The 2019 Le Teil surface-rupturing earthquake along the La Rouvière Fault within the Cévennes fault system (France): What does paleoseismology reveal?

J-F Ritz\textsuperscript{1,*}, S. Baize\textsuperscript{2}, N. Cathelin\textsuperscript{1,2}, C. Thomasset\textsuperscript{1,3}, M. Riesner\textsuperscript{4,7}, E. Hannouz\textsuperscript{5}, M. Ferry\textsuperscript{1}, C. Larroque\textsuperscript{6}, L. Audin\textsuperscript{5}, L. Bollinger\textsuperscript{4}, K. Manchuel\textsuperscript{3}, C. Sue\textsuperscript{5}, C. Vergniault\textsuperscript{3}, M. Rizza\textsuperscript{7}, H. Jomard\textsuperscript{2}, P. Arroucau\textsuperscript{3}, R. Le Roux-Malloul\textsuperscript{3}.

\textsuperscript{1} Géosciences Montpellier, Univ. Montpellier, CNRS, Univ. Antilles, Montpellier, France.
\textsuperscript{2} Institut de Radioprotection et de Sûreté Nucléaire (IRSN), Fontenay-aux-roses, France.
\textsuperscript{3} EDF-DIPNN-DI-TEGG, Aix-en-Provence, France.
\textsuperscript{4} Département Analyse Surveillance Environnement, CEA, DAM, DIF, 91297 Arpajon, France.
\textsuperscript{5} ISTerre, Université de Grenoble Alpes, Université Savoie Mont Blanc, CNRS, IRD, IFSTTAR, Grenoble, France.
\textsuperscript{6} Université Côte d'Azur, CNRS, Observatoire de la Côte d'Azur, IRD, Géozaur, 250 rue Albert Einstein, Sophia Antipolis 06560 Valbonne, France.
\textsuperscript{7} Aix Marseille Univ., CNRS, IRD, INRAE, Collège De France, CEREGE, Aix-en-Provence, France.

Abstract. The 2019-11-1, Mw4.9 Le Teil earthquake occurred within the NE termination of the Cévennes faults system (CFS) in southern France, along the La Rouvière fault (LRF), an Oligocene normal fault which was not known to be potentially active. This shallow moderate magnitude reverse-faulting event produced a 5 km-long surface rupture and strong ground shaking. No evidence of previous quaternary activity was observed in the morphology, raising the question whether the fault had been reactivated for the first time since the Oligocene or had broken the surface in the past without being detected in the morphology. To address this issue, we carried out paleoseismological investigations to analyze and characterize evidences of paleo-ruptures in Quaternary deposits. We discovered that at least one event prior 2019, occurred between 13.5 and 3.3 ka within the central part of the fault segment that broke in 2019, and that a possible earlier surface-rupturing event occurred within the northern part of this segment during the 16th century. Further investigations coupling sub-surface geophysical investigations and trenching are now carried out within the southern and northern segments of the LRF as well as along the other fault segments of the CFS.

1 Introduction and Tectonic Setting

The Mw 4.9 Le Teil earthquake occurred in southern France, in the Rhône river valley near Montélimar, on November 11, 2019 (Fig. 1A). It corresponds to a historically

* Corresponding author: jean-francois.ritz@umontpellier.fr

© The Authors, published by EDP Sciences. This is an open access article distributed under the terms of the Creative Commons Attribution License 4.0 (http://creativecommons.org/licenses/by/4.0/).
unprecedented event in several ways. For the first time, a surface rupture associated with an earthquake was observed and comprehensively measured on live in France [1, 2]. It was also the first time that an earthquake was clearly associated with the reactivation and the inversion of an ancient fault – i.e La Rouvière Fault - inherited from the Oligocene extensional period [1]. The La Rouvière Fault belongs to the Cévennes Faults system (CFS) a major crustal structure, inherited from a rich polyphased tectonic history that began during the Variscan orogeny. This NE-SW trending, 120 km-long fault system is located at the boundary between the Massif Central crystalline basement and the sedimentary basin of southeastern France. Several authors stated that this fault system could have been active, either normal [3] or transcurrent [4] during recent times, based on geomorphological analyses. However, definitive evidence of past surface-rupturing events was missing, leading to intense debate [4, 5, 6, and 7]. As for the LRF strictly speaking, no evidence allowing assessing its potential activity have never been reported in the literature, so that this fault segment is not reported in the IRSN fault data base [8].

