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# Insights on fault reactivation during the 2019 November 11, Mw 4.9 Le Teil earthquake in southeastern France, from a joint 3-D geological model and InSAR time-series analysis

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1        **Insights on fault reactivation during the November 11, 2019, M<sub>w</sub>4.9 Le Teil**  
2        **earthquake in south-eastern France, from a joint 3D geological model and**  
3        **InSAR time series analysis**

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## 28 Summary

29 The 2019, Mw4.9 Le Teil earthquake occurred in south-eastern France, causing substantial damage in this  
30 slow deforming region. Field observations, remote sensing and seismological studies following the event  
31 revealed that coseismic slip concentrates at shallow depth along a ~5 km long rupture associated with surface  
32 breaks and a thrusting mechanism. We further investigate this earthquake by combining geological field  
33 mapping, 3D geology, InSAR time series analysis and a coseismic slip inversion. From structural, stratigraphic  
34 and geological data collected around the epicenter, we first produce a 3D geological model of the region  
35 surrounding the rupture using the GeoModeller<sup>TM</sup> software. Our model includes the geometry of the geological  
36 layers and of the main faults, including the La Rouvière Fault, the Oligocene normal fault that ruptured during  
37 the earthquake. We generate a time series of surface displacement from Sentinel-1 SAR data ranging from  
38 early January 2019 to late January 2020 using the NSBAS processing chain. The spatio-temporal patterns of  
39 surface displacement for this time span show neither a clear pre-seismic signal nor significant post-seismic  
40 transient deformation. We extract the coseismic displacement pattern from the InSAR time series, highlighting  
41 along-strike variations of coseismic surface slip. The maximum relative displacement along the Line-Of-Sight  
42 is up to ~16 cm and is located in the southwestern part of the rupture. We invert for the slip distribution on the  
43 fault from the InSAR coseismic surface displacement field. Constraining our fault geometry from the  
44 geological model, acceptable fault dip ranges between 55° and 60°. Our model confirms the reactivation of La  
45 Rouvière fault, with reverse slip at very shallow depth and two main slip patches reaching respectively 30 cm  
46 and 24 cm of slip, both around 500 m depth. We finally discuss how the 3D fault geometry and geological  
47 structure may have impacted the slip distribution and propagation during the earthquake. This study is a step  
48 to reassess the seismic hazard of the many faults similar to the La Rouvière one along the Cévennes fault  
49 system, in a densely populated area hosting several sensitive nuclear sites.

50

51

52 **Key words:** Continental neotectonics; Seismic cycle; Radar interferometry; Time-series analysis; Earthquake  
53 source observations; Inverse theory

54

## 55 1 Introduction

56 On the 11<sup>th</sup> of November 2019, the Mw4.9 Le Teil earthquake struck the region of Montélimar, in the  
57 western Rhône valley in South-East France (**Fig. 1a**). The towns of Le Teil, Saint-Thomé, and Viviers, all  
58 located in the epicentral area, suffered important economic damages (~50M€). Thankfully, only a small  
59 number of injured people were reported. Partial building collapse happened in a radius of about 10 km  
60 corresponding to macroseismic intensities of VII to VIII (EMS98; Cornou et al., 2020). The earthquake caused  
61 the temporary shutdown of a nuclear power plant located 15 km to the north of the epicenter for security check.

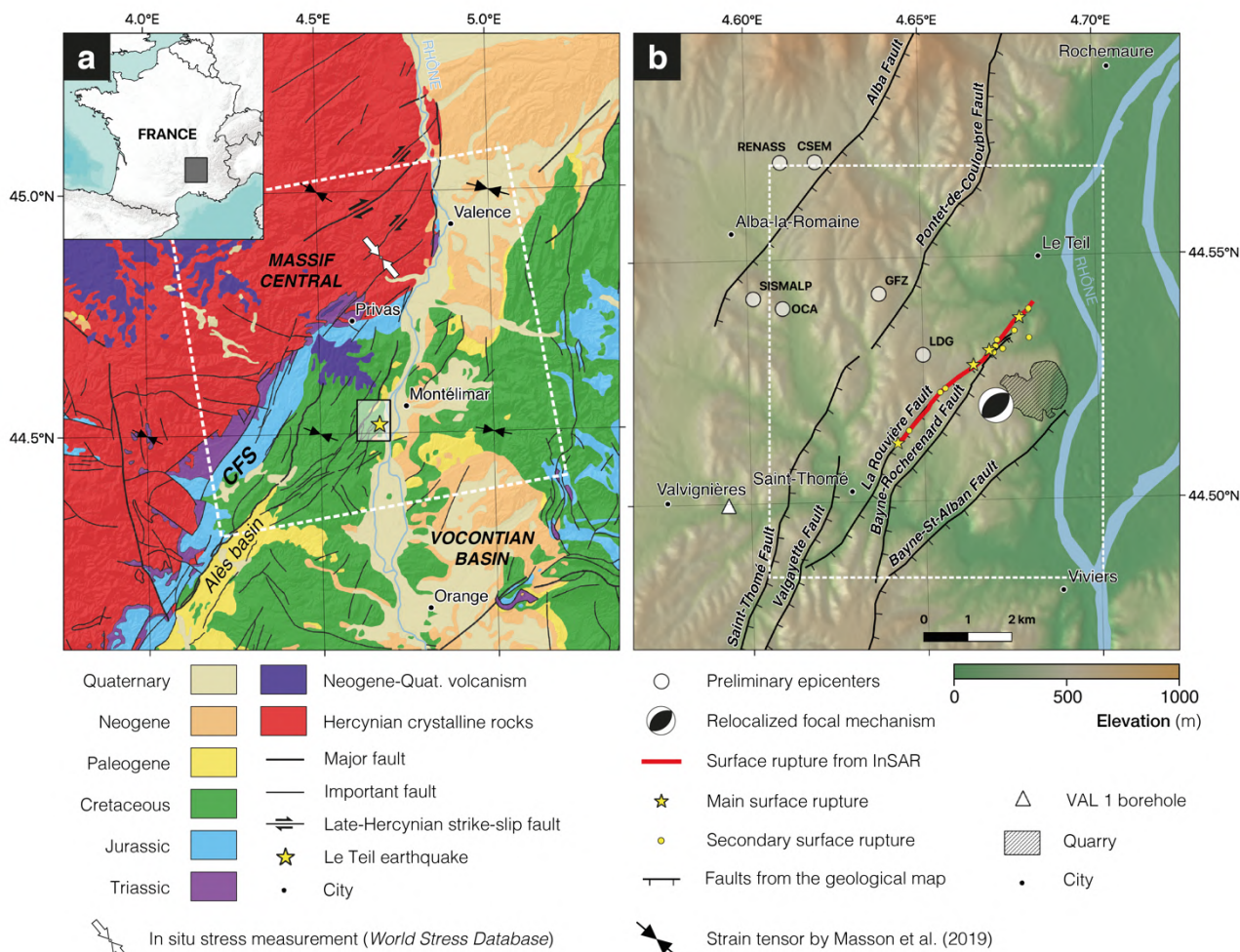
62 The first epicentral localizations obtained by seismological institutes all being inaccurate by several  
63 kilometers (**Fig. 1b**), it is the first Sentinel-1 interferograms that allowed a precise localization of the Le Teil  
64 earthquake (Cornou et al., 2020). These interferograms show a sharp surface rupture (Ritz et al., 2020)  
65 suggesting that the earthquake ruptured the La Rouvière Fault (LRF), a normal fault previously mapped  
66 (Kerrien et al. 1989) and considered inactive since the Oligocene. The reverse-faulting and very shallow (< 3  
67 km) focal mechanisms estimates matched InSAR imagery, suggesting a reactivation of the shallow part of the  
68 LRF in reverse motion, hence with an inversion of its kinematics. In addition, the strong mobilization of the  
69 French scientific community (Delouis et al., 2019; Cornou et al., 2020), guided by InSAR imagery, led to the  
70 identification of several surface breaks associated with the Le Teil event, matching both the preliminary trace  
71 inferred from InSAR data and the previously mapped trace of the LRF (Ritz et al., 2020) (**Fig. 1b**). Up to 13  
72 cm of surface displacement was measured on the field, and InSAR suggested up to 15 cm of relative surface  
73 motion.

74 The occurrence of such shallow reverse faulting earthquake along a previously thought to be inactive  
75 normal fault raises several issues. The reactivation of the LRF must be examined in the light of the geological  
76 context and the fault geometry. In addition, the potential triggering of the event by the surface unloading  
77 induced by excavation in a cement quarry located in the immediate vicinity of the LRF is still debated  
78 (Ampuero et al., 2020; De Novellis, 2020). The hypothesis of excavation induced triggering is favoured by the  
79 very shallow depth of the event and the lack of aftershock (Delouis et al., 2019). The reassessment of the  
80 seismic hazard zoning must also be considered in the whole Ardèche margin where faults similar to the LRF  
81 are collocated with several nuclear facilities and populated areas.



82           From a more fundamental point of view, as fault geometry and geological, lithological and structural  
83 inheritance appear to be key factors to understand the extent and the variability of slip during earthquakes (e.g.  
84 King & Nabelek, 1985; Wesnousky, 2006; Choi et al., 2018), the Le Teil earthquake represents a rare  
85 opportunity to study the interaction between pre-existing geological 3D structures and earthquake deformation  
86 in a slow deforming context. The very shallow slip distribution of this rather small event allows to put together  
87 different geological and geodetic datasets at a resolution (hundreds of meters) at which larger earthquake  
88 ruptures can hardly be studied.

89           We investigate the Le Teil earthquake combining field mapping, 3D structural and geological  
90 modeling, InSAR time series analysis and inversion for coseismic slip distribution. First, from field mapping,  
91 we constrain the geological formations and faults around the epicentral area and produce a 3D numerical model  
92 of the geological layers and faults, including the LRF. Then, we compute a one-year InSAR Sentinel-1 time  
93 series, covering ten months prior and three months after the earthquake, in order to both refine the spatial  
94 coverage of the coseismic displacement map in the near field and investigate whether pre-seismic deformation  
95 or afterslip may have occurred or not. We model the slip distribution using the surface deformation field of the  
96 Le Teil earthquake. We compare our slip distribution with the geological and morphological features of the  
97 area. This multi-disciplinary approach provides constraints about the geometry of the LRF, opening the  
98 discussion on the potential factors that controlled the reactivation of the fault and on the need to reassess  
99 seismic hazard in this region.



100

101

102 **Figure 1.** Geological and seismotectonic setting of the Le Teil earthquake. (a) Regional geological and  
 103 structural map (Chantraine et al., 1996). Black arrows show the principal horizontal compressive directions of  
 104 the strain tensor (Masson et al., 2019). White dashed outline shows coverage of reprocessed InSAR data. Black  
 105 rectangle shows the extent of b. (b) Surface rupture trace is in red. Yellow dots indicating location of field  
 106 observations of coseismic displacement from Ritz et al (2020). Faults in black are from Saint Martin (2009).  
 107 Rectangle in dotted white in panel b show coverage of the 3D geological model in Fig. 2. Revised location of  
 108 epicenter (yellow star in a) and focal mechanism are from Delouis et al. (2021).

109

## 110 2 Geological and structural history of Le Teil area

111 The Le Teil earthquake occurred in the so-called Vivaro-Cévenole margin in between the Hercynian  
112 crystalline basement of the Massif Central to the NW, and the Vocontian Mesozoic basin to the SE (**Fig. 1a**).  
113 The margin between these two domains corresponds to a ~900 m topographic change and a network of NE-  
114 SW faults that runs for more than 150 km from the Bas Dauphiné to the Languedoc. This fault network, called  
115 the Cévennes fault system (CFS), shows evidence for a long and polyphased structural history with  
116 compression, strike-slip and extension phases during the Paleozoic, extension phases during the Mesozoic and  
117 extension and compression phases during the Cenozoic.

118 NW-SE faults with apparent dextral offset affect the basement but not the Mesozoic cover (**Fig. 1a**)  
119 (e.g., Chantraine et al., 2006) and are interpreted as Late Hercynian strike-slip faults (Arthaud & Matte, 1975;  
120 Chardon et al., 2020) that may have been reactivated during the later deformation phases. The end of the  
121 Hercynian orogenic cycle corresponds to a carboniferous phase of detrital sediments and coal deposit as well  
122 as several deformation phases. Widespread erosion was then followed by the deposit of Triassic continental  
123 sediments. During the Mesozoic more than 10 km of marine sediments accumulated in the Vocontian basin.  
124 At that time, the Vivaro-Cévenole margin corresponded to a network of NW-SE synsedimentary normal faults  
125 delimiting tilted blocks (Elmi et al., 1983; 1996; Soechting, 1996). The precise mode and direction of extension  
126 varied through time with three extension stages: Middle Triassic pre-rift, Early-Middle Jurassic Thethysian  
127 rifting, and Late Jurassic-Early Cretaceous thermal subsidence (Elmi et al., 1983; Bonijoly et al., 1996). From  
128 the interpretation of three seismic lines, a gravimetry map, and two deep boreholes located ~25 km west of Le  
129 Teil (**Fig. 1a**), Bonijoly et al. (1996) propose a WNW-ESE balanced cross-section of the Vivaro-Cévenole  
130 margin. That section shows normal faults, mostly dipping to the SE, rooting on a SE dipping decollement  
131 within Carboniferous coal levels. Microstructural studies in the same area indicate a Triassic E-W extension  
132 (Bergerat & Martin, 1993) and a Lower Jurassic N-S extension, while the main normal faults strike ~N30  
133 (Bergerat & Martin, 1994; Martin & Bergerat, 1996). At other locations along the Vivaro-Cévenole margin,  
134 the Lower Jurassic extension is considered to trend NW-SE, in better accordance with NE-SW striking normal  
135 faults (Bles et al., 1989 and references therein). The Lower Cretaceous corresponds to the widespread  
136 sedimentation of the so-called Urgonian carbonate platform in the Vocontian basin, in a N-S extension context

137 (Bles et al., 1989 and references therein). Thermal modeling of Apatite fission track ages of samples from the  
138 Cévennes suggest that Mesozoic sedimentation extended further to the West than the present-day cover-  
139 basement boundary, but was eroded before the Upper Cretaceous (Barbaran et al., 2001; Gautheron et al.,  
140 2009).

141 Starting from the Aptian, sedimentation becomes detrital, probably because of local regression under  
142 far-field effects of the so-called Pyrenean N-S compression. At that time, the CFS was a left-lateral ramp  
143 bounding to the west the shortened cover with an ~17 km offset of Upper Jurassic recifal facies in the south  
144 (Bodeur, 1976). Associated NE-SW to N-S shortening occurred along several thrusts with decollements in the  
145 Triassic evaporites and Mesozoic marls (Arthaud & Laurent, 1995; Arthaud & Séguret, 1981).

146 At the end of the Eocene and during the Oligocene, rift basins straddle across western Europe from  
147 the North Sea to the Mediterranean Sea, contemporaneously with compression in the Western Alps, opening  
148 of the Golfe du Lion, and volcanism in the Massif Central (Illies, 1972; Bergerat, 1987; Serane et al., 1995;  
149 Dezes et al., 2004). At this time NW-SE extension prevails along the CFS, and several NE-SW normal faults  
150 are activated (Bles et al., 1989; Roure et al., 1992; and references therein). Some of the faults bound narrow  
151 rift basins filled with Oligocene deposits, the largest being the Alès basin (**Fig. 1a**) which is bounded by a  
152 major SE dipping fault (Arene et al., 1978). At the surface, the Alès fault dips 35° to the ESE but appears along  
153 seismic profiles as a ~15° dipping fault at depth (Roure et al., 1992; Sanchis & Séranne, 2000). The latest study  
154 considers that this fault has been active during a two stages extension history starting in the Eocene (Ludian)  
155 and connects with a decollement level in the Triassic (Sanchis & Séranne, 2000). Further North, the CFS  
156 appears to splay out, with the Lagorce-Vallon, La-Fare-Pontet-de-Couloubre and Larnar-Bayne-St-Alban  
157 faults (**Fig. 1a, Fig. 2**). Oligocene sediments were found in the hanging-wall (at SE) of some of these faults at  
158 Ellieux (Larnas F.), Couijanet (Baynes-St-Alban F.) and Rochemaure (Pontet-de-Couloubre F.) (**Fig. 1a; Fig.**  
159 **2**; Kerrien et al., 1989), suggesting that the faults are Oligocene normal faults. From a balanced cross-section  
160 across that part of the margin, Roure et al. (1992; 1994) (**Fig. 1a**) interpret the westernmost faults of the margin  
161 to be Lower Jurassic normal faults rooted in the Carboniferous, and the easternmost ones as Oligocene faults  
162 partly reactivating Lower Jurassic normal faults but rooted in the Triassic. The Bayne-St-Alban fault possibly  
163 connects with the Marsanne fault on the other side of the Rhône River that also separates Mesozoic from  
164 Oligocene sediments (**Fig. 1a**). The Pontet de Couloubre fault continues further NE and possibly connects with

165 the Valence fault that bounds a thick Eocene-Oligocene half graben buried below Plio-Quaternary and Miocene  
166 sediments (Deville et al., 1994; Kalifi, 2021). The Le Teil area is thus located in a relay zone between the N5  
167 trending Valence and the N40 trending Alès Oligocene normal faults (**Fig. 1a**).

