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1 Double surface rupture and hydraulic recharge of a three-fault
2 system during the Mw 4.9 earthquake of 11 November 2019 at Le
3 Teil (France)

4

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17 **Abstract**

18

19 The Mw 4.9 earthquake of 11 November 2019 at Le Teil (France) occurred at a
20 very shallow depth (about 1 km) inducing the surface rupture of La Rouvière fault,
21 nearby of a limestone quarry. Thanks to satellite differential interferometry, we
22 detected the existence of the secondary surface rupture of the quasi-parallel Bayne
23 Rocherenard fault. A newly processed seismic cross-section allowed us to construct
24 a local 3D fault system. Assuming that the earthquake was triggered by the
25 transient increase in hydraulic pressure following heavy rainfall before the event,
26 our numerical 3D simulations demonstrate that the hydraulic pressure gradient is
27 maximum just before the earthquake at the intersection of the two faults, the most
28 probable place of the hypocenter. This hydraulic effect is about two and a half
29 times larger than the cumulative effect of mechanical stress release due to the
30 mass removal from the surface quarry over the two past centuries.

31

32

33 **1. Introduction**

34 Large earthquakes usually occur along preexisting faults and plate
35 interfaces. However, intraplate earthquakes are difficult to assess, as many
36 damaging earthquakes are not associated to the known major faults, which were
37 considered as the highest seismic potential in the area¹. Because the recurrence
38 time of intraplate events is long, our knowledge and understanding of the fault
39 dynamics (structure, rheology, stress loading and interaction) are still limited and
40 causes other than the long-term tectonic stress loading are therefore considered
41 for some earthquakes. For example, the 2008 Mw 7.9 Wenchuan (China)
42 earthquake has a total fault length of more than 200 km in Longmenshan fault
43 zone. Before the occurrence of the earthquake, the highest seismic potential of
44 the area had never been attributed to the ruptured faults (causal faults) from the
45 seismic hazard assessment² view point. Although the tectonic stress loading is
46 undoubtable over the whole area, the nucleation process of this mega earthquake
47 has been discussed in relation to the near-by Zipingpu reservoir in terms of the

48 elastic stress change and pore pressure change³⁻⁸. Indeed, any positive
49 perturbation of stress on a causal fault can be suspected in triggering an
50 earthquake⁹. The lack of *in situ* measurements does not allow however any
51 definitive conclusion; the impoundment of the reservoir may have activated the
52 shallow micro-seismicity within a few kilometers below the dam^{5,6} but the link to
53 the hypocenter of the earthquake more than 10 km away is not clear.

54 The anthropogenic influence on earthquake triggering has been widely studied and
55 several authors produced overview of the likely cases¹⁰⁻¹⁵, covering a range of
56 magnitude between 1 and 8. At a local scale, the microseismicity at Gardanne,
57 southern France is correlated to the flooding of the underground abandoned mining
58 gallery with a time lag of about ten days¹⁶. The driving mechanism behind
59 triggering is not only human-driven but can also be related to natural variations
60 on the Earth's surface, namely climate variations¹⁷⁻¹⁹. It is reported that the
61 seismicity in Himalaya has a seasonal trend according to the annual monsoon
62 season, namely large amounts of precipitation in the summer^{20,21}. Among the
63 studies analyzing the rainfall effect, the seasonal pore pressure evolution was
64 discussed through fluid diffusion in the limestone of southeastern Germany¹⁹. The
65 seismicity triggered by rainfall in karstic domain, in Switzerland, was studied
66 through a fluid diffusion model in poro-elastic context²². The hypothesis of
67 "hydroseismicity" developed by John K. Costain²³⁻²⁶ attributes most intraplate and
68 near-intraplate earthquakes to the dynamics of the hydrologic cycle. Such
69 hydraulic perturbations may occur from a few kilometers to 10 km away if a
70 permeably connected fault system exists. In France, a correlation between heavy
71 rainfall and small earthquakes was shown in the Western Provence around the
72 Nîmes Fault²⁷ and in the Provence Alps at Castellane²⁸.