The rupture, with a focal depth estimated at 1.5 ± 0.5 km [1, 9] generated strong ground motion in the epicentral zone, with maximum vertical and horizontal accelerations exceeding the gravity acceleration near the fault [10]. The heaviest damage was observed in the villages of Le Teil and Viviers, with EMS98 macroseismic intensities of VII, or even locally VIII [11], a level of damage never reached in metropolitan France since the earthquake of Arette in 1967.

This significant earthquake raises important questions in terms of seismic hazard: Had the Rouvière fault already broken in the past? Could other faults of the NE termination of the Cévennes faults system, also produce this type of event? To answer these questions, a collaborative research program (FREMTEIL 2021-2023*) involving several academic laboratories as well as several institutes has been launched, with the support of the CNRS-INSU and the numerous institutional collaborators. In this paper, we present some of our paleoseismological investigations, which allow us to show that the Rouvière fault had already ruptured in the past.

(*) Acronym for “Faults, Ruptures and Strong Movements: What consequences for the seismic hazard in the TEIL region”

Fig. 1 (a) [after 1]: Seismotectonic map of the Rhône River Valley where the November 11th, 2019 Mw4.9 Le Teil earthquake occurred. The black and white sphere indicates the reverse faulting focal mechanism; red and purple circles are instrumental and historical seismicity, respectively; the green ellipse corresponds to the Tricastin swarm; black lines are faults from the Aubenas geological map [12] with the La Rouvière Fault (LRF) in red; CF: Cévennes Fault, MF: Marsanne Fault; the shaded DTM is from BD ALTI 25 m (IGN); MC and Al in the inset are Massif Central and Alps,

Fig. 2 [after 13]: Location of the 5 sites (number of trenches per site in parenthesis) where 13 trenches were dug across the La Rouvière Fault and/or the traces of 2019 earthquake surface rupture. The 25-cm-resolution shaded relief topographic map with the surface ruptures observations (red stars) are from [1].

Fig. 3 [after 13 and 14]: Summary of the age constraints obtained within trenches LR1-TB (left) and LR6-T1 (right) dug across the central segment of the La Rouvière Fault that broke on 11-11-2019 during the Le Teil surface rupturing earthquake.
分别。b [after 1]: 第一干涉图（包络相位）使用Sentinel-1合成孔径雷达数据获得。

2 古地震学调查沿着La Rouvière断层

我们沿着La Rouvière断层进行了古地震学调查，以分析和表征Quaternary沉积中的古破裂证据。在2019年（图2），在跨越地面断裂的断层的13个断面上挖掘了15个断面。在3个断面（LR4, LR1和LR6）内，形成了有利的Quaternary沉积物（斜坡冲积物和风成沉积物），其位置与古代LRF正常断层镜面相对，该断层是Barremian石灰岩雕刻的，用于记录过去的 coseismic变形。

图2 [after 13]: 5个断面（每个断面的个数在括号内）的位置，其间13个断面被挖掘，跨越了La Rouvière断层，以及2019年地震地面破裂的轨迹。图2中的25-cm分辨率的等高线地形图显示了地面破裂观测的红色星号，图2来自[1]。

AMS测年碳十四和OSL测年（从“块”收集到冲积物粘土-泥质中）在3个位于中央和南部的LRF（LR6-TB，LR6-TD，LR4-TA）的断面上，表明至少在2019年之前发生了一次事件，发生在约13 ka [13]。在LR1-TB中，我们获得了更多的年龄约束，在该事件中，这个先前事件的年龄被夹在13.5和3.3 ka之间（图3左）[14]。

图3 [after 13 and 14]: LR1-TB（左）和LR6-T1（右）断面的年龄约束的综合，这些断面跨越中央段的La Rouvière断层，该断层在2019年11-11-2019期间破裂，引起了Le Teil表面破裂地震。

在2019年北部的破裂段，收集于较年轻的沉积物中的木炭的放射性碳测年数据表明，发生在15世纪末到17世纪初的事件，具有与2019年事件相似的运动学特征（运动方向，位移量）（图3右）。