168 During the Miocene, continental and marine sedimentation takes place in the Rhodano-Provençal  
169 flexural basin coevally with intense folding and thrusting at the front of the western Alps (**Fig. 1a**) (Ford &  
170 Lickorish, 2004). In the Le Teil area, the Oligocene sediments are affected, together with the underlying  
171 Mesozoic sediments, by NNE-SSW folds: the Rochemaure and Bayne synclines (**Fig. 2**), and the Serre des  
172 Parts and Vivier anticlines (Elmi et al., 1996). As this compression appears to be mostly visible in the eastern  
173 part of the zone, it was termed “Rhodanian” and attributed to a Miocene compression (Elmi et al., 1996). Open  
174 folds and brittle faults affecting the Miocene molasse of Bas-Dauphiné also implies WNW-ESE to E-W  
175 compression (Blès & Gros, 1991). Such mild Late Miocene compression, also affecting most of the Massif  
176 Central, would be a far-field effect of the Alpine collision (Blès et al., 1989; Blès & Gros, 1991; and references  
177 therein). At the end of the Miocene, between 7.7 and 6.4 Ma effusive basaltic volcanism produced lava flows  
178 that reached Rochemaure less than 10 km north of Le Teil (Feraud, 1979; Bandet et al., 1974) (**Fig. 1a**).  
179 Contemporaneous dykes are mostly vertical and strike between N110 and N150 with a maximum between  
180 N135 and N150° and are compatible with a compression of that direction (Feraud & Campredon, 1983).

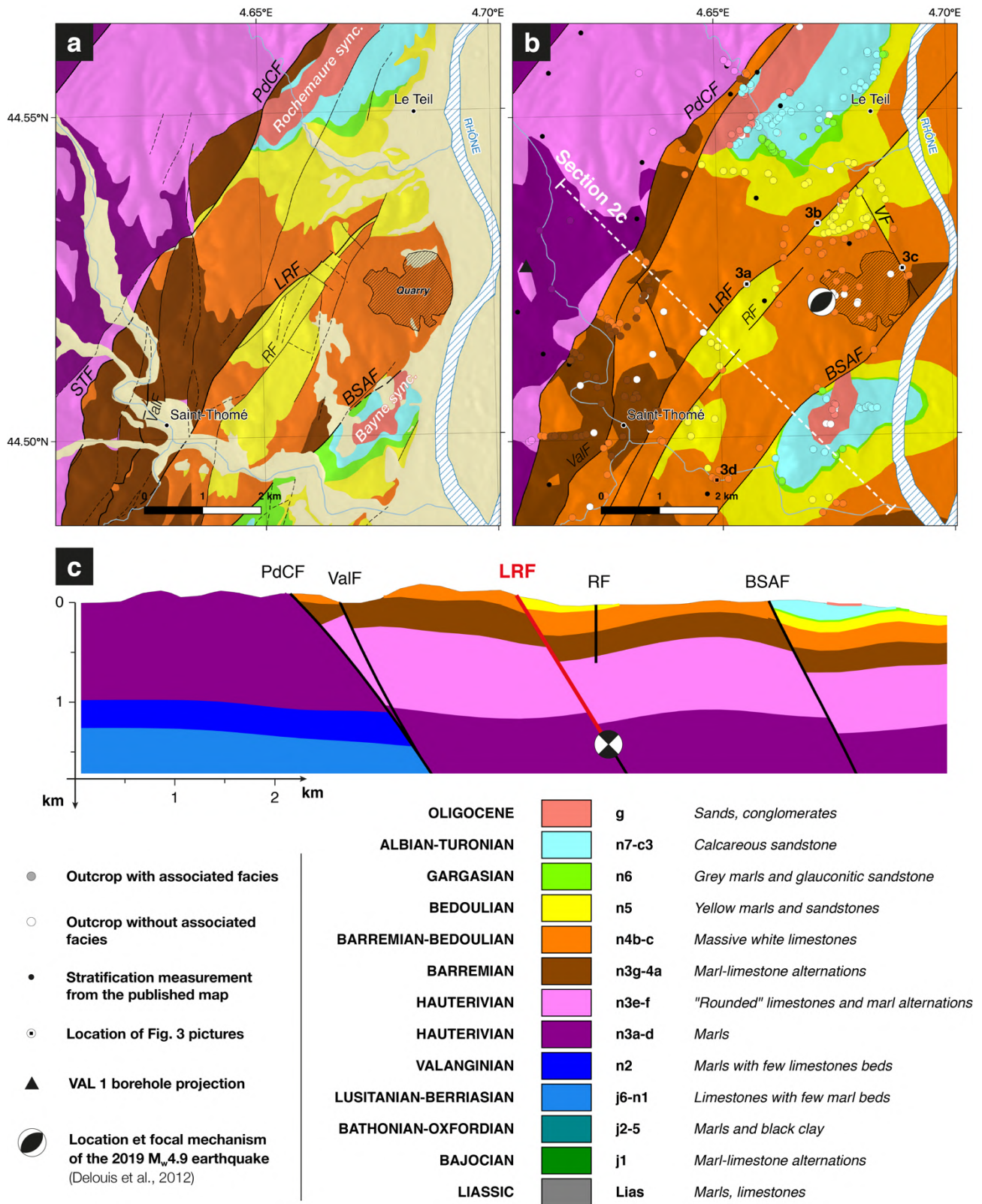
181 Post-Pliocene normal faults imply an E-W to NE-SW extension in Bas-Dauphiné that would result  
182 from a transcurrent state of stress with sigma 1 trending N-S to NW-SE and sigma 3 trending E-W to NE-SW  
183 (Blès & Gros, 1991). Because the southern part of the CFS has a clear geomorphic trace and offsets left-  
184 laterally valleys and Quaternary terraces, it has been interpreted to be active with an average slip rate of 0.1-2  
185 mm/yr (Lacassin et al., 1998a). Such conclusion is controversial and has stirred up intense scientific discussion  
186 (Ambert et al., 1998; Mattauer, 1998; Sébrier et al., 1998; Lacassin et al., 1998b). The Nîmes fault, located  
187 ~40 km to the SE, shares nearly the same trend and is considered as active (Grelet et al., 1993; Sébrier, 1997).  
188 While the paleo-seismic record is very sparse in France, a paleoearthquake was identified on the Nîmes fault  
189 in Courthézon, 50 km south of Le Teil, associated with reverse offsets on a ~N50 oriented fault (Carbon et al.,  
190 1993). The most recent synthesis of active faults in France considers the Nîmes fault as a Quaternary fault and  
191 the Alès basin border fault, as well as segments of the Pontet-de-Couloubre and Marsanne faults, as potentially  
192 active (**Fig. 1**; Jomard et al., 2017).

193           The SISFRANCE database on historical seismicity ([sisfrance.net](http://sisfrance.net)) reveals several earthquake swarms  
194 in 1773, 1873 and 1933-36, with maximum associated intensities of VII, 20 km SW of Le Teil (Cornou et al.,  
195 2020). Yet, one of the 1873 shocks could be located as close as 5 km south of Le Teil. The BCSF-RéNaSS  
196 catalogue ([renass.unistra.fr](http://renass.unistra.fr)) contains only one earthquake with a magnitude over 4, and two between 3 and 4  
197 at less than 60 km from Le Teil in the last decades (since 03/03/1981; Delouis et al., 2019). In 1923, a  $M_w$ 3  
198 earthquake is located at Le Teil (Manchuel et al., 2018). More recently in 2002-2003, a very shallow ( $< 200$   
199 m) earthquake swarm ( $M_L < 2$ ) was detected in the Tricastin area, 20 km SW of Le Teil (Thouvenot et al.,  
200 2009).

201           Present-day strain rates estimated by GNSS over the last 10 years are of  $1 \pm 0.4$  nanostrain/yr with a  
202 compression trending  $\sim N110$ , translating into  $\sim 0.1$  mm/yr of shortening over a 100 km long transect (Masson  
203 et al., 2019; Delouis et al., 2019) (**Fig. 1a**). In situ stress measurement in Boussenac, 36 km north of Le Teil,  
204 indicates a N140 maximum horizontal compression (**Fig. 1a**) (Heidbach et al., 2016).

205           As a summary, the Le Teil area is located in a continental intraplate zone where present deformation is  
206 slow, but not negligible, and where numerous faults are present. The most preeminent ones strike NE-SW, dip  
207 to the SE and are inherited from an Oligocene phase of extension.





208

209

210 **Figure 2.** Geological maps and cross-section of the rupture area. (a) Ardèche Geological map (Saint Martin,

211 2009) with original geological units grouped according to the 3D model stratigraphic pile shown below (see

212 section 3.2 and Fig. S1). Faults' names as defined by Elmi et al. (1996). (b) Surface map of the 3D geological  
213 model. Coloured dots indicate location of surface observations used to constrain the 3D model; circled dots  
214 labelled 3a to 3d show location of Fig. 3 pictures. The star shows location of the Le Teil earthquake epicenter  
215 (Delouis et al., 2021) (c) Geological cross-section across the 3D model, along the trace shown in b. The star  
216 shows the projected location of the Le Teil earthquake hypocenter (Delouis et al., 2021) and the red segment  
217 of the LRF represents the part that ruptured during the earthquake. *PdCF*: Pontet-de-Couloubre fault; *STF*:  
218 Saint-Thomé fault; *ValF*: Valgayette fault ; *LRF*: La Rouvière fault; *RF*: Rocherenard fault ; *VF*: Violette  
219 Fault; *BSAF*: Bayne-St-Alban fault.



## 220 3 Geological 3D model

221 In order to discuss potential relationships between the geological structure and the earthquake rupture,  
222 we build a 3D geological model of a 7x10 km area surrounding the surface rupture and the epicenter to a depth  
223 of 3 km below sea level. The surface geology of le Teil area was already described on geological maps of  
224 Aubenas (Kerrien et al., 1989) and Montélimar (Lorenchet et al., 1979) at the scale of 1:50 000, as well as on  
225 the harmonized map of Ardèche (Saint Martin, 2009). However, the design of a 3D geological model requires  
226 new fieldwork and the re-definition of geological units.

227

### 228 3.1 Methods

229 We build a 3D geological model using the GeoModeller™ software. In such a model, layer  
230 orientations measured in the field are interpolated to define a potential field that describes the geometry of the  
231 corresponding formation (Lajaunie et al., 1997; Calcagno et al., 2008). The base of each formation is an  
232 isopotential surface that goes through contact point(s) relative to the underlying formation. The formations  
233 parallel to each other are grouped into series. A geometrical relationship must be defined for each series  
234 (erosive or onlapping) depending on whether it crosscuts the underlying ones or not (Calcagno et al. 2008).  
235 This approach is well adapted to model the geometry of sedimentary series but requires the definition of the  
236 series and having as many structural measurements (orientations of the layers) and contact points as possible.  
237 Faults are considered as discontinuities in the potential fields. They are defined by their own potential-field,  
238 from orientation and location data, and can be set as infinite if they are continuous across the whole model, or  
239 finite if they end within the model box. It is necessary to define which formations and other faults are cut by  
240 each fault.

241

### 242 3.2 Stratigraphic pile

243 Most formations outcropping in the model zone are Lower Cretaceous marine sediments including  
244 limestones, marls, and marl-limestones alternations. The so-called Urgonian facies (Barremian, lower-Aptian),  
245 ubiquitous in the Vocontian basin, corresponds to a more than 200 m thick layer of massive light limestones  
246 that are exploited by the cement industry (which includes a historical Lafarge site, active since 1833, and a

247 large active quarry still in operation). Overlying layers are mainly silico-clastic, with sandstones, marls and  
248 calcareous sandstones of Upper Aptian, Albian, Cenomanian and Turonian age. That transition is due to a  
249 progressive emersion, considered as a far-field effect of the Pyrenean orogenesis, but it is not associated with  
250 a major angular unconformity. A main stratigraphic unconformity is present at the base of the Oligocene  
251 continental deposits (conglomerates and colored sands).

252 The model stratigraphic pile is built from the stratigraphy described in detail for the 1:50000 Aubenas  
253 geological map (Elmi et al., 1996), taking into account the 3D model specificities. Superficial, mostly  
254 Quaternary, deposits are not described in the 3D model. According to the geological map, 16 other formations  
255 outcrop in the zone. Whilst all these formations have been identified in the field, some of them were merged  
256 and only 8 formations appear in the model pile (**Fig. 2; Fig. S1**). Underlying formations do not outcrop in the  
257 restricted zone at the surface but appear in the model as 5 distinct formations (**Fig. 2; Fig. S1**). Names given  
258 to the new formations do not reflect precise stratigraphic ages. Despite some sedimentation gaps and slight  
259 unconformities, all Mesozoic formations have been gathered in the same series, while the Oligocene  
260 corresponds to a discordant series.

261

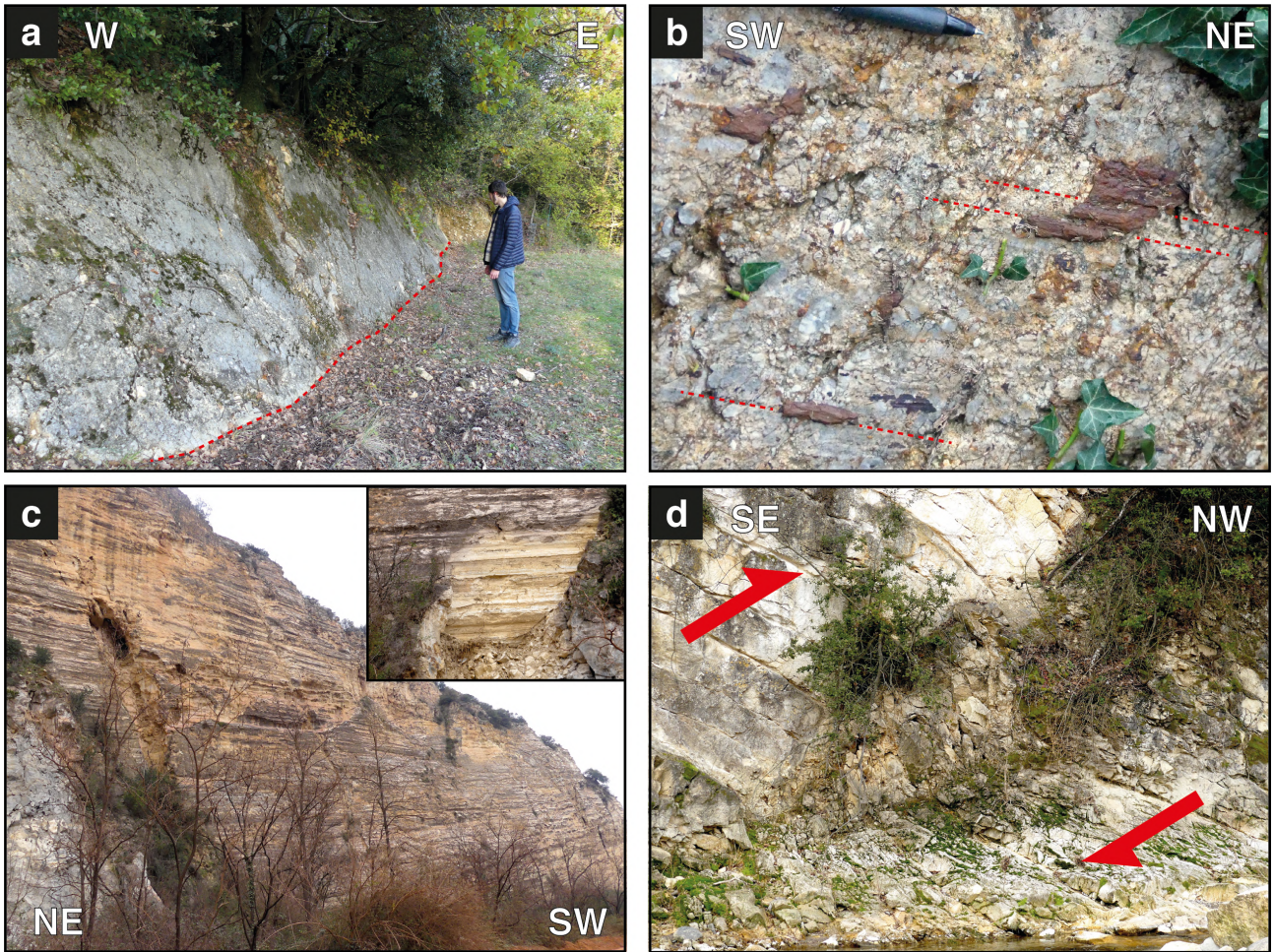
### 262 **3.3 Fieldwork**

263 During ten days of fieldwork, we collected data at more than 300 locations (**Fig. 2b**). We used these  
264 data to build a geological database aimed at standardizing the storage, referencing, and sharing of geological  
265 data. Most of these data consists in the determination of the facies and in their attribution to the stratigraphic  
266 chart and formations of the 3D model pile, as well as measurements of the strike and dip of the stratification  
267 (**Fig. S2**). Other data are defined as contact points at the base of a series or as fault location (**Fig. S2**).