73 The 2019 Mw4.9 Le Teil (France) earthquake heavily damaged nearby

74 areas²⁹. Regardless of its moderate magnitude, this earthquake ruptured the
75 shallowest part of the known fault (only the first 2 km depth at most) and showed
76 rupture traces on the ground surface (Figure 1). The area had been known with
77 some historical earthquakes; however, earthquakes of this magnitude with surface
78 ruptures had never been taken into account in local/regional seismic hazard
79 assessment^{30,31}. As a first analysis, some authors pointed out that a nearby
80 limestone quarry may have contributed to the stress loading on the causal fault³²⁻
81 ³⁴. Using the seismograms available from the mainshock and aftershocks, Delouis
82 *et al.* (2021) shows that the best inferred epicenter is probably located not inside
83 but rather southwest of the surface quarry³⁵. Conversely, we investigate in this
84 work the so-called "hydraulic triggering hypothesis". Indeed, the studied area
85 suffered heavy rainfall during the month before the seismic event. Therefore, a
86 permeably connected fault system may play a role of conducting the pore pressure
87 change at depth. We focus on the local hydraulic system in the study area derived
88 from an updated regional geological model. The movement of moisture in partially-
89 saturated media is simulated using a 3D diphasic flow double permeability model
90 with the soil moisture data recorded during the period 2010-2019 as surface
91 boundary and the Rhône river as edge boundary conditions. We then discuss the
92 possible triggering mechanism by comparing the results of the hydraulic model
93 with those of a 3D mechanical model that simulates the mass withdrawal due to
94 the quarry exploitation in a similar geological configuration. We try to answer two
95 essential questions: (1) How large is the hydraulic overpressure due to the
96 meteoric water recharge vs. the Coulomb stress change due to the mass
97 withdrawal from the surface quarry? (2) Is the estimated location of the maximum
98 hydraulic overpressure consistent with the estimated hypocenter location?

99

100 2. Results

101 2.1. Geological and hydraulic context around the fault system

102 First, we collect the prior information on the fault system around Le Teil,
103 independently of its co-seismic rupture process. The concerned area is located in
104 the Rhône Valley in Southeastern France near the Montélimar city. The Urgonian
105 limestones that are extracted from the nearby quarry were deposited in the early
106 cretaceous epoch, during the Upper Barremian–Lower Aptian age and, afterwards,
107 some calcareous marlstones are deposited during the Aptian–Albian age, east of
108 La Rouvière Fault (LRF) (Figure 1). The available geological map³⁶ of the studied
109 area at a scale of 1:50 000 shows the existence of several, mostly NE-SW striking
110 fault segments in the area. The observed surface rupture³⁰ is consistent with the
111 portion of the already mapped La Rouvière fault (LRF). The geometry of each
112 segment of the geological map is studied through the differential SAR
113 interferometry (DInSAR) analysis using the available Sentinel-1 images. The
114 interpretation of seismic cross section is presented in the next section.

115 The hydraulic parameters in the Barremian limestones are highly variable.
116 The continuous medium (“matrix”) and the “fault” elements are characterized by
117 a large range of porosity and permeability^{37,38} (Table 1). For the “matrix”, we use
118 a permeability of 10^{-16} m² and a porosity of 20% corresponding to the average
119 values measured in the Low Noise Underground Laboratory (LSBB)
120 (<https://lsbb.cnrs.fr/>) in the host rock of Upper Barremian limestones (Urgonian
121 facies)³⁷. For the “fault”, a homogeneous high fault permeability value of 10^{-11} m²
122 (i.e. a hydraulic conductivity of $k \sim 10^{-4}$ m s⁻¹ at 500 m depth) and a mean fault
123 porosity of 10% are chosen to explore the infiltration in a highly conductive,
124 intensively fractured fault zone that is representative of fast fluid conduits in the
125 shallow subsurface. Such high permeability values are expected in the porous

126 layers along the fault zones in the Upper Barremian/Urgonian limestones³⁸⁻⁴⁰.
127 These hydraulic parameters are used in the reference simulations of our 3D double
128 porosity double permeability model (Table 1).

129

130 2.2. Surface traces of the fault system using DInSAR

131 Spaceborne Differential SAR interferometry (DInSAR) has been widely used
132 during the past decades to track land subsidence or uplift related to groundwater
133 extraction or underground gas storage⁴¹. The same method has been also
134 successfully used for identifying ruptures due to earthquakes and quantifying the
135 co-seismic motion^{42,43}. We particularly aim to refine the location of ruptures with
136 a particular interest on La Rouvière fault (LRF) and the surrounding ones mapped
137 on the 1:50 000 geological maps³⁶. To carry out this analysis, four interferograms
138 were produced using SAR data from the Sentinel-1 mission (Method section and
139 Figures S1-S4). After visual analysis of the four produced interferograms set (Table
140 S1), only track A059 has sufficient quality on the area of major deformation. The
141 interpretation of this interferogram is shown in Figure 2. The final geocoded
142 product has 15 m spatial sampling. While the main rupture along LRF is clearly
143 identified on the A059 interferogram, a secondary rupture can be suspected from
144 the pattern of the deformation at the extremities of the ruptured area (Figure 2c
145 and 2d). This latter coincides mostly with the mapped Bayne Rocherenard Fault
146 (BRF) in the south-western area of the studied area, and this continues in the
147 north-eastern direction, always parallel to the LRF, after the intersection with the
148 Paurière Fault (PF) (Figure 2e). The interferometric coherence is better on the
149 south-western part of the BRF than on its north-eastern part (more black pixels in
150 Figure 2e). Figure 3 compares the identified positions with the cartographic
151 representation of the faults as well as the differential motion along the rupture