在2019年北部的破裂段，收集于较年轻的沉积物中的木炭的放射性碳测年数据表明，发生在15世纪末到17世纪初的事件，具有与2019年事件相似的运动学特征（运动方向，位移量）（图3右）。

在2019年北部的破裂段，收集于较年轻的沉积物中的木炭的放射性碳测年数据表明，发生在15世纪末到17世纪初的事件，具有与2019年事件相似的运动学特征（运动方向，位移量）（图3右）。
3 Conclusions and perspectives

Our study demonstrates that the LRF have had previous surface rupturing earthquakes prior to the 2019 event, without any clear consistent morphological imprint. We thus infer that in plate interiors such as metropolitan France, active faults capable of producing such earthquakes are not necessarily detectable in the morphology. Concerning the La Rouvière Fault example, this can be explained by the small amount of displacement and a long return period (consistent with the $0.5–1.0 \times 10^{-9}$ yrs$^{-1}$ low strain rate measured by GPS in the region [15]), easily balanced or even exceeded by erosion processes.

To go further in the characterization of potential active faulting along the other faults segments of the Cévennes fault system, we are now performing detailed geophysical surveys at the intersection areas between the different faults and the Quaternary markers. Figure 4 shows an example of such an approach within the Marsanne fault, which bounds the northeastern termination of the Cévennes fault system along its southeastern border (see “MF” in Fig.1B).

![Fig. 4](image)

**Fig. 4** [after 16]: (A) Location of UHRS profile across the Marsanne fault (MF) LRF= La Rouvière Fault. (B) Seismic line (lower section = potential interpretation).

The UHRS (Ultra High Resolution Seismic) survey [see for instance 17] was performed at a site where the Marsanne fault is mapped below Plio-Quaternary deposits (Fig. 4A). It shows an interruption of the horizontal continuity of some reflectors that are interpreted as the occurrence of the fault bellow the young deposits (Fig.4B). This result enables us to precisely locate the trench that we will open soon to analyze the Quaternary activity of the Marsanne fault.

References

1. Ritz, J.-F., Baize, S., Ferry, M., Larroque, C., Audin, L., Delouis, B., and Mathot, E., *Surface rupture and shallow fault reactivation during the 2019 Mw 4.9 Le Teil earthquake, France*. Commun. Earth Environ., 1:10. [https://Doi.Org/10.1038/S43247-020-0012-Z](https://DOI.Org/10.1038/S43247-020-0012-Z) (2020)
2. Cornou, C., and 90 co-authors, Rapid Response to The Mw 4.9 Earthquake Of November 11, 2019 In Le Teil, Lower Rhône Valley, France. Comptes Rendus. Géoscience, Académie des sciences (Paris), 2021, 353 (S1), pp.1-23. https://doi.org/10.31219/osf.io/3afs5 (2021)

3. Bishop, P. and Bousquet, J. P., The Quaternary Terraces of the Lergue River and activity of the Cévennes fault in the lower Hérault Valley (Languedoc), southern France. Z. Geomorph. N. F., 33 : 405-415, (1989)

4. Lacassin R., Meyer B., Benedetti L., Armijo R. et Tapponnier P., Signature morphologique de l'activité de la faille des Cévennes (Languedoc, France), Comptes Rendus de l’Académie des Sciences, 326 : 861-866, (1998a)

5. Ambert P., Philip, H., and Ritz, J-F., Commentaire à la note de Robin Lacassin et al., intitulée : « Signature morphologique de l'activité de la faille des Cévennes (Languedoc, France) ». Compte Rendus de l’Académie des Sciences, 327: 857-859, (1998)

6. Sébrier M., C. Bellier, O., Peulvast, J. P., & Vergély, P., Commentaires à la note de Robin Lacassin, Bertrand Meyer, Lucilla Benedetti, Rolando Armijo et Paul Tapponnier: « Signature morphologique de l'activité de la faille des Cévennes (Languedoc, France) », Comptes Rendus de l'Académie des Sciences-Series IIA-Earth and Planetary Science, 327(12), 855-859, (1998)