268 One key point of 3D geological modeling is to define the fault network. In the Le Teil area, because  
269 of the dense vegetation cover, most faults are defined from the mapping of the sedimentary formations, but  
270 some faults may be directly observed in the field. The La Rouvière fault was already mapped previously  
271 (Kerrien et al., 1989), and we carefully checked its trace along which fault planes are exposed at four locations  
272 (e.g. **Fig. 3a**). While the main fault trace trends N50 on average, local fault planes trend from N5 to N80.  
273 Observations of slickensides on fault planes suggest that the more easterly trending planes have a large strike-  
274 slip component (**Fig. 3b**). The LRF have locally a clear geomorphic expression (Ritz et al., 2020), and we were

275 able to precisely map its trace between the outcropping planes on a LiDAR Digital Elevation Model (DEM)  
276 acquired one week after the earthquake, with a resolution of 25 cm (same data used by Ritz et al., 2020). Both  
277 this trace and fault plane measurements collected on the field constrain the geometry of the LRF in the 3D  
278 model.

279 About two kilometers west of Le Teil, the Pontet-de-Couloubre fault and the Valgayette fault are 200  
280 m apart from each other and bound the Rochemaure Oligocene basin (**Fig. 2b**). The two faults merge further  
281 north. Several other NNW-SSE (~N150) strike-slip faults, unreported in previous mapping, are visible in the  
282 field, including spectacular fault planes (**Figs 3c, S3b and S4**). Our fault mapping is mostly in agreement with  
283 the existing geological maps. Differences arise as only the main faults appear in the 3D model. We also slightly  
284 changed the trace of some of them and found some unreported faults (**Fig. 2**). The main faults in the 3D model  
285 are NE-SW striking, SE dipping normal faults crossing the whole zone, affecting both the Cretaceous and  
286 Oligocene deposits: *Alba*, *Pontet-de-Couloubre* (that was previously considered as two distinct faults: Pontet-  
287 de-Couloubre and Saint-Thomé faults), *Valgayette* (with a different trace), *La Rouvière*, and *Bayne-St-Alban*  
288 faults (**Fig. 2**). Three other finite faults, as they do not cross the whole area, are also considered in our 3D  
289 model: the Rocherenard fault (shorter and subdivided in two branches with respect to previous mapping), and  
290 two previously unreported faults trending N150 including the Violette fault.



291

292

293 **Figure 3.** Field observations. (a) [Site LT11] Fault plane striking N45-60°E attributed to La Rouvière Fault  
 294 (LRF). Neither clear slickensides nor evidence of recent coseismic slip was found on this plane, although it  
 295 appears collocated with the InSAR-derived rupture (within its location's uncertainties). (b) [Site LT5b]  
 296 Slickensides (N80-22°) on the LRF fault plane striking N73-72°S. (c) [Site LT122] 200m long, >30m high  
 297 fault plane striking N150, delimiting an abandoned quarry face in Le Teil cement quarry. This plane displays  
 298 well-marked slickensides close to horizontal (inset: closer view). (d) [Site LT106] Knee-bend, close to faulting,  
 299 with a horizontal fold axis trending ~N55. This compression evidence could be associated with the recent  
 300 Alpine tectonic phase responsible for the Le Teil earthquake. Locations of sites 3a to 3d are shown on Fig. 2.

### 301 **3.4 Other constraints**

302 We used 15 strike and dip measurements from the Ardèche geological map (Saint Martin, 2009), at  
303 locations that we could not explore (**Fig. 2b**, **Fig. S2**), to complement our field data. As the 3D geological  
304 model does not assume any formation thickness, it is necessary to dispose of contact points for the formations  
305 that do not outcrop. For this purpose, we used the interpreted log of the Valvignère (VAL 1) 4600 m deep  
306 borehole (**Fig. S5**) (<http://infoterre.brgm.fr/page/banque-sol-bss>). Although this borehole is located 1 km  
307 outside the model box (**Fig. 1b**), the stratification is almost flat in this area. Therefore, we could safely translate  
308 it within the box at a location with similar elevation and outcropping formation (**Fig. S2**).

309 As the dataset remains heterogeneous, with for example few data in the eastern part of the model  
310 because of the Quaternary sediments cover in the Rhône valley or in the Le Teil urban area, and with very few  
311 constraints at depth, the initial GeoModeller solution barely manages to fit all surface observations. It is thereby  
312 necessary to add additional constraints to the model. The methodology is somewhat the same as that followed  
313 by a geologist drawing cross-sections at depth from information limited to the surface, making some basic  
314 assumptions, such as the continuity of the layers (in the absence of faults) and the approximate conservation  
315 of their thicknesses. We hence define ad-hoc additional constraints to the model. The resulting geological map  
316 reproduces most of the surface observations (**Fig. 2b**), with some discrepancies considered as negligible. It is  
317 worth noting that the 3D geometry of the faults at depth is only defined from field-based measurements.

318

### 319 **3.5 Results**

320 The resulting 3D geological model is provided in a 3D PDF format in Supplementary Materials, while  
321 3D views in **Fig. S6**, and 2D views of the model are shown in **Figs 2b, c** and **S7**. The surface map shows the  
322 same general pattern as the previous geological maps (Kerrien et al., 1989; Saint Martin, 2009), with the same  
323 major faults and the Bayne and Rochemaure syncline folds (**Figs 2** and **S7**). However, they differ by several  
324 points. **(1)** The existing maps show necessarily more complexity and details than our simplified model. **(2)** We  
325 locally have different interpretations regarding the fault network. For instance, on previous maps, the northern  
326 part of the LRF fault is cut by four, possibly dextral, NW-SE faults. We did not detect such faults and, based  
327 on the LiDAR DEM and field work, we assume that the fault is continuous. In the same area, we map the  
328 Rocherenard fault as discontinuous and not connected to La Rouvière fault to the NE. Conversely, we add in



329 the 3D model two finite faults with a N150 azimuth, because we have clear field evidence of their importance  
330 in the local structure (**Figs 3c** and **S4**). We interpret these faults as dextral faults linked to the N-S Pyrenean  
331 compression phase. **(3)** Consistent with our field observations, the two syncline folds limbs have significantly  
332 lower dips than those depicted on previous geological maps (**Fig. S7**). However, their fold axes are compatible  
333 with a post-Oligocene NW-SE compression, associated with the “Rhodanian” deformation phase according to  
334 Elmi et al. (1996). At other locations we observed folds with axes compatible with that deformation phase  
335 (**Fig. 3d**). These structures are too small to be visible in the 3D model, but out of our mapping zone (South of  
336 Bayne syncline), two large NE-SW anticlines are described by Elmi et al. (1996).

337           The geological 3D model allows us to estimate apparent normal offsets of ~1000m and  $\geq 150$ m for the  
338 Pontet-de-Couloubre-Valgayette and Bayne-St-Alban respectively. The offset on the LRF ranges between 100  
339 and 200 m.

## 340 4 InSAR time series analysis

341 The coseismic interferograms produced in the days following the Le Teil earthquake played a key role  
342 in guiding the early post-seismic field missions in the earthquake area (Delouis et al., 2019; Cornou et al.,  
343 2020). This dataset helped to constrain the location and spatial extent of the surface rupture, guiding further  
344 seismological, geodetic and tectonic studies of the earthquake (Mordret et al., 2020, Ritz et al., 2020, De  
345 Novellis, 2020, Causse et al., 2021, Vallage et al. 2021).

346 However, past studies of the earthquake involving InSAR data rely on the analysis of only a limited  
347 number of individual coseismic interferograms. All were computed from radar images acquired by the ESA's  
348 Sentinel-1 satellites a few days before and after the earthquake (Cornou et al., 2020, Ritz et al., 2020, De  
349 Novellis, 2020, Vallage et al. 2021). These interferograms were processed and unwrapped using different  
350 methodologies and remain affected by atmospheric phase delays and coherence loss. Here we use a time series  
351 analysis of Sentinel-1 data acquired every 6 days over a period of about ten months before the earthquake and  
352 three months after the earthquake. This approach aims **(1)** to improve the signal-to-noise ratio and refine the  
353 coseismic surface displacement field (Grandin et al., 2017, Liu et al, 2021), in particular the surface slip  
354 distribution along fault, by mitigating stratified tropospheric phase delays and averaging temporally  
355 uncorrelated atmospheric noise (see section 4.1), and **(2)**, given the shallow depth of the earthquake, to  
356 investigate potential shallow deformation along the fault during the pre- and post-seismic periods.

357

### 358 4.1 Data and Methods

359 We derive a time series of surface displacement from Sentinel-1 images acquired in Interferometric  
360 Wide Swath mode along one ascending track (relative orbit A059, **Table 1**). We use the complete data archive  
361 between 2019/01/04 and 2020/01/29, from sub-swath IW3 only (incidence angle of  $\sim 44^\circ$ ), cropped in an 80  
362 by 80 km zone around the earthquake epicenter (**Fig. 1a**). We follow a Small Baseline Subset (SBAS) approach  
363 to take advantage of the redundancy on the phase information in a network of interferograms in order to  
364 compensate for temporal decorrelation and atmospheric delays (Berardino et al., 2002). Our network of  
365 interferograms (**Fig. S8**) includes both short and long temporal baselines, with a maximum timespan of 11  
366 months, resulting in 254 interferograms built from 66 images.

367 The interferogram processing and time series inversion are performed using the NSBAS software  
368 (Doin et al., 2011), partly derived from ROI\_PAC (Rosen et al., 2004) and adapted to Sentinel-1 data for  
369 spectral diversity corrections (Grandin, 2015). Orbital and topographic corrections are performed using ESA  
370 precise orbits and the Shuttle Radar Topography Mission (SRTM) 1-arc second Digital Elevation Model (Farr  
371 et al. 2007). Corrections from stratified tropospheric phase delays are computed using the ERA5 reanalysis  
372 data from the European Centre for Medium-Range Weather Forecast (ECMWF) (Doin et al. 2009; Jolivet et  
373 al. 2011). Interferograms are multilooked by a factor of 4 in azimuth and 16 in range for unwrapping, leading  
374 to a final pixel size of about 80 m. Filtering is made through a weighted average of the phase gradient, based  
375 on colinearity (Pinel-Puysegur et al., 2012), in sliding windows of 6 pixels. Unwrapping is performed using  
376 the branch-cut algorithm (Goldstein et al., 1988). The coherence threshold used to build masks before  
377 unwrapping is adapted depending on the temporal baseline of the interferograms, and on whether the  
378 interferogram contains coseismic signal or not. We set the unwrapping to be more restrictive for the long  
379 temporal baseline interferograms than for the short baseline ones, in order to avoid unwrapping errors due to  
380 temporal decorrelation. For the coseismic interferograms only, a manual cut is also introduced to prevent the  
381 unwrapping path from crossing the rupture. The trace of this manual cut (**Fig. 4**) is both consistent with the  
382 phase discontinuity visible on the wrapped unfiltered interferograms, with the main surface ruptures we  
383 observed on the field, and with the LRF inherited scarp revealed by the LiDAR high-resolution DEM (Ritz et  
384 al., 2020). Unwrapped interferograms are first visually checked in order to detect large unwrapping errors.  
385 We iteratively compute the time series to recover the phase evolution at each date of acquisition from the  
386 unwrapped differential interferograms. Considering a typical SBAS approach, the phase delays of unwrapped  
387 interferograms are inverted pixel by pixel to solve for the total phase delay of each date relative to the first  
388 date. We apply an additional linear constraint in case sub-networks of interferograms for a pixel could not be  
389 connected due to unwrapping issues (Lopez-Quiroz et al., 2009). After a first inversion, we remove the noisiest  
390 interferograms from the dataset as well as those presenting large scale unwrapping errors, using a Root Mean  
391 Square (RMS) misclosure criterion (pixelwise misclosure within the interferogram network after time series  
392 inversion, Lopez-Quiroz et al., 2009). The network thus reduces to 199 interferograms based on 60 images  
393 (**Fig. S8**). Residual unwrapping errors are automatically corrected in an iterative procedure during the final  
394 NSBAS time series computation, using network adjustment to minimize the RMS misclosure (see RMS



395 misclosure averaged per pixel in **Fig. S9a**).

396 In the following analysis, we mask pixels that are not covered by at least one coseismic interferogram.  
397 Indeed, some pixels close to the rupture zone are not necessarily unwrapped on coseismic interferograms due  
398 to decorrelation. As the time series inversion is performed for each pixel independently, if a pixel has not been  
399 unwrapped in any coseismic interferogram, the pre- and post-event interferograms' sub-networks are disjoint  
400 for this pixel. In that case, the algorithm extrapolates the pre-event linear trend to the post-event period (Lopez-  
401 Quiroz et al., 2009), leading to potentially incorrect coseismic displacement values at these pixels.  
402 In a last step, we perform a temporal decomposition of the unfiltered time series to extract the coseismic  
403 displacement (similarly to Grandin et al., 2017) as well as a linear velocity. The LOS displacement at a given  
404 pixel  $d_{LOS}$  at a time  $t$  writes as:

405

$$406 \quad d_{LOS}(t) = a \cdot t + b \cdot H(t_{cos}) + c \quad (1)$$

407

408 where  $a$  is the velocity,  $b$  the coseismic offset,  $H$  a Heaviside step function,  $t_{cos}$  the date of the earthquake, and  
409  $c$  an offset parameter to account for atmospheric noise in the first image of the time series (used as reference).  
410 We do not include a seasonal term in this decomposition as the relatively short time span of the time series  
411 (one year) does not provide enough information to constrain it well. Finally, maps of ground velocity,  
412 coseismic displacement and cumulative residual of the decomposition are geocoded for further analysis.