152 traces. The main rupture along LRF exhibits motion up to 14 cm in Line of Sight
153 (LOS) in the central part of the rupture (points LRF5 to LRF14 between 1000-
154 3000m), that is consistent with previous results³⁰. The differential motion along
155 BRF is estimated up to 4 cm, about one third of the main motion along LRF (Figure
156 3). The south-western part along BRF (BRR1 to BRR10 between 2000-3800m
157 distance) moved two times less (about 2 cm) than the north-eastern part (BRR11
158 to P8 between 3900-5400m). The LRF motion moved more on the central part of
159 the rupture (points LRF5 to LRF14 between 1000-3000m). This interferogram
160 interpretation suggests the re-positioning of the north-eastern part of BRF. Most
161 of the surface rupture evidences documented in the field³⁰ are close to LRF on the
162 geological map³⁶, but one of them is found near the point P7 along the fault trace
163 in Figure 3a, consistent with our proposed north-eastern extension of BRF. To be
164 consistent with DInSAR analysis, we need therefore to reconstruct the fault model
165 in the area: the found trace of BRF does not intersect with LRF on the ground
166 surface, and this fault remains secondary in terms of the differential displacement.
167 The 3D geometry is presented in the next section using a newly processed seismic
168 cross-section.

169

170 2.3. 3D geometry of the fault system using M201 cross-section

171 In order to clarify the possible connectivity of the two faults (LRF and BRF), we
172 re-interpret the seismic cross-section (M201, available on www.minergies.fr),
173 whose location is shown in Figures 1 and 3. This profile was acquired by CGG
174 company during 1962-1963 and retreated in 2020 by BRGM after Le Teil
175 earthquake. Our seismic interpretation⁴⁴ of the geological layers in Figure 4 is
176 partly based on the Valvignères exploration well drilled in 1963 (BSS002ARWX well
177 at <http://infoterre.brgm.fr/>, see location in Figure S6). Since our work aims to

178 study the hydraulic and mechanical influence from the ground surface, we only
179 focus on the local shallow structure of the first 2 km depth and follow from west
180 to east La Rouvière (LRF), Bayne Rocherenard (BRF) and Paurière (PF) faults
181 (Figure 5). LRF is a south-east dipping fault, consistent with the focal mechanism
182 and finite source inversions of Le Teil earthquake^{32,35}. The seismic cross-section
183 indicates that BRF is branching from LRF and PF is branching further from BRF.
184 The position of each fault on the ground surface allowed us to estimate the dip
185 angles, supposing that the dip angles are approximatively constant (see Texts S1-
186 3 in Supplementary Information). We found a true dip angle of 54° for LR and this
187 value between 45° and 60° is consistent with previous works³⁰. This shapes the
188 geometry of our model at a local scale. This model is derived from an updated 3D
189 geological model at a regional-scale⁴⁴ (up to 100 km horizontally and down to 5
190 km depth).

191 The SC03 borehole drilled by the quarry owner near the point P0 of the new
192 BRF trace (Figure 3a) provides us some additional evidences that support this 3D
193 fault model. The SC03 core samples show indeed at 90.5 m depth a near-vertical
194 natural fracture with calcite veins (Figure S5) and at 112.5 m depth the geological
195 evidence for fluids overpressures with angular fragments organized in a jigsaw
196 puzzle pattern. Both observations indicate a possible intersection of SC03 with the
197 new north-eastern part of BRF (Supporting Information, see Text S3). Another
198 interesting observation is that an important quantity of water was lost at 83 m
199 depth during the SC03 geotechnical drilling in 2016 inside the Le Teil quarry
200 perimeter (personal communication of the quarry owner LAFARGE CEMENTS). We
201 infer that the BRF fault zone could form a drain along the fracture network leading
202 to fault parallel flows.

203

204 2.4. Hydraulic simulations using ComPASS

205
206 The precipitation data are compared with the seismic events during the
207 period 2010-2019 in a rectangular area of 50 km x 25 km around the Teil quarry
208 (Figure S6). Seismic data are extracted from the French national RéNaSS
209 catalogue and the rainfall is measured by the weather station at Montélimar
210 (44.58°N, 4.74°E) (Figure S6). The three most intense rainfalls between 2010 and
211 2019 (4th May 2010, 4th November 2014, 24th October 2019) are followed by a
212 seismic event in this restricted area, which occurs between 8 and 18 days after
213 these rainy episodes (Figure S6). The same delay was observed in other studies
214 within a similar carbonate geological context^{19,28}. However, the number of events
215 in this comparison is quite limited (only 12) and a statistical analysis is therefore
216 not possible. Using our re-constructed fault model, we estimate here the pressure
217 variations at depth linked to the infiltration of meteoric water in the period
218 preceding the earthquake of 11 November 2019. In order to exclude as much as
219 possible the evapotranspiration and surface runoff contributions, we use the soil
220 moisture data at 30 cm (SM30) instead of the rainfall data during the period 2015-
221 2019 (Figure 6). In order to simulate the previous period between 2010 and 2015,
222 we use also the surface soil moisture (SSM) data acquired by the SMOS satellite
223 (Figures 6 and S6). These data (SM30 or SSM) are used as input for the nodes at
224 the top surface of the domain, except for those that belongs to the Rhône river
225 where a constant/fixed boundary condition is applied (see Method section). Figure
226 5 illustrates the model volume consisting of the reconstructed fault model including
227 the three-fault system (LRF, BRF and PF) as well as two other dipping faults close
228 to the Rhône River. We adopt a so-called hybrid dimensional model coupling a 3D
229 model of the matrix with a 2D model in fault planes using ComPASS^{45,46} (Method
230 section).