7. Lacassin, R., Meyer, B., Benedetti, L., Armijo, R., Tapponnier, P., Réponse aux commentaires de Ambert et al., Mattauer et Sébrier et al. Comptes Rendus de l’Académie des Sciences - Series IIA - Earth and Planetary Science 327, 861–866, (1998b)

8. Jomard, H., Cushing, E. M., Palumbo, L., Baize, S., David, C., & Chartier, T., Transposing an active fault database into a seismic hazard fault model for nuclear facilities–Part 1: Building a database of potentially active faults (BDFA) for metropolitan France. Natural Hazards and Earth System Sciences, 17(9), 1573-1584 (2017)

9. Delouis, B., Oral, E., Menager, M., Ampuero, J. P., Trilla, A. G., Régnier, M., and Deschamps, A., Constraining the point source parameters of the 11 November 2019 Mw 4.9 Le Teil earthquake using multiple relocation approaches, first motion and full waveform inversions. Comptes Rendus. Géoscience, 353(S1), 1-24 (2021)

10. Causse, M., Cornou, C., Maufroy, E., Grasso, J. R., Baillet, L., and El Haber, Exceptional ground motion during the shallow Mw 4.9 2019 Le Teil earthquake, France. Commun. Earth Environ., 2(1), 1-9 (2021)

11. Schlupp, A., Sira, C., Maufroy, E., Provost, L., Dretzen, R., Bertrand, E., Beck E. and Schaming, M., EMS98 intensities distribution of the “Le Teil” earthquake, France, 11 November 2019 (Mw 4.9) based on macroseismic surveys and field investigations. Comptes Rendus. Géoscience, 353(S1), 1-28 (2021)

12. Elm, S., Busnardo, R., Clavel, B., Camus, G., Kieffer, G., Béard, P. and B. Michaëly, Notice 53 explicative, Carte géologique de France (1/50 000), Feuille Aubenas (865). Orléans : BRGM, 170 p. 54 Carte géologique par Y. Kerrien (coord.), S. Elmi, R. Busnardo, G. Camus, G. Kieffer, J. Moinereau, 55 A. Weisbrod (1989) (1996)

13. Ritz, J-F., S. Baize, M. Ferry, E. Hannouz, M. Riesner, L. Bollinger, C. Larroque, L. Audin, K. Manchuel, M. Rizza, H. Jomard, C. Sue, P. Arroucau, J. Billant, Analyzing the paleoseismic history of the La Rouvière fault, unexpected source of the 11-11-2019, Mw4.9 Le Teil surface rupturing earthquake (Cévennes fault system, France), EGU General Assembly 2021, EGU21-13044 (2021)
14. Ritz J-F, Baize S., Ferry M, Hannouz E., Riesner M., Cathelin N., Thomasset C., Bollinger L., Larroque C., Audin L., Manchuel K., Rizza M., Jomard H., Sue C., Arroucau P., Le Roux-Mallouf R. Paleoseismological investigations of the La Rouvière fault, unexpected source of the 11-11-2019, Mw4.9 Le Teil surface rupturing earthquake (Cévennes fault system, France), AFEQ workshop, Strasbourg March 14-18 (2022)

15. Masson, C., Mazzotti, S., Vernant, P., and Doerflinger, E., Extracting small deformation beyond individual station precision from dense Global Navigation Satellite System (GNSS) networks in France and Western Europe. Solid Earth, 10: 1905–1920 (2019)

16. Ritz J-F., Baize S., Audin L., Authemayou C., Graveleau F., Kaub C., Lacan P., Leclerc F., Larroque C., Antoine P., Manchuel K., Mugnier J-L., Rizza M., Vassallo R. Arroucau P., Billant J., Bollinger L., Ferry M., Fillon C., Geoffroy L., Jomard H., Le Roy P., Migeon S., Perrin C., Perrot J., Ratzov G., Reicherter K., Soubigou O., Vergniault C., Viaplana M., Van Der Woerd J., Perspectives in studying active faults in metropolitan France, Comptes Rendus. Géoscience, (in press)

17. Vergniault, C., Strobbia, C., Deida, G-P., and Dupuy, D., Surface seismic methods comparison to image the near surface basement. Journées scientifiques de l’AGAP Qualité, 28-30 Oct. 2019 (2019)