413

## 414 **4.2 Results**

415 The coseismic LOS displacement map (**Fig. 4a**) displays less noise than single interferograms for the  
416 same track, thanks to the time series analysis procedure described above. This coseismic map shows an  
417 excellent spatial coverage on the NW side of the earthquake rupture (foot-wall), while higher decorrelation on  
418 the hanging-wall leads to slightly worse coverage on the SE side. In the LOS, we observe up to 10 cm of  
419 positive displacement (toward satellite) on the hanging-wall and 7 cm of negative motion on the foot-wall  
420 (away from satellite), with a maximum relative displacement reaching 16 cm in the SW part of the rupture,  
421 close to the location  $4.65^{\circ}\text{E}, 44.52^{\circ}\text{N}$  (**Figs 4a and d**). Other smaller local slip maxima can be noticed in the

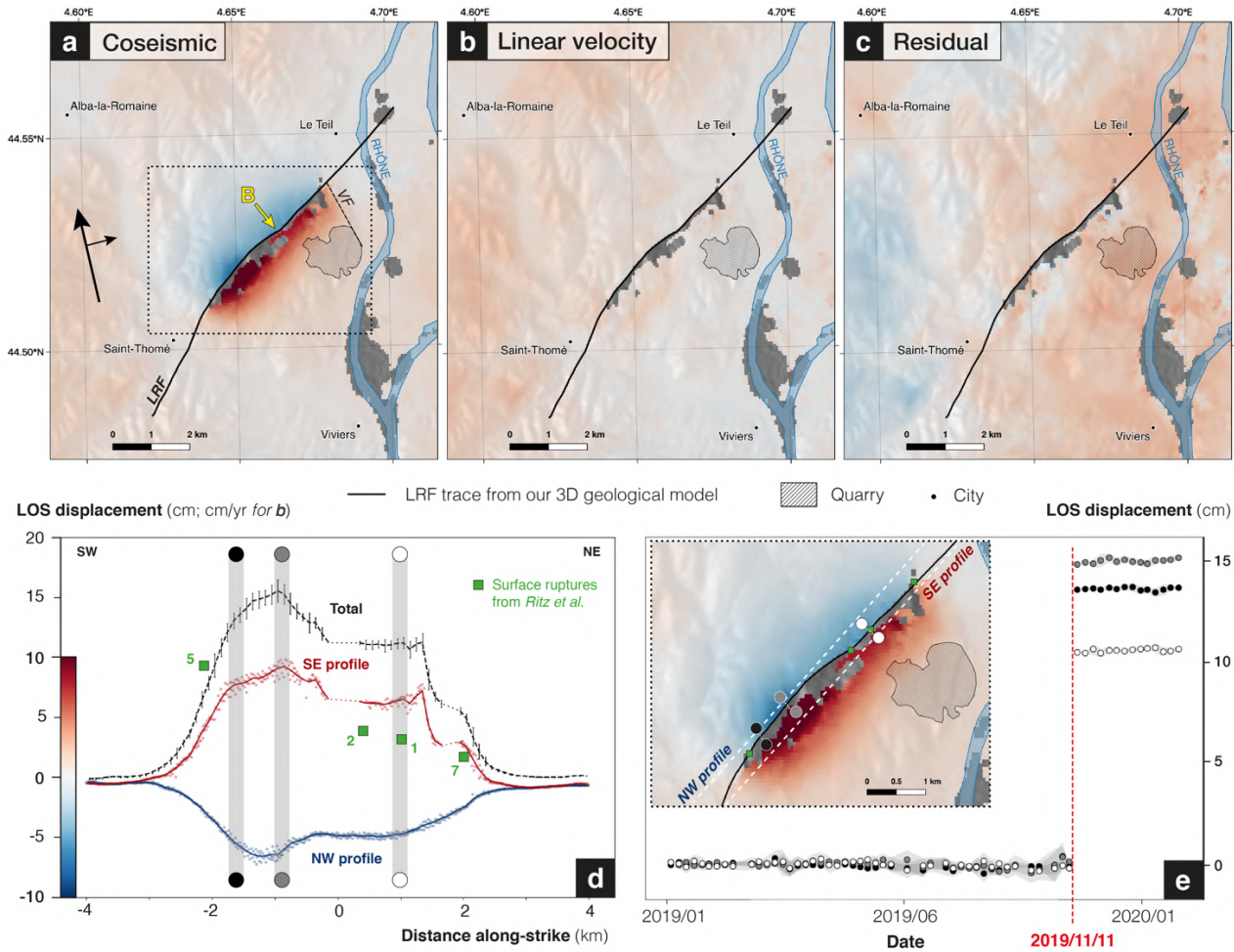
422 NE part of the rupture. Our results confirm that the total rupture length is about 5 km (**Fig. 4d**).

423 The green squares in **Fig. 4d** indicate the vertical offsets measured by Ritz et al. (2020) using terrestrial  
424 LiDAR, projected in the LOS, so that they are comparable to our InSAR relative displacements (black profile  
425 in **Fig. 4d**), assuming that the displacements measured by InSAR are mainly in the vertical direction. Surface  
426 displacements measured by LiDAR at sites #1, #2 and #7 are much smaller than the total amount of  
427 displacement retrieved by InSAR. This inconsistency is most likely explained by a difference of scale and  
428 resolution between the techniques used, since InSAR measures the distributed deformation (at tens of meter  
429 scale) while field LiDAR measures more localized deformation (at centimeter scale). This would be consistent  
430 with the suggestion by Ritz et al. (2020) that the deformation is more distributed in the north-eastern segment  
431 of the rupture. On the contrary, LiDAR measurement #5 indicates a slightly larger displacement than the one  
432 estimated by InSAR. This might be explained by the 500 m distance between our two profiles. If the  
433 deformation is very localized in this part of the rupture, as suggested by Ritz et al. (2020), the relative  
434 displacement between these two InSAR profiles may not capture the maximum of the displacement because  
435 they are not close enough to the fault. Therefore, the field measurement could exceed the InSAR measurement  
436 there.

437 The linear velocity of the time series decomposition is difficult to interpret (**Fig. 4b**). Given the very  
438 low compression rate in the Le Teil region ( $\sim 0.1$  mm/year in the  $\sim N110$  direction, Masson et al, 2019), this  
439 linear term most likely represents the aliased seasonal atmospheric signal, dominating, especially as our time  
440 series covers a relatively short time span (one year).

441 After removing the coseismic and linear trend from the unfiltered time series, we analyse the  
442 cumulative residual displacement map to detect potential pre-seismic deformation or afterslip. We do not  
443 identify (**Fig. 4c**) any clear spatial pattern in the vicinity of the LRF that could be interpreted as pre- or post-  
444 earthquake deformation. The cumulative displacement map from post-seismic dates only does not show such  
445 pattern either. Thus, we conclude that there was no post-seismic deformation for this earthquake, or at least no  
446 *detectable* post-seismic deformation (it might be too small or too deep to be seen with InSAR). It justifies the  
447 simple decomposition strategy adopted, into linear and coseismic terms only, without a post-seismic  
448 logarithmic term. The analysis of the relative LOS displacement between points located on either side of the  
449 Le Teil earthquake rupture only a few hundred meters from each other confirms no relative pre- or post-seismic

450 motion (**Fig. 4e**). Such a relative displacement between points situated at very close distance can be assumed  
451 to be little affected by atmospheric noise because spatially correlated noise is largely removed by the double-  
452 difference operation. No obvious signal arises in the relative time series associated with these points, although  
453 it shows a higher dispersion from May 2019 to the date of the earthquake (0.29 cm and 0.48 cm before and  
454 after May, respectively). However, due to the short time-span covered and the lack of a specific spatial pattern  
455 near the fault, we interpret this higher dispersion as a residual uncorrelated seasonal signal, possibly of  
456 atmospheric or hydrological origin, rather than actual pre-seismic deformation.



457

458

459 **Figure 4.** InSAR time series decomposition results (a) Coseismic Line Of Sight (LOS) displacement and (b)  
 460 linear LOS velocity, best-fitting the InSAR time series over the entire observation time span. (c) Cumulative  
 461 residual displacement of the InSAR time series decomposition, after removing coseismic signal and cumulative  
 462 displacement due to linear trend. (d) Along-strike distribution of coseismic LOS displacement. Red (resp. blue)  
 463 profile shows slip distribution along the southeastern (resp. northwestern) side of the fault; see location of  
 464 profiles in e. Black profile is the differential between red and blue profiles and represents the total relative  
 465 displacement along the rupture trace (error bars correspond to the sum of the standard deviations of the two  
 466 profiles). Green squares are vertical surface displacements (projected on LOS) measured by terrestrial LiDAR  
 467 from Ritz et al. (2020), with their original numbering. Grey vertical bars indicate along-strike location of sites  
 468 for which InSAR time series are shown in e. (e) Relative time series for three pairs of points located on each  
 469 side of the rupture (black, grey, white dots located on inset map from a. 2 sigma envelope of noise level is

470 shown in light grey. Color code for InSAR maps in a to c and e is shown on vertical axis of d (*in cm for a, c,*  
 471 *e; in cm/year for b*). Positive LOS changes indicate motion toward the satellite. The yellow “B” in a indicates  
 472 a fault bend discussed in section 6.2. *LRF*: La Rouvière Fault; *VF*: Violette Fault.

473

474

## 475 5 Coseismic slip inversion

476 We rely on InSAR data as the only geodetic data available to invert for the coseismic slip distribution  
 477 at depth, using the CSI python library ([github.com/jolivet/csi](https://github.com/jolivet/csi); Jolivet et al., 2015). We use as input the LOS  
 478 coseismic displacement map extracted from our time series as described in section 4 for track A059, and  
 479 unwrapped coseismic interferograms for the other three tracks (**Table 1, Figure S11**). These single  
 480 interferograms were processed following the same workflow and parametrization as described in section 4.1,  
 481 except for the multilooking factors, which are 2 in azimuth and 8 in range for unwrapping, leading to a final  
 482 pixel spacing of about 40 m.

483

484 **Table 1.** InSAR dataset used as input for the slip inversion.

Sentinel-1 track	Type of data	Acquisition dates	Final downsampling distance (m)
A059 (ascending)	Coseismic displacement extracted from the time series	Between 2019-01-04 and 2020-01-22	200
A161 (ascending)	Interferogram	2019/11/01-2019/11/13	400
D037 (descending)	Interferogram	2019/11/11-2019/11/17	400
D139 (descending)	Interferogram	2019/11/06-2019/11/12	400

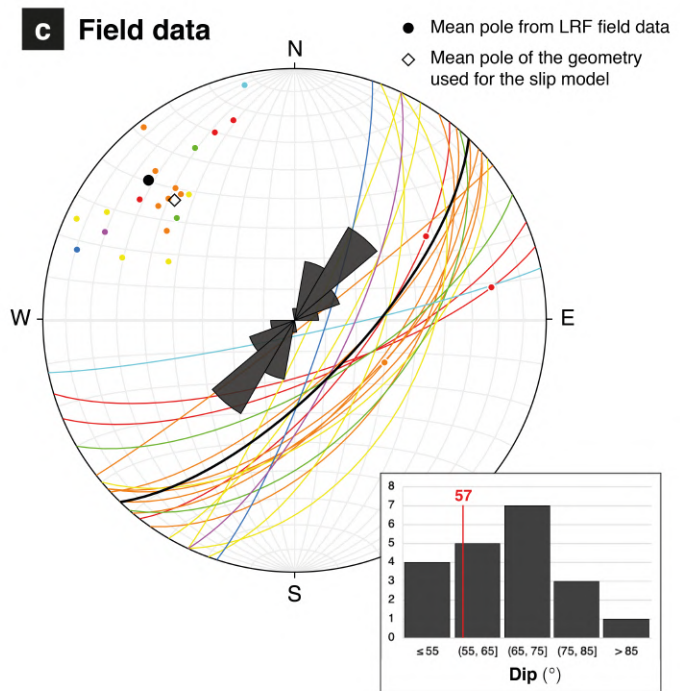
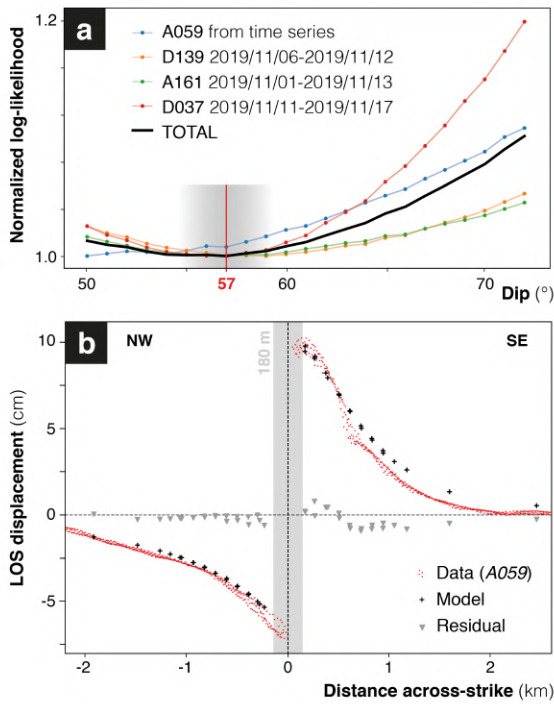
485

486 We downsample the four InSAR datasets using a distance-based algorithm in CSI (pixel size decreases  
 487 as an exponential function of the distance to the fault trace). As we have more confidence in the displacement  
 488 map derived from our time series, especially in the near-field, we downsample this dataset using a final 200 m  
 489 resolution (closest to the fault) while using 400 m for interferograms. This leads to a greater number of data

490 points (about 1100), and therefore a greater weight in the inversion for track A059 than for the other three  
491 tracks (about 470 data points each). In order to prevent some of the downsampled pixels to cut across the  
492 surface trace of the fault, we remove all points within a 180 m buffer in the vicinity of the fault trace. Our  
493 dataset still preserves a high level of detail on the near-fault deformation signal enhanced by the time series,  
494 helping to constrain the shallow part of the slip distribution.

495 We model surface displacements due to slip on dislocations embedded in a homogeneous elastic half-  
496 space. Our fault model is tied to the surface trace of the LRF defined in our 3D geological model derived from  
497 field observations and LiDAR analysis and projected onto the free surface of the elastic half-space. From this  
498 trace, striking N43 in average, we build a fault plane with a constant dip (the value of which is detailed  
499 hereafter) to the South-East, discretized into triangular patches. The patch size is ~150 m at the surface,  
500 increasing to ~300 m at the base of the fault (at a depth of around 4 km). We compute the Green's functions  
501 relating unit slip on each triangular patch to surface displacements using the method of Meade (2007) for  
502 triangular patches. We perform a static inversion using a non-negative least squares strategy (Tarantola, 2005),  
503 with the regularization scheme of Radiguet et al. (2011). We account for uncertainties in the InSAR data  
504 through the calculation of a data covariance matrix describing the spatial correlation of the pixels (Lohman &  
505 Simons, 2005; Sudhaus & Jónsson, 2009; Jolivet et al., 2014; Jolivet et al., 2015).

506 With this setting, we explore the influence of fault dip on the slip distribution for fault planes with  
507 dips ranging between 30 and 75°. We compare the different models using a posterior log-likelihood (LLK)  
508 function quantifying the misfit associated with each fault geometry (a low LLK indicates smaller misfit).  
509 Considering the four InSAR tracks the LLK curves show that a dip between 55° and 60° is favoured by the  
510 data, (**Fig. 5a**). This range is consistent with the dips measured on LRF fault planes on the field with an average  
511 fault plane striking N44-69°SE (**Fig. 5c**). We use a fixed dip of 57° for the final inversion.



512

513

514 **Figure 5.** Dip exploration from InSAR analysis and comparison with field data for La Rouvière Fault (LRF)

515 (a) Dip exploration for InSAR data inversion, based on normalized log-likelihood function. Colors represent

516 different tests made using single coseismic interferograms or coseismic slip map extracted from time series

517 analysis (Fig. 4a). Black curve shows the average function for the whole data set, with best-fitting dips in the

518 range 54-59° and a minimum misfit for 57°. (b) Fault-perpendicular LOS coseismic displacement profile

519 (located in Fig. 6d) for A059 track extracted from time series analysis (red dots), compared with corresponding

520 final model profile (black crosses), and model versus data residuals (grey triangles). Data within 180 m from

521 the fault were discarded in the inversion (see text for details). (c) Field observations of LRF planes, shown in

522 a stereonet (equal area, lower hemisphere projection). Each color corresponds to an outcrop. The mean LRF

523 pole (solid black circle; N314-21°) and plane (black line) are computed from averaging individual poles and

524 planes of each outcrop. The circles located on lines represent slickenside measurements. The pole of the

525 average fault geometry used for slip inversion from InSAR data (white diamond; N315-33°) is shown for

526 comparison. Inset shows dip distribution of the LRF planes measured on the field, compared to the 57° value

527 chosen for the final InSAR data inversion.