231 In the reference case noted Ref16, we assume a permeability of 10^{-18} m^2 in the
232 surface Apto-Albian clayey layer (Figure 5b), that is about 100 times lower than
233 Upper Barremian limestones layer due to the clay fraction (Table 1). Soil moisture
234 data at 30 cm depth (SM30) are used over the period 2015-2019 (Figure 6). The
235 date of 24th September 2019 corresponds to a relative minimum pressure during
236 the period 2015-2019 (Figure 7d-e). The differential of pressure (ΔP) for the period
237 preceding the earthquake (between 24th September 2019 and 11th November
238 2019) is shown in Figure 7a-b. A peak value of ΔP appears along the intersection
239 line between BRF and LRF (Figure 7c) which is higher than the peak value along
240 the intersection line between PF and LRF (Figure 7a). ΔP reaches the maximum
241 value of 0.98 MPa (982 kPa or 9.8 bars) at $Y = 1963 \text{ m}$ (Figure 7c) near the
242 junction of the three-fault system LRF, BRF and PF. The temporal evolution of the
243 pressure at this node is shown in Figure 7d between Mai 2015 and December 2019,
244 revealing that the pressure gradient is maximum during the period just before the
245 earthquake of November 11, 2019 (red dot). Using the 10-day SSM products for
246 descending overpasses starting from 2010, we demonstrate that this pressure
247 gradient is also maximum just before the earthquake during all the decade 2010-
248 2019 (Figure S6). Therefore, a maximum overpressure on LRF takes place near
249 the junction of the three faults at around 1,200 m depth. We verify here that the
250 intersections between two or multiple faults are the most probable location zones
251 for the hypocenter of an earthquake triggered by a hydraulic recharge according
252 to the "hydroseismicity" concept developed by Costein²⁵.

253 The simulation results are qualitatively stable since the surface moisture is
254 transported principally by BRF to the depth and the peak of the pore pressure
255 appears around the junction of the three faults. Another case called Ref20
256 corresponds to a simplified scenario with a homogeneous permeability of 10^{-16} m^2

257 in the matrix (Table 1). In that case, we obtain a differential pressure of about
258 0.975 MPa. This counterintuitively indicates that the surface clays does not play a
259 predominant role in establishing the hydraulic overpressure on LRF at depth. If we
260 use SSM instead of SM30, the maximum differential of pressure decreases to the
261 value of 0.9 MPa (Table 1). This slight decrease of the simulated overpressure is
262 consistent with the observation that the SMOS-CATDS products underestimate
263 generally the *in situ* soil moisture at Berzème (Figure 6), as already reported in
264 southern France by others⁴⁷ (average bias of -9.5 vol.%).

265

266 3. Discussion

267

268

Our simulations show that the pore pressure change may reach 0.98 MPa at
269 a depth of around 1.2 km at the intersection of LRF and BRF. It is thus naturally
270 questioned how this is significant comparing to the mechanical impact due to the
271 mass removal at Le Teil historical quarry nearby. Prior analytical evaluation of
272 Coulomb stress, based on Boussinesq solution in a homogeneous half-space elastic
273 medium show variations of 0.15 to 0.2 MPa^{32,48}. It is important to note that the
274 earlier amplitude value of about 1 MPa proposed by De Novellis et al. (2020) was
275 later corrected⁴⁸. We perform new 3D numerical simulations using 3DECTM distinct-
276 element code⁴⁹ to represent our improved geological model including
277 discontinuities as well as lithology in a 3D medium. The spatial distributions of $\Delta\sigma_n$
278 and $\Delta\tau$ on LRF are shown in Figure 8c and Figure 8d, respectively (Method section).
279 The variations of the Coulomb Failure Function (ΔCFF) show a maximum change
280 of 0.25 MPa at around 1 km depth on LRF (Figure 8b), a value of the same order
281 as the Boussinesq solution^{32,48}. When we look carefully at the LRF, one peak (0.25
282 MPa) exists above the intersection with BRF, while another peak (0.24 MPa)
283 appears along the intersection of LRF and BRF, promoted by the plasticity of the

