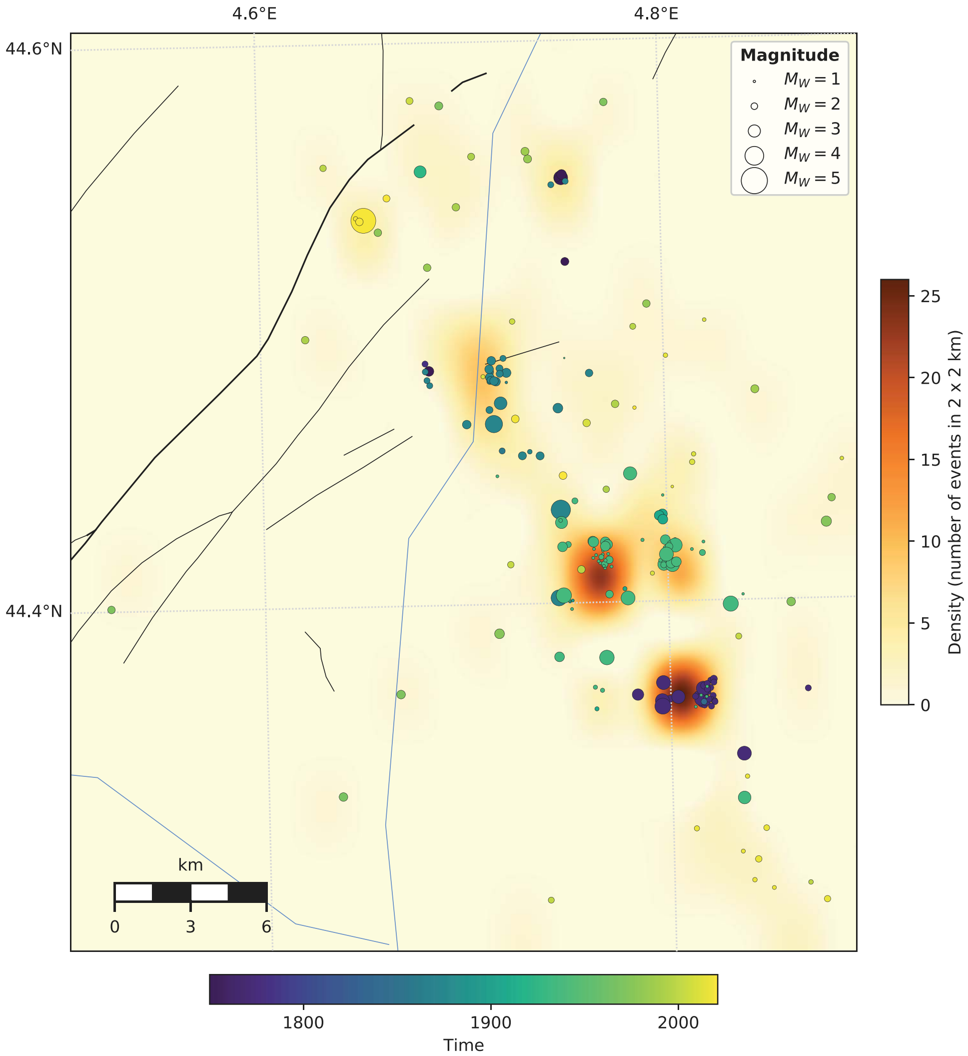
Supplementary Table S2. Correlation between the historical epicentres and the two folds for a distance of 10 km. Beyond the threshold r99 the hypothesis that the correlation rate is due to chance is rejected