528

529 We then explore the regularization parameters of the inversion, introduced through a model covariance  
530 matrix. Three parameters are used in the regularization (Radiguet et al., 2011; Maubant et al. 2020):  $\sigma_m$  a  
531 damping value and  $\lambda$  the correlation length, relative to a scaling factor  $\lambda_0$ , fixed at the minimum interpatch  
532 distance (150 m). We optimize the values of  $\sigma_m$  and  $\lambda$  through L-curves analysis (**Fig. S10**), by choosing the  
533 best compromise between model roughness (quantified by maximum slip) and the misfit to the data (Radiguet  
534 et al., 2011). We use the values  $\sigma_m = 0.7$  and  $\lambda = 2.5$  km for the final inversion.

535 The LOS surface displacements predicted by our preferred slip model match well the InSAR data (**Fig.**  
536 **S11**), with RMS of residual displacements ranging between 0.18 and 0.51 cm. Consistently with its  
537 overweighting in the inversion process, the displacement field on track A059 is especially well reproduced  
538 with a 0.43 cm RMS misfit (**Fig. 6d**). Our model slightly overestimates the coseismic LOS displacement in  
539 the hanging-wall (**Fig. 5b**). After testing several faults dips, we conclude that such feature cannot be fitted with  
540 a constant dip geometry, as suggested by the  $\sim 5^\circ$  range of equivalent probability dips in **Fig 5a**. Our model  
541 though is the best compromise for optimizing the fit to LOS displacement for each track and on both sides of  
542 the fault.

543 The resulting slip distribution inverted for the Le Teil earthquake has an equivalent moment magnitude  
544 of 4.9, consistent with seismological estimates (Delouis et al., 2019; Cornou et al., 2020; Vallage et al., 2021).  
545 The scalar seismic moments are  $3.11 \times 10^{16}$  N.m and  $0.9 \times 10^{16}$  N.m for dip-slip and strike slip, respectively,  
546 showing a dominating reverse dip-slip motion (**Figs 6a and b**). This is consistent with the surface InSAR data  
547 (**Fig. S11**) displaying a dominance of the vertical motion in the hanging wall (displacement toward satellite  
548 for both looking angles) and a dominance of fault-perpendicular horizontal motion in the footwall with respect  
549 to vertical motion (opposite signs of motion on ascending and descending tracks). The dip-slip distribution  
550 along the fault is characterized by two areas of larger slip: a large one in the SW part of the fault with a  
551 maximum slip of 30 cm at 500 m depth and a smaller one in the NE part of the rupture with a maximum dip  
552 slip of 24 cm at similar depth. Displacements modelled at the surface have lower amplitudes, with a maximum  
553 dip-slip component of 23 cm on the shallowest patches (**Fig. 6a**). The slip profiles along depth (top left inset  
554 in **Fig. 6a**) highlight this shallow slip deficit reaching 23% of the maximum slip, which will be discussed later.

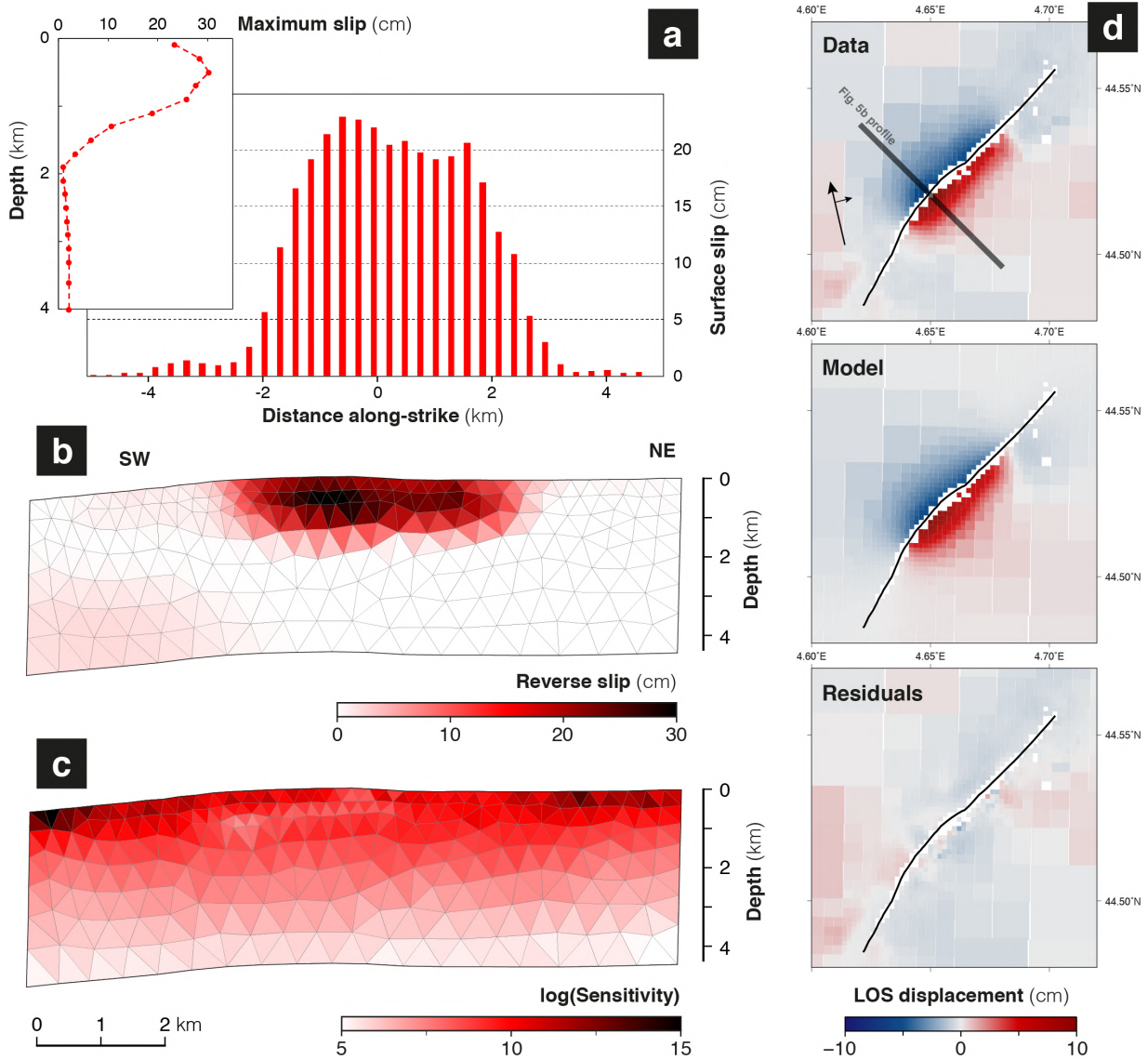
555 We performed extensive testing on the strike-slip component of the slip model, which produced very  
556 variable distributions and senses of slip. Together with the high dependency of the strike-slip distribution to



557 the setting of the inverse problem (non-negative least square inversion versus bounded inversion for example),  
558 this suggests that the strike-slip component is poorly constrained by our dataset. While the best-fitting model  
559 that we present here includes a minor (< 9 cm, **Fig. S12**) left-lateral component, we estimate we cannot trust  
560 either its distribution, or the sense of the strike-slip motion, and do not discuss them further.

561 To qualitatively assess the robustness of our slip model along fault strike and depth, we compute the  
562 sensitivity of the inversion (Loveless & Meade, 2011) (**Figs 6c and S12b**). Note that sensitivity is a purely  
563 qualitative indicator (the absolute values actually depend on the number of data we use in the inversion). Only  
564 Bayesian approaches could provide a meaningful confidence interval to the estimated slip values. For the dip-  
565 slip component, despite small shallow variations due to lack of data close to the fault, sensitivity only decreases  
566 significantly below 2 km depth where slip vanishes. We therefore state that our modelled dip-slip distribution  
567 is correctly constrained by the data above that depth. Note that the sensitivity for the strike-slip component  
568 appears on average about one order of magnitude lower than the dip-slip one (**Fig. S12b**).

569



570

571

572 **Figure 6.** Best slip model. (a) Along-strike distribution of surface slip in our final slip model (dip-slip  
 573 component only). Inset shows depth distribution of maximum slip. (b) Slip distribution for dip-slip component  
 574 (strike-slip is shown in Fig. S6). (c) Sensitivity (Loveless & Meade, 2011) of the inversion for the dip-slip  
 575 component (see Fig. S12 for the strike-slip one). (d) *Top*: downsampled data from time series analysis of A059  
 576 track, used for slip inversion; *Middle*: Model; *Bottom*: Residuals.

577

## 578 6 Discussion

### 579 6.1 Reactivation of LRF and rupture geometry

580 Our results, combining 3D geological mapping, InSAR time series analysis and slip inversion suggest  
581 a reactivation of the La Rouvière fault during the 2019 Le Teil earthquake. The trace of the LRF defined in  
582 our 3D geological model is compatible with the rupture displayed by the InSAR signal. Moreover, although  
583 no direct evidence of reactivation was found on the LRF planes, the main evidence of surface rupture  
584 associated with the Le Teil earthquake (on which vertical offset could be measured by Ritz et al., 2020) are  
585 located very precisely on our trace of LRF (**Fig. S13**). Other evidence was found within several tens to  
586 hundreds of meters from the LRF trace, but were less probably directly related to the rupture (e.g. gravitational  
587 collapse). Our slip model using a geometry based on the LRF fault trace is able to reproduce InSAR data with  
588 a very good level of agreement, reinforcing the consistency of the reactivation hypothesis.

589 Thanks to a time series approach, we improve the coverage of the displacement field extracted from  
590 InSAR, compared to interferograms produced just after the earthquake and used in published studies. We show  
591 the absence of pre-event deformation or afterslip, while providing, for one Sentinel-1 track, an accurate  
592 coseismic LOS displacement map. Although our unwrapping approach is more conservative than in some other  
593 works (Ritz et al., 2020; De Novellis et al., 2020), we ensure we can trust all our unwrapped displacements,  
594 especially for the highly decorrelating zone in the SW neighbourhood of the rupture. Doing so, we limit the  
595 risk of over-interpreting the data.

596 It should be noted that the InSAR displacement map from our times series does not show a multi-  
597 segmented rupture, contrary to what has been suggested so far (Ritz et al., 2020; De Novellis et al., 2020).  
598 Instead, our data favours a single rupture trace, collocated with the LRF trace. We compared the previously  
599 published rupture traces with our coseismic displacement map (**Fig. S13**). The trace from De Novellis et al.  
600 (2020) appears to be inconsistent with our data, **(1)** as their main segment is too straight and does not follow  
601 the InSAR discontinuity, and **(2)** as our displacement map does not display any evidence for a secondary  
602 rupture along La Chade fault. The rupture trace from Ritz et al. (2020) generally follows the surface trace of  
603 the LRF that we infer. However, our data are not consistent with secondary ruptures in the NE part of the  
604 hanging-wall. As the secondary ruptures presented in these two studies are not mutually consistent, we

605 speculate that inconsistencies mainly stem from noise in in the coseismic interferograms they used, which are  
606 mitigated in our time series analysis.

607         Additionally, our study brings additional constraints on the LRF dip, both at the surface and at depth.  
608 Field measurements of LRF planes yield a mean strike of N44 and dip of 70° to the SE (**Fig. 5c**), however  
609 associated with a large dispersion (95% confidence interval about  $\pm 17^\circ$ ). The inversion of the InSAR data  
610 reveals a best fitting dip in the range 55-60° (**Fig. 5a**). Considering the uncertainty on these estimates, we argue  
611 that the LRF should not show substantial variations of dip angle in the depth range ruptured by the Le Teil  
612 earthquake ( $< 2$  km), although we cannot exclude a slight steepening close to the surface. De Novellis et al.  
613 (2020) used a 52° dip on the LRF for their two faults slip model, and a 62° dip for their single fault geometry,  
614 consistent with our modeling results. Vallage et al. (2021) find best fitting dips for a single fault of 60° using  
615 InSAR, still in agreement with our estimates. Regarding seismological estimations of the focal mechanism,  
616 Vallage et al. (2021) propose a nodal plane striking N45-65°SE, while Delouis et al. (2021) propose nodal  
617 planes striking N45 to N65 and dipping 40 to 60°E from waveform inversion. They are all consistent with our  
618 results and also suggest that the LRF has a similar dip from the surface to at least 1-1.5 km depth, where the  
619 earthquake likely nucleated.

620

## 621 **6.2 Potential interactions between 3D geology, fault geometry and earthquake slip**

622         The implementation of a local 3D geological model, combined with the slip model derived from  
623 InSAR offers the opportunity to study potential interactions between the earthquake slip and the pre-existing  
624 three-dimensional geological structure. The more recent relocations of the point source of the Le Teil  
625 earthquake by Delouis et al. (2021) can be discussed together with our slip distribution. The epicentral area  
626 that they estimate is located between the western part of Le Teil quarry and the LRF (**Fig. 1a; Fig. 2b**), with a  
627 source depth between 1 and 2 km (**Fig. 2c; Fig. 7**; Delouis et al., 2021). It is consistent with our estimate of  
628 the fault location and dip.

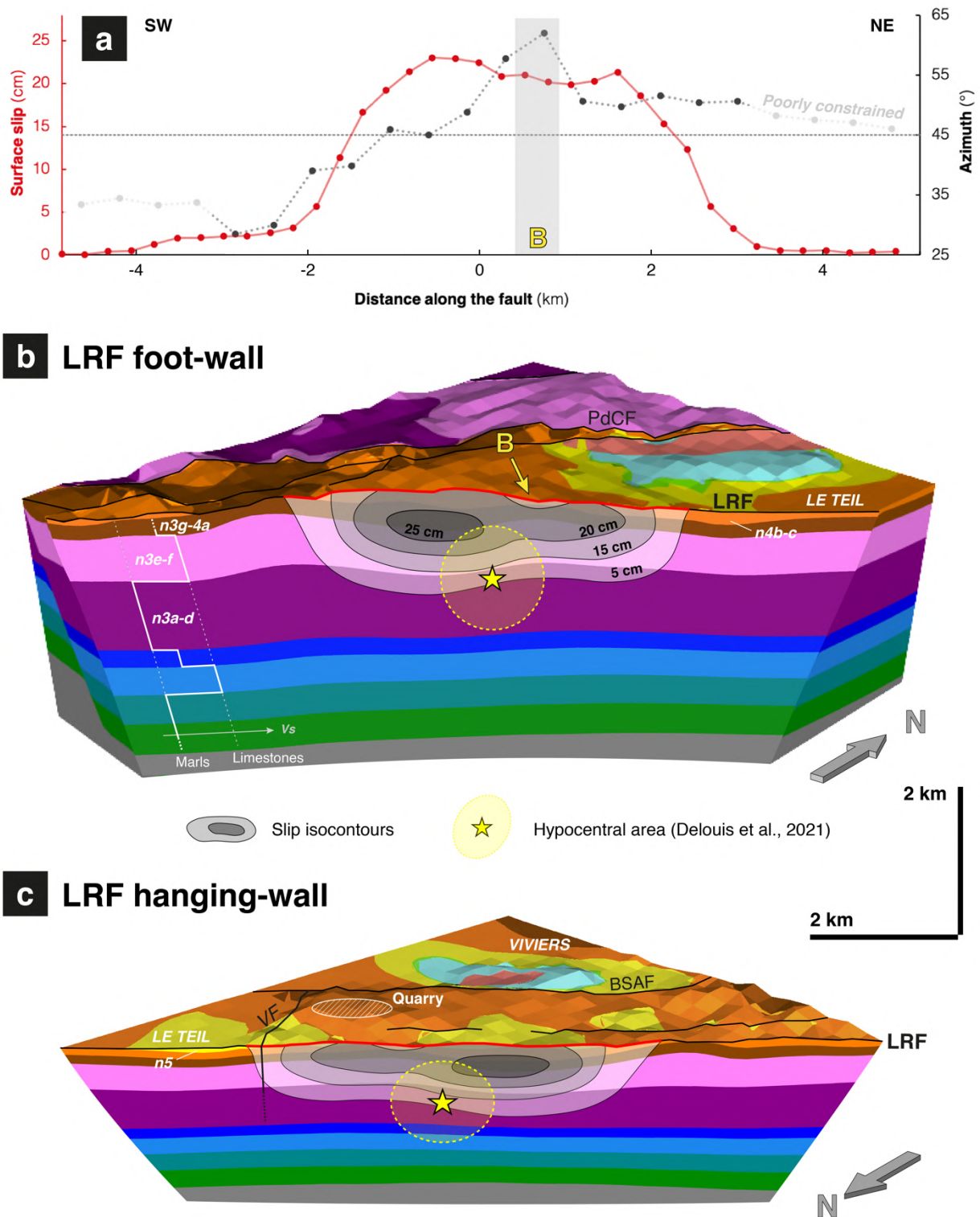
629         Our fieldwork allows us to map a previously unknown fault, displaying post-Cretaceous strike-slip  
630 motion (**Fig. 3c**), with a N150 orientation, that we named Violette fault (VF). In the field, we found no evidence  
631 of any fault north of its inferred crossing point with the LRF. We therefore map the VF fault stopping on the  
632 LRF fault, assuming that the LRF is more recent. Our InSAR coseismic displacement map shows that the uplift

633 of the hanging-wall vanishes to the NE in the area where the VF intersects the LRF (**Fig. 4a**). Consistently,  
634 our modeled slip on fault tapers down to zero to the NE in the interaction zone between the VF and LRF (**Fig.**  
635 **7c**). We speculate that the connection area of the two faults could have acted as a barrier to the north-eastward  
636 propagation of the earthquake, as already documented for other cases in literature (e.g. Klinger et al., 2006;  
637 Walters et al., 2018).