284 fault element. An important portion of shear stress on LRF is generated along the
285 fault line between LRF and BRF (Figure 8d). The Coulomb stress change ΔCFF is
286 simulated by 3DECTM on all the considered fault segments (Figure S7). The
287 maximum value of ΔCFF among all the faults appears not on LRF but on BRF (0.39
288 MPa at maximum). It is worthy to note that the mechanical stress change can be
289 larger around the intersection of LRF and BRF and that BRF is more favorably
290 located than LRF in terms of the mechanical stress change. The Coulomb stress
291 change $\Delta CFF = |\Delta\tau| - \mu\Delta\sigma_n$ should be compared to the hydraulic term $\mu\Delta P$ with ΔP
292 of about 1 MPa and μ of 0.6 (Method section). The study highlights that the
293 hydraulic term $\mu\Delta P$ (0.6 MPa) is about two and a half times larger than the
294 mechanical stress change (0.24 MPa) due to the mass removal from the ground
295 surface. Moreover, the mechanical unloading remains a long-term quasi-static
296 process over nearly 200 years while the hydraulic effect is a dynamic process
297 immediately preceding the earthquake nucleation.

298 Another important discussion point is the consistency of the multiple
299 relocation approaches of the hypocenter location. The studied area had not been
300 covered by a dense seismic network before the earthquake. The closest station of
301 the permanent network is far from the source area by about 30 km (OGLP station
302 in Résif; <https://seismology.resif.fr/>), thus the hypocenter location using any
303 catalogue has a significant uncertainty of several km³¹. However, a local network
304 was installed just after the seismic event and the hypocenter of the Le Teil
305 earthquake has been recently relocated using multiple approaches³⁵ (e.g.
306 calibration from aftershocks). The most probable hypocenter location is at
307 (44.5188 N, 4.6694 E, and 1.3 km depth) with an error of about 500m. This
308 epicenter position is very close to the surface projection of the intersection of LRF
309 and BRF (Figures 8 and 9). It is also close to the projected locations of the

310 maximum overpressures of both Ref16 and Ref20 reference simulations. A near-
311 by blast monitoring station CLAU recorded the mainshock (Figure 9). Although this
312 short period sensor was *a priori* only calibrated for micro-vibrations of quarry
313 blasts, we found that the first particle motion could bring some useful information
314 after testing one known blast event (Method section and Figure S9). The azimuth
315 and its associated uncertainty of the first wave arrival of the mainshock is
316 estimated to N164°E \pm 16° (Figure 9). This direction is also consistent with our
317 suggested epicenter locations. Observing this accordance between the
318 seismological analyses and our hydraulic- and mechanical- modeling, we suggest
319 that the intersection of LRF and BRF might have played an important role for the
320 nucleation process of the Le Teil earthquake. Furthermore, the same authors³⁵
321 address the question of the indetermination of the dip angle for the mainshock
322 (between 40° and 65°). The causal fault system is perhaps more complex than
323 one single fault (LRF). It is well known that the nucleation process of an earthquake
324 may occur around the geometrical irregularity of a complex fault system⁵⁰⁻⁵². The
325 steeper BRF (69° dip in our study) may therefore have played a role in both seismic
326 events, the mainshock and the aftershock.

327

328 4. Conclusion: a hydraulic triggering mechanism

329

330 We developed here two separate numerical models and used a decoupled
331 modeling approach to compare the potential mechanical and hydraulic triggering
332 factors for the earthquake of 11 November 2019 at Le Teil (France). The 3D
333 geometry of the fault system was reconstructed through the surface rupture
334 evidences of BRF found by our DInSAR interpretation (in addition to LRF) and a
335 newly processed local seismic cross-section. Using the soil moisture data in the
336 studied zone during the decade between 2010 and 2019, we carried out hydraulic

337 numerical simulations in the three dimensional volume. The near-vertical BRF
338 geometry could have serve as major drain of the strong rainfall during the month
339 before the earthquake, thus increasing the pore pressure at depth so as to possibly
340 trigger a very shallow earthquake on LRF. The pore pressure at depth becomes a
341 local peak just before the 2019 Le Teil earthquake at the intersection of the two
342 segments BRF and LRF, very close to the hypocenter location determined by other
343 seismological studies³⁵. The estimated amplitude is close to 1 MPa, about four
344 times more important than the normal stress change elastically loaded on the fault
345 due to the mass removal of the quarry from the ground surface (Figure 8). This
346 work thus suggests a hydraulic triggering mechanism at shallow depth on a
347 network of faults under long-term tectonic stress loading. The hydraulic recharge
348 of similar fault systems may be the scope of future works in order to improve the
349 local seismic hazard assessment around sensitive areas.