Beginning	End	Localization	Number of events	Number of correlations	$\rho_{0.99}$	Structure
1773-01-23	1773-02-24	TRICASTIN (CLANSAYES)	3	3	2	Echavarelles
1852-11-20		TRICASTIN (DIEULEFIT)	1	0	—	—
1873-07-14	1873-09-04	TRICASTIN (CHATEAUNEUF-DU-RHONE)	4	4	2	Donzère-Est
1905-04-10		BARONNIES (VAISON-LA-ROMAINE)	1	0	—	—
1907-12-09		TRICASTIN (DIEULEFIT)	1	0	—	—
1911-12-14		TRICASTIN (TULETTE)	1	0	—	—
1934-05-01	1936-07-07	TRICASTIN (GRANGES-GONTARDES)	25	24	19	Echavarelles
1938-04-29		TRICASTIN (LA GARDE-ADHEMAR)	1	1	1	Echavarelles
1975-02-19		BAS-VIVARAIS (BOURG-SAINT-ANDEOL)	1	1	1	Echavarelles

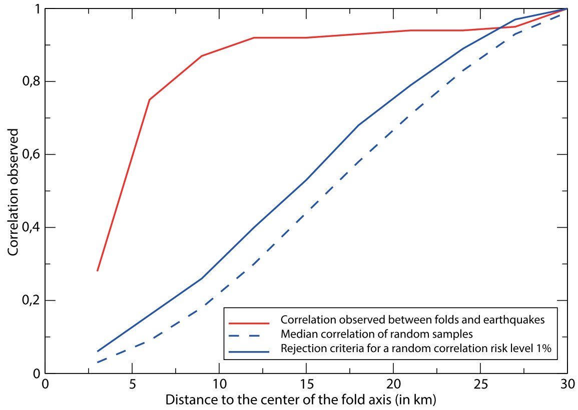
independent random catalogues of 155 earthquakes uniformly distributed in a region of 10 × 20 km and centred on the two folds. Actually, it would be difficult to draw a set of maximal intensities similar to observed intensities because their localisations are not independent, so we directly draw epicentres. The test is based on the probability value “α” of exceeding a correlation threshold “rα”, corresponding to the risk to reject the hypothesis represented by the assumed distribution (the null hypothesis), whereas it is true. The decision rule is to reject the null hypothesis if the correlation rate has a small probability to follow the assumed distribution. The significance level value “α” is subjective but usually chosen as 5% or 1%. For the three main crises, 1772–1773, 1873–1876 and 1933–1936, their spatial and time correlation rates are not due to chance (Table S1; S2; Figure S2). The poor number of events in the isolated clusters does not allow rejecting the hypothesis of a correlation due to chance.

Supplementary Table S3. Calculations of the Coulomb stress variations (ΔS) resulting from the changes in water thickness. These calculations have been done (1) on fault planes similar to the post-Oligocene fault planes observed in the field, and (2) on the preferential rupture planes deduced from the examination of the regional stress field from focal mechanisms, taking a friction coefficient of 0.6