638 The combination of our 3D geological model and the slip model also allows one to study potential  
639 geological constraints on the depth extension of slip during the earthquake. As mentioned earlier, the Le Teil  
640 earthquake is very shallow, and slip does not exceed 25% of its maximum value (i.e. slip < 8 cm) at depths  
641 larger than 1.5 km (**Fig. 6a**). Our 3D geological model shows a lithological transition at ~1 km depth ( $\pm 100$   
642 m between the foot-wall and the hanging-wall of the LRF) between massive limestone units (n3e-f) on the top  
643 and an underlying thick (~1 km) marl unit (n3a-d) (**Figs 7b and c**). This transition is likely associated with a  
644 downdip drop of rock rigidity along the LRF plane. This feature was previously noticed in local velocity  
645 models (Causse et al., 2021), by the need to introduce a low-velocity zone about 1 km thick at depths greater  
646 than 1200 m. Earthquake propagation is known to be facilitated in high rigidity media. Specifically, in a region  
647 where geological units are similar to those observed in Le Teil region, Gratier et al. (2013) showed that  
648 limestones' layers favour seismic slip while marls often creep. Thus, our results suggest that while most of slip  
649 occurred in massive limestones (n3e-f and n4b-c, i.e. the Urgonian limestones), the n3a-d marls layer could  
650 have prevented the earthquake nucleation and/or propagation at greater depth.

651 According to our slip model, the coseismic slip reached the surface along the whole rupture length  
652 (~5km), but with heterogeneous amounts of surface slip. Two main slip maxima can be identified in the surface  
653 slip distribution (**Figs 6a and 7a**), corresponding to the two main slip patches of the slip distribution at depth.  
654 A significative change in the LRF strike, marked by a peak at N60, is observed in between these two maximum  
655 slip locations and is marked "B" in **Figs 4a, 7a and 7b**. This change in azimuth is well resolved since the  
656 central portion of the LRF was mapped using a 25cm LiDAR DEM and complemented by field measurements  
657 (while the SW and NE parts of the LRF — greyish in **Fig. 7a** — were only constrained by a few outcrops).  
658 Such type of geometrical complexity may act as barrier to earthquake rupture propagation (King & Nabelek,  
659 1985; Wesnousky et al., 2006; Klinger, 2006). Hence, we suggest that this change in the LRF surface geometry  
660 could have restrained the slip propagation. We have no constraints on the potential downdip continuation of

661 this relay zone. However, considering the shallowness of the slip distribution, its impact could remain  
 662 significant at depth, and maybe have contributed to the delimitation of the two slip maxima.



663  
 664 **Figure 7.** 3D summary of Le Teil earthquake rupture characteristics. (a) Along-strike coseismic surface slip  
 665 distribution derived from our model (in red, dip-slip component only) compared to along-strike variations of

666 local fault azimuth (in grey). Poorly constrained azimuths due to limited LRF field evidences are plotted in  
667 lighter grey. The yellow “B” letter shows the main bend mentioned in the text. (b) and (c) 3D views of the NW  
668 (b) and SE (c) part of our 3D geological model, cut along the LRF fault plane. The detailed lithological  
669 description is in Fig. 2. A qualitative velocity model, assumed to represent the variability of rigidities of rocks  
670 observed in the field is plotted in b (left side). The isocontours of the slip distribution inferred from InSAR are  
671 superimposed in grey, together with hypocentral area (in yellow) from seismological data (preferred relocation  
672 of the mainshock by Delouis et al., 2021, with associated uncertainty of ~500 m). *PdCF*: Pontet-de-Couloubre-  
673 Fault; *LFR*: La Rouvière Fault; *VF*: Violette Fault; *BSAF*: Bayne-St-Alban Fault.

### 674 **6.3 A singular earthquake**

675           The characteristics of this earthquake make it out of range in the Wells & Coppersmith (1994)  
676 empirical relationships. According to these scaling laws, a 5 km surface rupture length is usually associated  
677 with a  $M_w$  5.8-6.1 event, and a 30 cm maximum displacement should result in a  $M_w$  6.3-6.5 earthquake. The  
678 Le Teil earthquake does not fit either the updated relationships from Leonard (2010) between rupture length  
679 and seismic moment. However, these relationships are not necessarily suited for very small and shallow events,  
680 for which small scale variations of physical parameters of the crust could play a critical role (e.g. 2010  $M_w$ 4.9  
681 Pisayambo earthquake, Champenois et al., 2017).

682           The shallow slip deficit displayed by our model is also present in the InSAR-derived slip models from  
683 previous studies (Delouis et al., 2019; De Novellis et al., 2020; Vallage et al., 2021). In the framework of a  
684 homogeneous elastic half-space inversion, it is difficult to assess whether Surface Slip Deficit (SSD; Fialko et  
685 al., 2005) is a real feature or an artifact resulting from the lack of data coverage close to the fault, or caused by  
686 neglecting the likely complexities of the elastic medium (Xu et al., 2016; Marchandon et al., 2021). Slip  
687 modeling is probably more sensitive to these parameters for such a small event than for larger events, for which  
688 the spatial resolution is often decreased for the sake of computational tractability. Taking advantage of the 3D  
689 geological model built in this study to create a layered 2D, or even 3D, elastic model, and use it to compute  
690 the Green's functions, although technically feasible, is beyond the scope of the present study. This would  
691 require a way to quantify the physical parameters of the rocks from the different geological facies we observed  
692 in the field. This could be achieved through lab experiments on samples or the comparison of the 3D geology  
693 with a local velocity model derived from seismological observations. A good resolution in the very shallow  
694 part (depth <500m) of such an elastic model would be needed to improve tangibly the fit of the surface  
695 displacements.

696           The Le Teil earthquake occurred on an ancient normal fault, for which we observe no evidence of  
697 post-Oligocene activity. As suggested by Ritz et al. (2020), although the LRF has a clear geomorphic  
698 expression, it is not sharp enough to result from a significant seismic activity in the last tens of thousands of  
699 years. An ongoing work by Ritz et al. (2021) suggests from paleoseismological trenches that the LRF could  
700 have hosted at least one event in the historical period, with kinematic features consistent with reverse motion.  
701 Pending the outcome of these paleoseismological results to come up, based only on geomorphology, we cannot



702 know how recent the first reactivation of the LRF as reverse fault since Oligocene is, as the very slow  
703 deformation relative to the erosion rates likely hinders the preservation of this recent activity.

704         Why this earthquake occurred on the LRF, when it is not the fault displaying the largest cumulative  
705 offset in the area according to our 3D geological model, is still a matter to debate. Actually, fieldwork and 3D  
706 geological modeling have not given us any argument to explain the occurrence of an earthquake on the LRF  
707 rather than on any other. The very shallow depth of the event and the small number of aftershocks (Cornou et  
708 al, 2020), coupled with the presence of a large active quarry in the LRF hanging wall have led some to propose  
709 that the earthquake was induced by a reduction of normal stress along the LRF due to the artificial discharge  
710 (De Novellis et al. 2020). This hypothesis has led to a national and international public media debate raising  
711 major issues of liability and seismic risk. It has been discussed by a national scientific commission (Delouis et  
712 al., 2019) and scientific publications (Ampuero et al., 2020, De Novellis et al. 2020), but no definite answer  
713 has yet been reached. Our study did not focus on this aspect, and we found no element which could help in the  
714 debate. InSAR time series shows no localized deformation that could be associated with the quarry discharge.  
715 Tracking such a signal, if it exists, would probably necessitate to study a much longer InSAR time series.

716         The geological and structural framework in which the 2019 Le Teil event occurred, characterized by  
717 NE-SW oriented faults cutting limestones and marls units, is quite ubiquitous along the right-bank of the Rhône  
718 river between latitudes 44.3 and 44.8°N (**Fig. 1a**). Moreover, many other smaller quarries exploit the Urgonian  
719 limestones in this region. The assessment of the seismic potential of the many faults similar to the LRF,  
720 potentially in relation with quarrying activities, is of paramount importance, given the presence of two nuclear  
721 power plants located 15 km north and 25 km south of Le Teil. Future studies combining 3D geology, sub-  
722 surface imaging and paleo-seismology should help improve the knowledge of faults' activity in this slowly  
723 deforming region. Furthermore, the integration of geological datasets at regional scale, together with  
724 seismological observations could benefit to seismic hazard assessment, for example through the identification  
725 of geological units associated with a higher probability of seismic slip (such as the Urgonian limestone layer,  
726 e.g. Thouvenot et al. 2009).

727

## 728 7 Conclusion

729           The 2019  $M_w$ 4.9 Le Teil earthquake, while not causing heavy fatality, reveals a critical lack of  
730 knowledge regarding the activity of the northeastern part of the Cévennes fault system, emphasized by a high  
731 vulnerability due to the proximity to nuclear facilities and populated areas.

732           Our study helps characterize the Le Teil earthquake through a multidisciplinary approach. The 3D  
733 geological modeling that we carried out provides an updated view of the local geological and structural context  
734 in which this event occurred. Our InSAR work enhances the coseismic displacement map proposed previously  
735 from single interferograms, and rules out the existence of a significant deformation in the 10 months before  
736 and 3 months after the event. The inversion of InSAR data for slip distribution reveals the consistency between  
737 InSAR observations and the modeled 3D geometry of the Oligocene La Rouvière fault. The slip model shows  
738 almost purely reverse faulting along a single  $\sim$ 5 km long rupture, with two main slip patches reaching 30 cm  
739 and 24 cm of slip, respectively, at 500m depth, and a fault dip of 55-60°. The rupture ends at the intersection  
740 between the La Rouvière fault and the previously unmapped Violette fault which may have acted as a barrier.  
741 Our analysis also suggests that both a fault bend and rigidity contrasts in the local stratigraphy influenced the  
742 slip distribution. These results confirm that the area is currently undergoing a WNW-ESE shortening which,  
743 whilst slow, could reactivate older faults inducing damaging seismicity, and therefore calls for a reassessment  
744 of the seismic hazard.

745

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## 754 Data availability

755 Sentinel-1 data are available online through PEPS (<https://peps.cnes.fr>) or Copernicus  
756 (<https://scihub.copernicus.eu>) platforms. Precise orbits were downloaded from European Space Agency's  
757 Sentinel-1 website (<https://qc.sentinel1.eo.esa.int/>, in March 2020). SRTM data are provided on Earthdata  
758 portal (<https://earthdata.nasa.gov>). ECMWF ERA5 data are available at <https://www.ecmwf.int>.

759 The database of geological observations (DataGeol) generated during this study is available at  
760 <https://zenodo.org/record/4836308#.YLDijDYzYWp>. The 3D geological model can be downloaded at  
761 [https://zenodo.org/record/5974794#.Yf\\_USC\\_pUI](https://zenodo.org/record/5974794#.Yf_USC_pUI). The principal maps extracted from the InSAR time series  
762 analysis can be downloaded at <https://zenodo.org/record/4836335#.YLDokS8isWo>.

763

764

## 765 Authors contribution

766 P.H.L. and C.L. conceived the study. L.M. and P.H.L. did fieldwork. L.M. and S.C. did geological 3D  
767 modeling. L.M. and C.L. processed and analyzed the InSAR time series. L.M., R.J. and C.L. carried inversion  
768 of slip distribution. R.G. and O.C. contributed to InSAR processing. L.A. provided the LiDAR data and  
769 contributed to its analysis. L.M., P.H. L., C.L., R.J., R.G. and M.M. contributed to the interpretation and  
770 discussion of the results, and writing the manuscript.

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- 1059

1060 **Supplementary Material**

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1063 The 3D geological model can be downloaded at  
1064 [https://zenodo.org/record/5974794#.Yf\\_USC\\_pPUI](https://zenodo.org/record/5974794#.Yf_USC_pPUI).

1065 (To open with Adobe Acrobat Reader)