350

351 5. Methods

352

353

354 *Differential SAR Interferometry (DInSAR)*

355 The displacements are estimated along the sensor's Line of Sight (LOS), which is
356 the sensor-to-target direction. DInSAR measures the projection of real motion
357 along the LOS and provides 1D displacement measurements. Those measurements
358 are relative in space and time: they are spatially related to a reference point, and
359 temporally to the date of the first available satellite acquisition. Four
360 interferograms were produced using Sentinel-1 data (Table S1). The processing is
361 based on the Gamma processing software (<https://gamma-rs.com>). In order to
362 interpret these interferograms for identifying and quantifying surface ruptures, an
363 unwrapping additional step is required. For this step, we used the Minimum Cost
364 Flow (Constantini, 1998) procedure implemented in Gamma. Unwrapped AO59

365 interferogram is shown in Figure 2. The visual examination allows a first estimation
366 of the LRF rupture location and the positions of the extremities of a candidate for
367 the BRF rupture (Figure 3). In order to obtain additional candidates we added
368 positions of faults from the 1:50 000 geological map (see Figure S1). These faults
369 were imported in the tool for profiles stacking and displacement estimation
370 included in the Cosi-corr software^{53,54}. Lateral profiles are automatically generated
371 by the software perpendicularly to the fault candidate (20 on LRF and 20 + 3 added
372 manually on BRF). Our objective is first to validate points on the fault candidate
373 as reliable observations if significant differential motion between each side of the
374 profile is observed and then to quantify this motion. In addition, if the "jump" on
375 the displacement profile is not exactly on the candidate's position this procedure
376 allows to adjust the position by displacing the candidate accordingly to the jump's
377 position. Figure S2 illustrates the use of the tool on the south-west of the LRF.
378 Finally, the obtained points are connected in order to obtain a continuous rupture
379 trace. This proposed procedure was found to be sensitive enough for interpreting
380 the initial interferometric information and the results obtained are in fairly good
381 agreement with ground failure observations (Figure 2). Although it cannot be fully
382 exhaustive (minor motions could be missed), this provides a good representation
383 of the positions of the LRF and BRF and a quantification of their surface
384 displacements have been proposed. Furthermore, some unwrapping issues can
385 occur close to the ruptures for two main reasons. First, some sectors of the area
386 have poor coherence because of possible surface changes occurred during the 6
387 days time-span due to the earthquake itself or due to the presence of locally
388 vegetated land covers. Secondly, the observed motion on the ruptures is larger
389 than quarter of wavelength (i.e. 14 mm). One noteworthy point is the fact that
390 two parallel ruptures introduces a specific unwrapping issue (illustrated in Figure

391 S3). This may have influenced on the location and quantification of the rupture
392 traces. Complements on the unwrapping issues can be found, for example, in
393 Hanssen⁵⁵ and Raucoules *et al.*⁵⁶. For these reasons, it is important to
394 compare/validate the interpretation of the interferogram in respect to the prior
395 knowledge of faults (e.g. ground observations or boreholes). The consequence is
396 that it introduces an ambiguity on the distribution of the measured slip between
397 the two faults. This issue may explain the different results provided by Ritz et al.
398 (2020)³⁰ using the same Sentinel-1 data (Figure S4). As this ambiguity cannot be
399 resolved only on the basis of the interferometric information, we use therefore
400 additional observations (surface ruptures evidences or/and cores of boreholes).

401

402 *Hydraulic simulations by ComPASS using soil moisture data*

403

- 404 • *Soil Moisture (SM30) data at the Berzème station (SMOSMANIA)*

405 The SMOSMANIA network (Soil Moisture Observing System - Meteorological
406 Automatic Network Integrated Application) is based on the existing automatic
407 weather station network of Meteo-France. The SMOSMANIA soil moisture data are
408 freely available on the web site of the International Soil Moisture Network
409 (<https://ismn.geo.tuwien.ac.at/en/>). The stations form a Mediterranean-Atlantic
410 transect following the marked climatic gradient between the two coastlines. The
411 average distance between two neighbouring stations is approximately 40 km which
412 is consistent with the spatial resolution of remote sensing soil moisture products
413 (e.g. SMOS). The station at Berzème is located at less than 15 km from Le Teil
414 (Figure S6). The vegetation on these sites is made up of natural fallow land, cut
415 once or twice a year. Since April 24, 2015, four soil moisture probes (ThetaProbe
416 ML3) are installed per station at depths of 5, 10, 20 and 30 cm. The ThetaProbe is