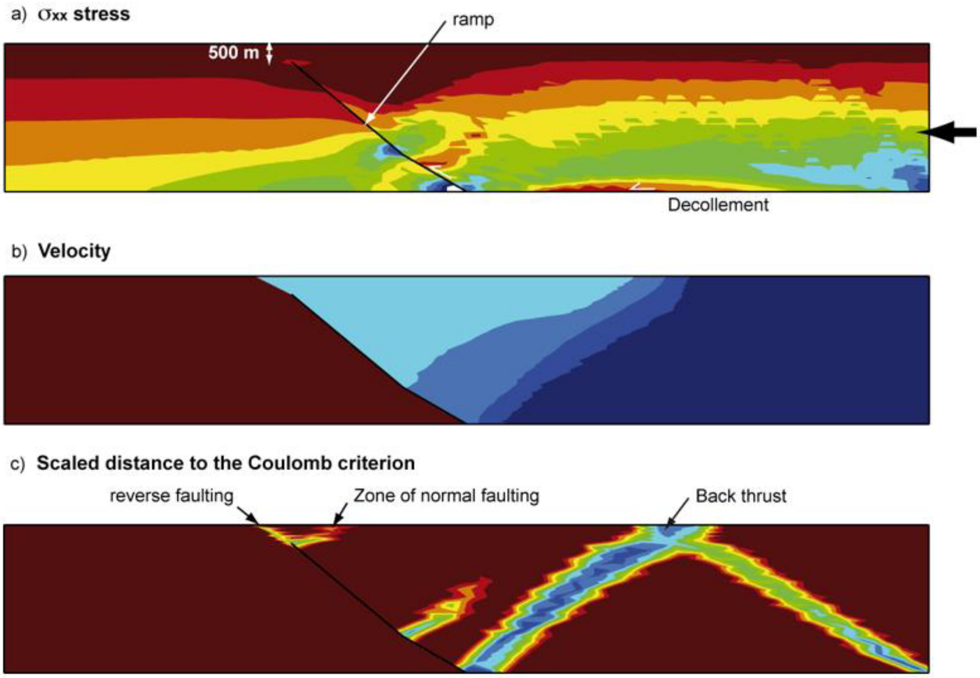
Karst	Equivalent water thickness (m)	Pression (Pa)	Karst length (km)	Karst-seismicty distance (km)	Seismicity depth (m)	Fault orientation	σ_n (Pa)	τ_n (Pa)	S (Pa)
Ardeche	0.24	2354.4	20	15	300	85° W	−16.9	−1.3	8.9
	0.36	3531.6	20	15	300	85° W	−25.4	−1.9	13.4
	0.36	3531.6	20	15	300	80° W	−24.8	−4.1	10.8
	0.36	3531.6	20	15	300	80° E	−25.0	−4.1	10.9
	0.36	3531.6	20	15	1000	85° W	−83.9	−3.4	46.9
	0.36	3531.6	20	15	1000	85° E	−85.3	−3.4	47.8
	1.00	9810.0	20	15	300	85° W	−70.6	−5.2	37.2
	1.00	9810.0	20	15	300	80° W	−68.8	−11.2	30.1
	1.00	9810.0	20	15	300	80° E	−69.5	−11.2	30.5
	1.00	9810.0	20	15	1000	85° W	−233	−9.5	130.3
	1.00	9810.0	20	15	1000	85° E	−236	−9.4	132.8
Local	0.24	2354.4	10	0.1	300	85° W	−1002	537.3	1139
	0.36	3531.6	10	0.1	300	85° W	−1503	805.9	1708
	0.36	3531.6	10	0.1	300	80° W	−1316	464.3	1253
	0.36	3531.6	10	0.1	300	80° E	−2084	1065	2316
	0.36	3531.6	10	0.1	1000	85° W	−1351	809.1	1619
	0.36	3531.6	10	0.1	1000	85° E	−1737	1115	2157
	1.00	9810.0	10	0.1	300	85° W	−4177	2238	4745
	1.00	9810.0	10	0.1	300	80° W	−3655	1289	3483
	1.00	9810.0	10	0.1	300	80° E	−5789	2960	6433
	1.00	9810.0	10	0.1	1000	85° W	−3752	2247	4499
	1.00	9810.0	10	0.1	1000	85° E	−4826	3097	5993



Supplementary Figure S1. Historical and instrumental seismicity from FCAT17 catalogue [Manchuel et al., 2018] complemented with the LDG catalogue [Duverger et al., 2021] color-coded as a function of time (colorbar). Density map of events, sampled within 2 × 2 km cells and smoothed.



Supplementary Figure S2. Correlation observed between the folds and earthquakes as a function of the epicentral distance between the seismicity and the center of the fold (red line) compared to the median correlation between the folds and purely random earthquake catalogues (blue line—dashed) associated with the probability of wrongly rejecting the null hypothesis (blue line—plain).



Supplementary Figure S3. (a) Distribution of the stress Sxx obtained for a blind thrust. The friction on the ramp is fixed at 10°. The stress varies from 0 (dark red) to −350 MPa (dark blue). (b) Normalised displacement along x with a velocity varying from 0 (dark red) to −1 (dark blue). (c) Distribution of the scalar of the distance to the Coulomb criteria varying from 0 (dark blue) to 1 (dark red).