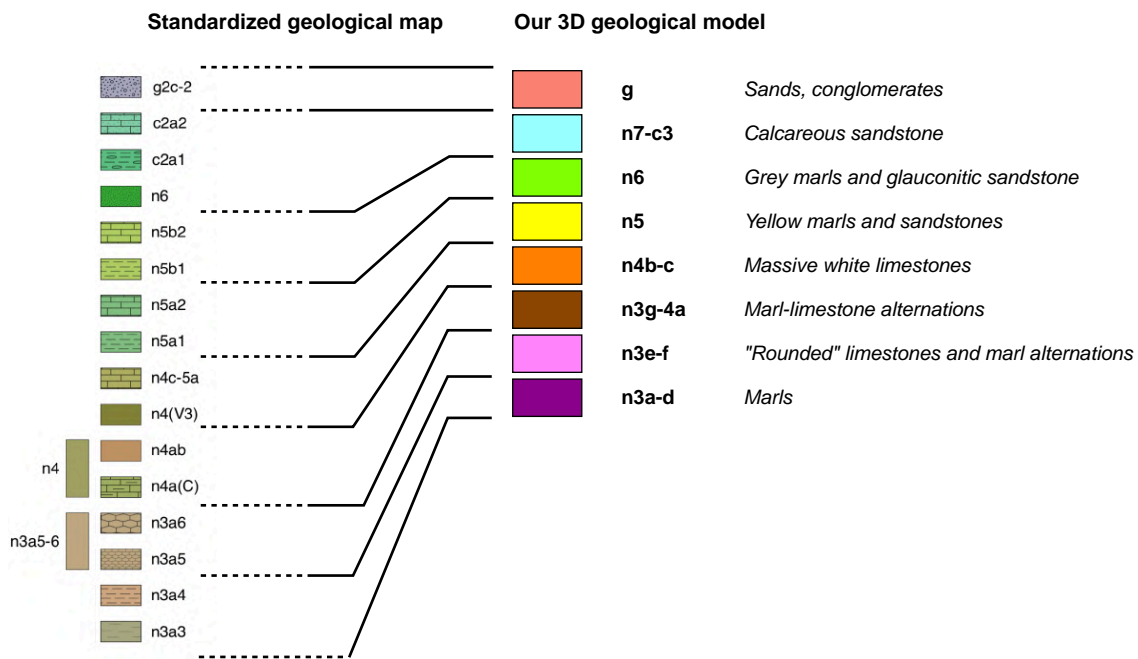
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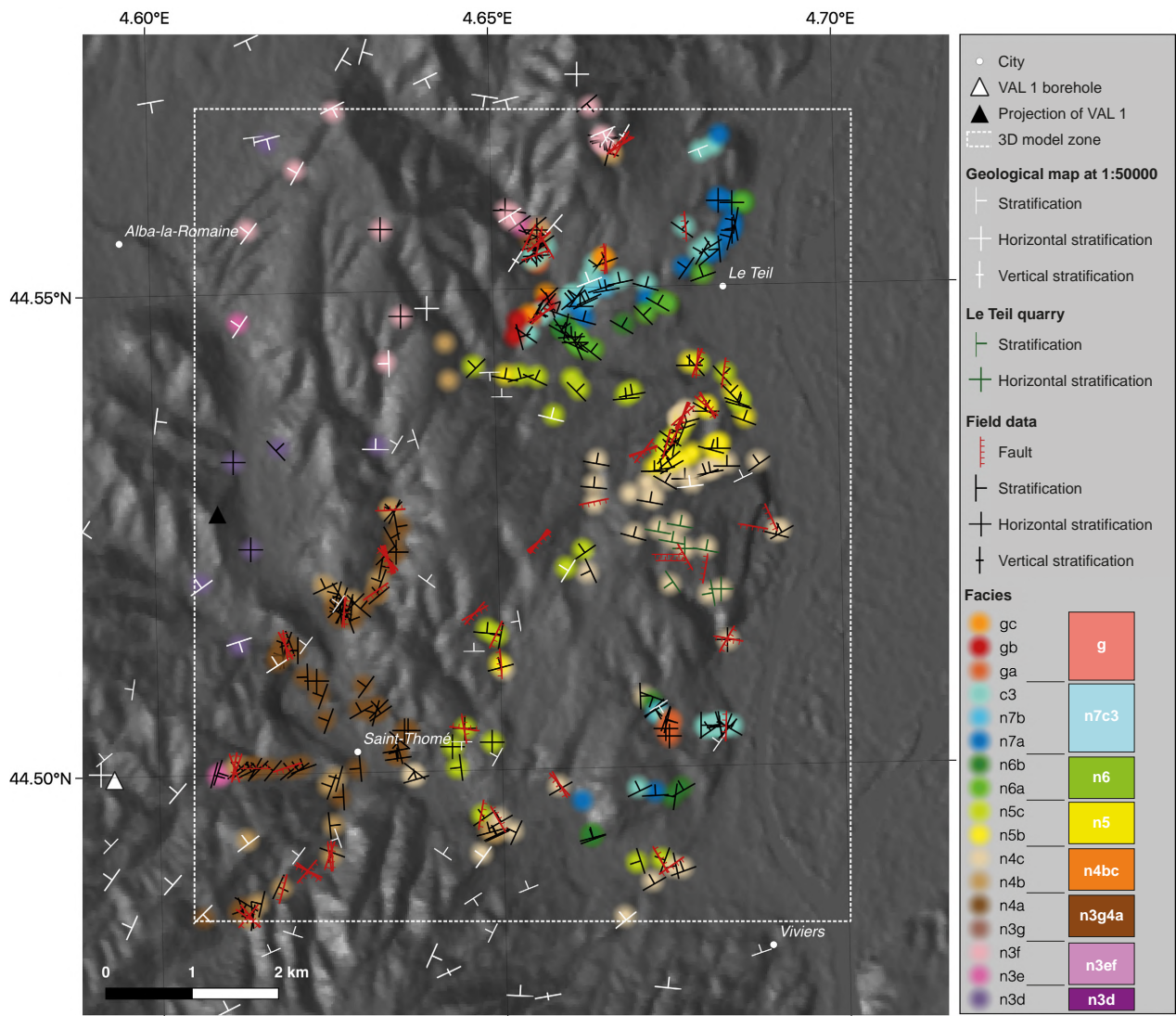


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1072 **Figure S1.** Correspondence of stratigraphic logs between published geological maps, and our 3D model, for  
1073 units outcropping in the 3D model zone.

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1077 **Figure S2.** Complete data set used as input for 3D geological modeling.

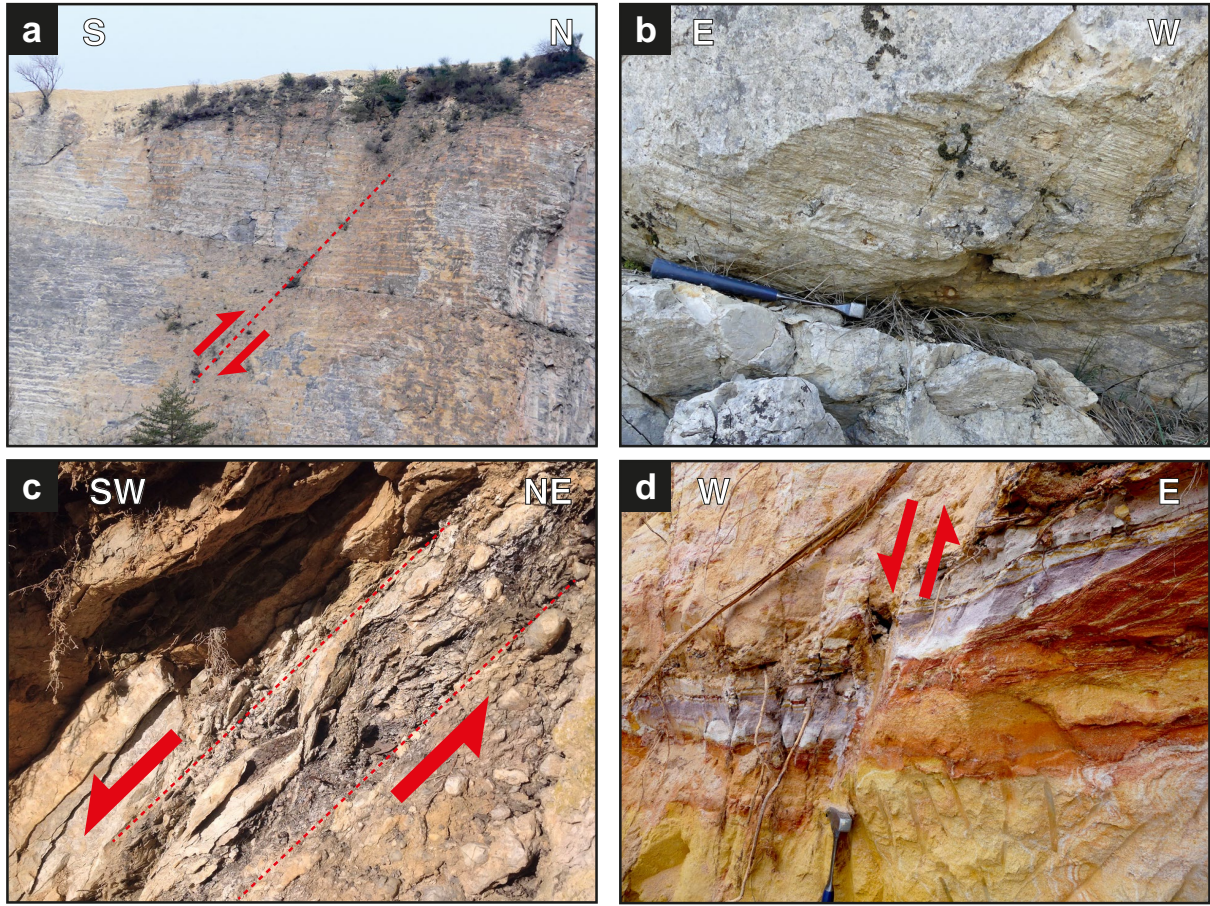
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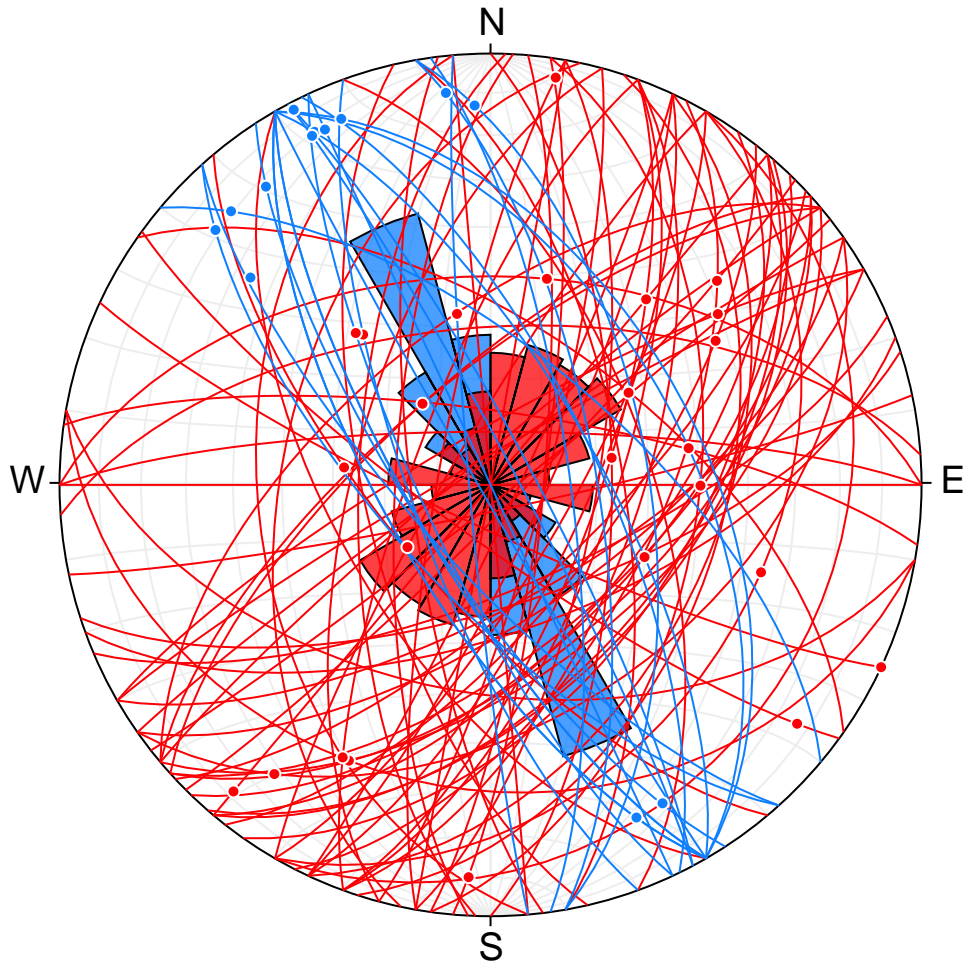
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1083 **Figure S3.** Additional field observations. (a) [Site LT123] Thrust fault in barremian limestones, striking  
 1084 ~N100 and offsetting a stratigraphic level by a few meters. (b) [Site LT62] Fault plane showing strike-slip  
 1085 slickensides in limestones. (c) [Site LT59] Shear zone oriented ~N150 with C-S criteria suggesting a partially  
 1086 normal faulting. (d) [Site LT29] Normal fault in typical Oligocene colored sands, with 17 cm offset. Sites'  
 1087 location is shown in Fig. S7.

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1092 **Figure S4.** Stereonet of all fault field measurements. The ~N150 strike-slip faults are in blue. All other faults  
1093 measured are in red. Fig. 5(c) shows only the measurements corresponding to La Rouvière fault.

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VAL 1 BOREHOLE				INTERPRETATION FOR 3D MODEL			
Absolute depth (bottom)	Relative depth (bottom)	Thickness	Formation	Thickness	Formation	General facies	Remarks
-147	0		Surface		n3ef		
547	694	694	HAUTERIVIAN	694	n3ad	Marls with clayey limestone layers Glaucopitic at bottom	Thickness not consistent with the geological map, which describes a max. thickness of 850 for the whole n3 unit. Despite that, we keep borehole thickness.
765	912	218	VALANGINIAN	890	n2	Marls with clayey limestone layers	Thickness largely under-estimated in this borehole because of a fault. Corrected using geological map description
803	950	38	BERRIASIAN	358	j6n1	Limestones, marl layers	
886	1033	83	TITHONIAN				
927	1074	41	KIMMERIDGIAN				
1123	1270	196	LUSITANIAN				
1205	1352	82	OXFORDIAN	389	j25	Marls, black clays	
1436	1583	231	CALLOVIAN				
1512	1659	76	BATHONIAN				
1925	2072	413	BAJOCIAN	413	j1	Clayey limestones and calcareous marls alternations	
3228	3375	1303	Upper LIAS SUP. (Toarcian-Aalenian)	1303	Lias	Marls, marl-limestone alternations	Uncertainties on the thicknesses.
3422	3569	194	Middle LIAS (Carixian-Domerian)	194	156	Marnes, marnes claires	NOT IN THE MODEL
3953	4100	531	Lower LIAS (Hettangian-Sinemurian)	531	114	Clayey limestones	
			TRIASSIC				

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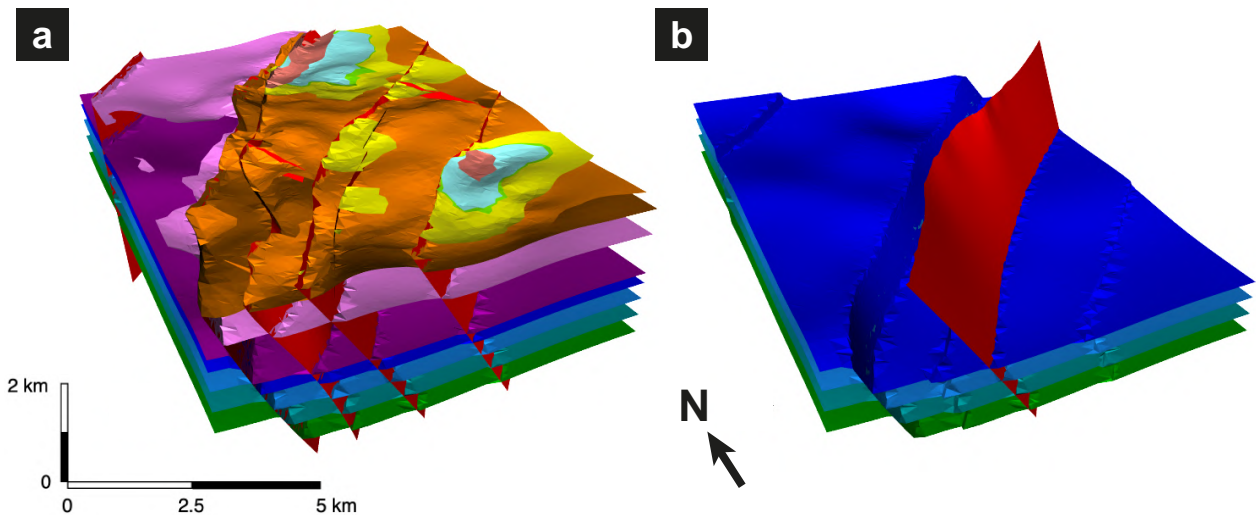
1097 **Figure S5.** VAL 1 borehole interpretation. The borehole is located at 4.5935°E, 44.4997°N.

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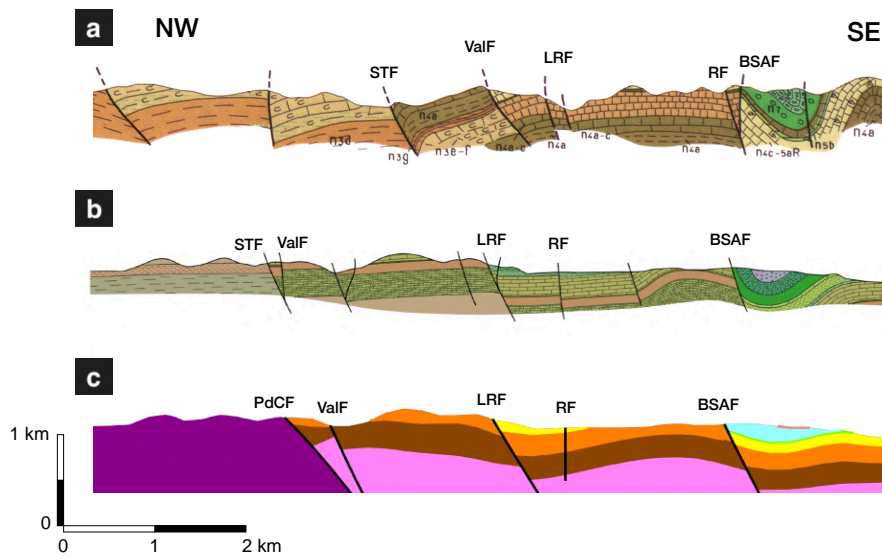
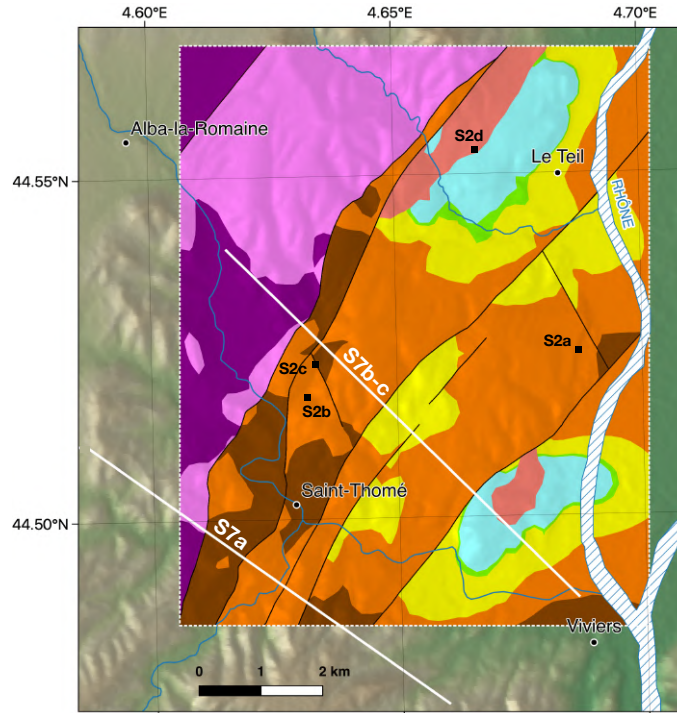


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1103 **Figure S6.** 3D view of the geological model. Color code for units as in Fig. 2. (a) Complete view. (b) Truncated  
1104 view to highlight La Rouvière Fault geometry.