417 a capacitance probe using the dielectric permittivity properties of the soil to
 418 estimate the volumetric soil moisture content. The data at depth of 30 cm (noted
 419 SM30) are used in the hydraulic simulations Ref16, Ref20 (Table 1) and Ref6
 420 (Table S4). The water content or soil moisture content is the quantity of water
 421 contained in the soil. The normalized water content (or effective saturation S_e) is
 422 depended on the volumetric water content SM30 (raw data), the residual water
 423 content θ_r (about 12% between 2015 and 2019 at the Berzème station) and the
 424 saturated water content equivalent to porosity ω (about 42% at 30 cm at the
 425 Berzème station):

$$426 \quad S_e = \frac{(SM30 - \theta_r)}{(\omega - \theta_r)}$$

427

- 428 • *SMOS Level 3 Surface Soil Moisture (SSM) Products*

429 The first satellite mission to focus primarily on the collection of soil moisture
 430 data was the European SMOS satellite that was successfully launched on the 2nd
 431 of November 2009 by ESA. The surface soil moisture data acquired by the SMOS
 432 satellite between 2010 and 2019 are used in the numerical modeling as boundary
 433 conditions for the whole nodes at the top surface, except for those belonging to
 434 the Rhône river. We use here the term Surface Soil moisture (SSM) to refer to the
 435 volumetric soil moisture in the first few centimeters (0–5 cm) of the soil. It must
 436 also be noted that ascending and descending overpasses are bound to show
 437 different values of the retrieved parameters that may not be always comparable,
 438 and they are, thus, retrieved separately. The SMOS Level 3 SSM products are
 439 downloaded through the website of the Centre Aval de Traitement des Données
 440 SMOS (CATDS, <https://www.catds.fr>). The data are presented over the Equal-Area
 441 Scalable Earth (EASE grid 2)²⁵ with a sampling of about 25 km x 25 km and the
 442 studied area is included in one grid cell called L2 (Figures 1a and S6). The CATDS

443 provides either a 10-day SSM product (that contains median, minimum and
 444 maximum values of soil moisture) or a 3-day product. The 3-day products for
 445 ascending overpasses are used between Mai 2015 and December 2019 (Figure 6)
 446 and the 10-day aggregated products for descending overpasses are used between
 447 March 2010 and December 2019 (Figure S6). As the residual water content θ_r is
 448 almost zero for SMOS acquisitions, the normalized water content (or effective
 449 saturation S_e) depends only on the volumetric water content SSM and the porosity
 450 ω (about 50% at 5-10 cm in the studied area given by the Harmonized World Soil
 451 Database):

$$S_e = \frac{SSM}{\omega}$$

452

- 453
- 454 • *Hydraulic parameters (matrix, fault)*

455 The hydraulic parameters in the Barremian / Urgonian limestones are highly
 456 variable in the host rock, the damaged zone and the core fault³⁷⁻⁴⁰. In the Urgonian
 457 carbonates at Russel (<https://lsbb.cnrs.fr/>, about 90 km southeast of Le Teil), the
 458 observations show the presence of discontinuities (joints, veins, faults and
 459 stylolites) that influence the hydraulic properties from core to reservoir scale³⁸:
 460 the porosity varies from 1% to 20% and the permeability varies in a range between
 461 10^{-17} m² and 10^{-11} m². These hydraulic parameters are used by the ComPASS
 462 platform^{45,46} (<https://github.com/BRGM/ComPASS>) for the reference cases (Table
 463 1) and the sensitivity cases (Table S4).

464

- 465 • *ComPASS platform*

466 The ComPASS code is able to handle complex networks of fractures with
 467 intersecting for non-isothermal compositional multiphase Darcy flows. The so-
 468 called hybrid dimensional model couples a 2D model in fractures with a 3D model

469 in the matrix. The model is discretized using a fully implicit time integration
470 combined with the Vertex Approximate Gradient (VAG) finite volume scheme which
471 adapted to polyhedral meshes and anisotropic heterogeneous media. The fully
472 coupled systems are assembled and solved in parallel using the Single Program
473 Multiple Data (SPMD) paradigm with one layer of ghost cells. This strategy allows
474 for a local assembly of the discrete systems. Simulations can be run on
475 unstructured meshes including complex networks of fractures with intersecting,
476 immersed and non-immersed fractures. The fully coupled systems are assembled
477 and solved in parallel using the PETSc library and can be run on large computing
478 clusters. An efficient preconditioner is implemented to solve the linear systems at
479 each time step and each Newton type iteration of the simulation.

480

- 481 • *Mesh, time step, convergence, element number used by ComPASS*

482 The open-source software platform under LGPL license named SALOME
483 (<http://www.salome-platform.org>) has been used to generate the mesh for the
484 whole domain, in order to, ultimately, simulate fluid flows in the faulted region
485 using the ComPASS platform. The platform relies on the MED format, an internal
486 data model, which describes meshes and fields stored as sequences of Hierarchical
487 Data Format 5 (HDF5) structures. It also takes distributed meshes into account,
488 thus facilitating parallel computations. The geological units and faults (Figure 5)
489 were meshed by a tetrahedral conformal meshing using the SALOME code. The
490 unstructured mesh is composed of more than 140,000 tetrahedral elements where
491 the mesh size has been constrained for specific boundary elements (top surface,
492 faults, intersection of faults). The fault is meshed as a two-dimensional (2D)
493 surface with triangular elements which are interconnected with the surrounding
494 matrix using conformal meshing. The finest elements are localized at the fault top