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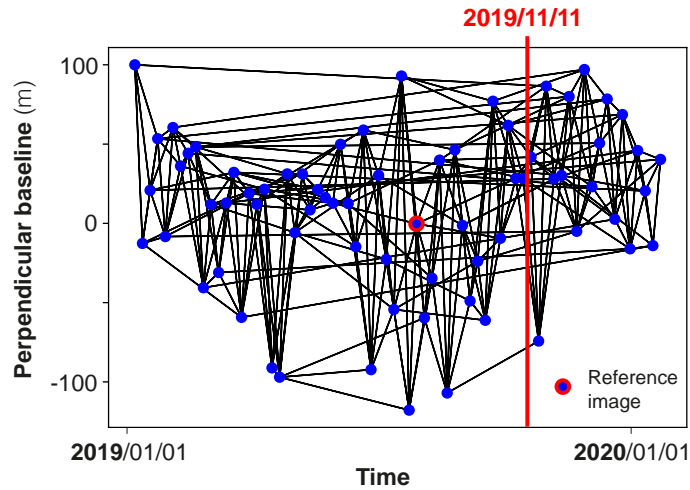


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1107 **Figure S7.** Comparison of published and this study geological cross-sections. (a) Cross-section published in  
 1108 the Aubenas 1:50000 geological map (Kerrien et al. 1979), located SW of the 3D model zone. (b) Cross-section  
 1109 made from the standardized 1:50000 geological map (Saint Martin, 2009), across the 2019 Le Teil rupture on  
 1110 LRF. (c) Cross section made from our 3D geological model, along the same trace than b. We refer to Aubenas  
 1111 geological map for stratigraphic description of a, stratigraphy of b and c is shown in Fig. S1. *PdCF*: Pontet-  
 1112 de-Couloubre fault; *STF*: Saint-Thomé fault; *ValF*: Valgayette fault *LRF*: La Rouvière fault; *RF*: Rocherenard  
 1113 fault; *BSAF*: Bayne-St-Alban fault.

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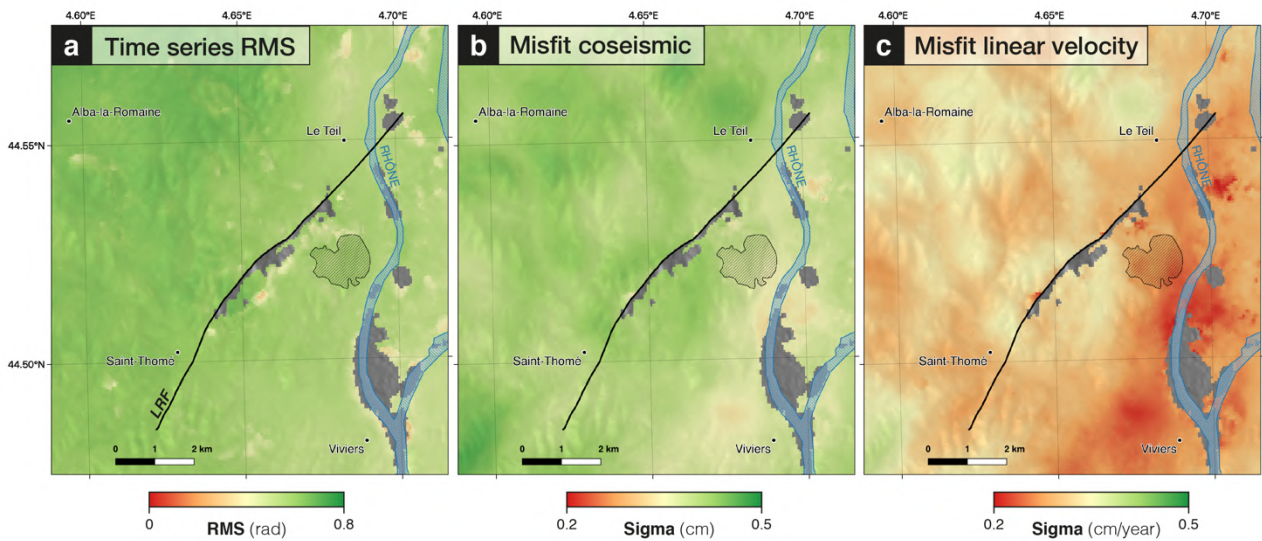


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1116 **Figure S8.** Relative perpendicular baseline as a function of time for SAR images (blue dots with reference  
 1117 image in red) and interferograms (black lines) network used in time series analysis.

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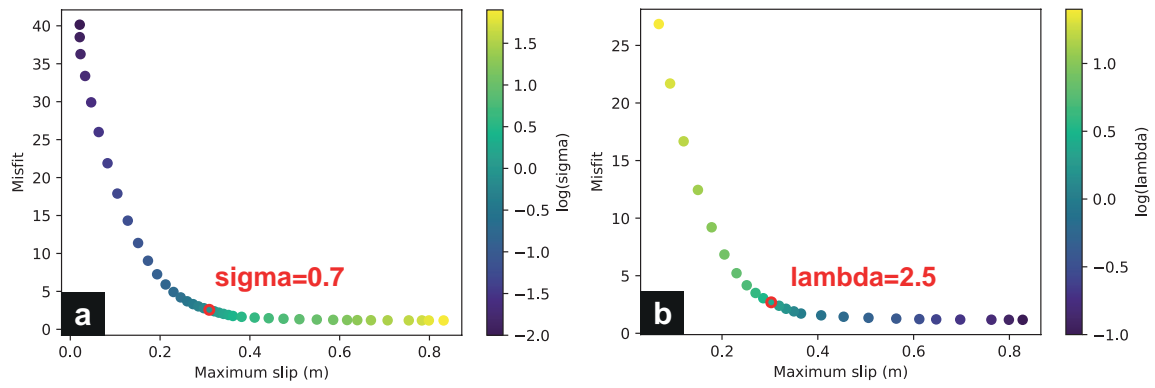


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1121 **Figure S9.** Uncertainties associated with the InSAR times series. (a) Root Mean Square misclosure of the time  
 1122 series inversion averaged per pixel. (b) and (c) Misfits from the temporal decomposition of the time series,  
 1123 relative to the estimations of the coseismic step and the linear velocity, respectively.

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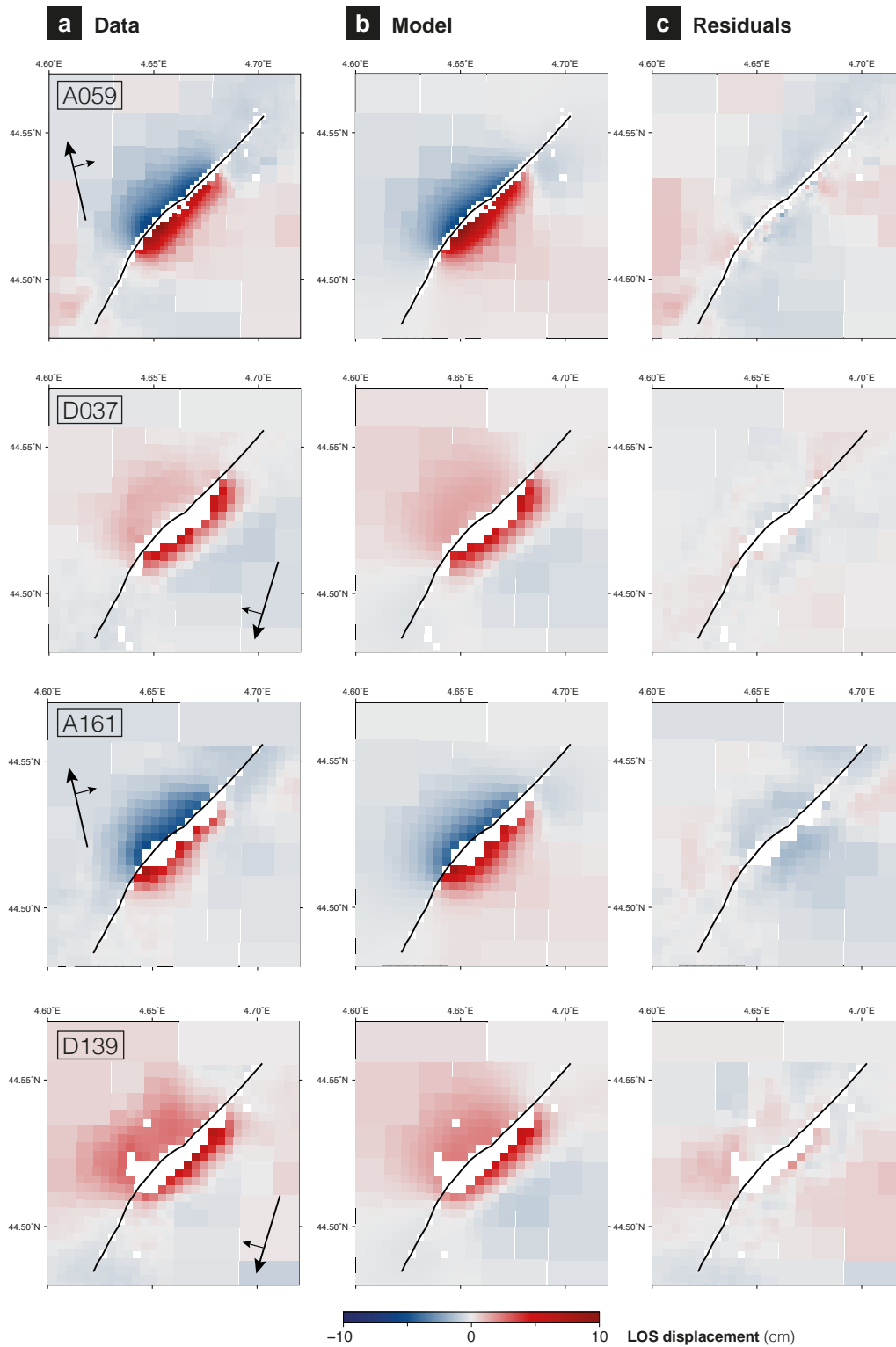
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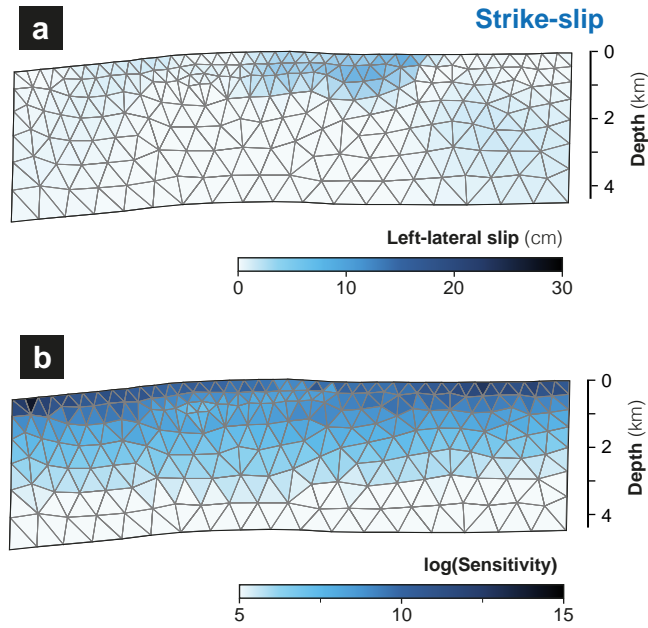
1127 **Figure S10.** Exploration of regularization parameters used in slip inversion (see text for details).

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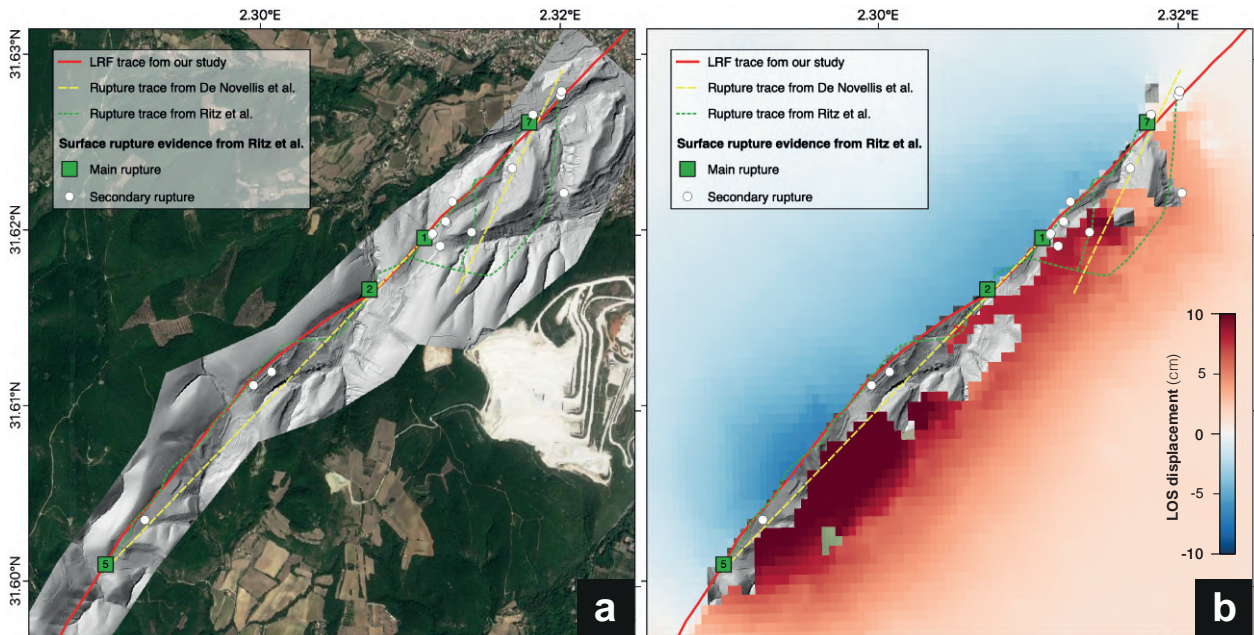
1130 **Figure S11.** Left (a) : Downsampled coseismic InSAR displacement field (derived from time series analysis  
 1131 on top or single interferograms at middle and bottom); center (b) : modelled surface displacement; and right (c)  
 1132 : residuals for best fitting model.



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1134 **Figure S12.** Slip distribution and inversion sensitivity for strike-slip component.

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1137 **Figure S13.** Comparison of different rupture traces already published, from field or InSAR measurements :

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green squares, white dots and dashed blue lines from Ritz et al. (2020); yellow dashed line from

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DeNovellis et al. (2020); with the surface rupture trace used in this study (red line). Rupture traces

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superimposed (a) on satellite image (source) and LiDAR topographic map (source) and (b) coseismic

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displacement field from this study.

1142 **References**

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