495 (triangles side lengths around 18 m). The top surface of the domain is composed
496 of triangles with side length of approximately 50 m as well as triangles at the
497 intersection of faults. Then, the finest tetrahedrons are localized close to the top
498 surface and around the faults while the mesh becomes coarser by moving away
499 from faults and the top surface (where triangles have side lengths of more than
500 250 m). For each simulation and at each time step, the nonlinear system is solved
501 using a Newton algorithm. The GMRES stopping criterion on the relative residual
502 is fixed to 10^{-8} . The Newton solver is convergent if the relative residual is lower
503 than 10^{-8} as well. For each simulation, the initial timestep is about one hour and
504 the maximum timestep is one day.

505

- 506 • *Hydraulic model and numerical simulations by ComPASS*

507 The model domain is set for a dimension of 5 km by 4 km by 3.5 km. The top
508 surface of the model corresponds to the elevation of the area. The domain is
509 composed of the geological units and faults in the studied area (Figure 5). Each
510 unit and fault is considered homogenous in porosity and permeability (e.g. the
511 permeability of the Apto-albian geological unit, see table 1). As a preliminary step,
512 the initial state of the hydraulic system, is achieved by performing a first simulation
513 over a long period (about 100 years) to reach an equilibrium state in the
514 unsaturated zone where a diphasic flow "air/water" is simulated. In the initial state,
515 the whole domain is considered fully saturated with a hydrostatic pressure state.
516 For the boundary conditions, two different Dirichlet conditions are considered for
517 the nodes at the top surface. At the nodes which belong to the Rhône river, we fix
518 a constant pressure (1 bar) and a constant saturation (0 for the gas saturation).
519 At the other nodes of the top surface, the gas saturation is gradually increased
520 over time from a fully saturated state until to reach 0.9 (corresponding to a water

521 saturation Se of 0.1). The “no flow” boundary condition is applied on the four
522 lateral and bottom boundaries. In the unsaturated zone, the values of relative
523 permeability are defined by the power law $K_{rw} = Se^2$ and $K_{ra} = (1 - Se)^2$ for the
524 water and air phase, respectively. The capillary pressure function P_c is given by
525 the Corey law $P_c = -b \times \ln(Se)$ with $b = 2 \times 10^5 Pa$. This first step gives an initial state
526 with an unsaturated zone in the upper part of the hydraulic model, at equilibrium
527 with the Rhône river. In the second step, the effective water saturation Se is
528 changed every three (or ten) days during the period between 2010 (or 2015) and
529 the end of 2019 for all the nodes at the top surface (except for the Rhône river
530 nodes for which a constant water saturation of 1 is fixed). The variations of the
531 water saturation, occurring over time, results in pressure variations/pulses in both
532 unsaturated and saturated zones. More specifically, an increasing of water
533 saturation at the top of the model, which is related to rainfall events results in
534 pressure variations from the surface towards greater depth.

535

536 *Mechanical simulations by 3DECTM*

537 To model the mechanical effect of mass withdrawal on different faults, we use the
538 Distinct Element Method of 3DECTM code⁴⁹ (Version 5.2, Itasca Consulting Group
539 Inc.) that explicitly handles discontinuities as mechanically active joints. The model
540 size is set for a dimension of 19 km by 12 km by 6 km oriented N110°E to be
541 aligned with principal deformation directions⁵⁷. A limit of the 3DECTM is that
542 discontinuities are defined only by flat surfaces. Each mechanical fault in the model
543 corresponds to the mean plane of the geological fault, constraining the geometry
544 of LRF by the observed fault trace position and a dip of about 50°. We attribute
545 Coulomb behavior to these faults and their properties given in Table S2 are chosen
546 according to the values measured for discontinuities in Barremian shale in the

547 French Low Noise Underground Laboratory (<http://lsbb.eu>)⁵⁸. As far as the
548 lithology is concerned, we extract three layers from the 3D geological model: the
549 basement, the Upper Jurassic and the Hauterivian layer (Figures 5 and 8). The
550 discretization using tetrahedral meshes was done directly within the 3DECTM, the
551 mean edge length is 200 m and the mesh is refined around the ground surface of
552 mass removal and the target faults using a mean edge length of 100 m (Figure
553 S7). The model parameters of the porous elastic medium are summarized in Table
554 S3. In the first step, we realize an initial equilibrium to account for the initial state
555 consisting of a gravitational loading plus a tectonic loading. We assign stress
556 boundary conditions to the model (Figure 8a). As there is very few constraints on
557 stress values, we define a reference model with a maximal horizontal stress of
558 $\sigma_H = 1.3\sigma_v$ and a minimal horizontal stress of $\sigma_h = 1.1\sigma_v$ where σ_v is the vertical
559 principal axis (minimum) defined by confining pressure. The top of the model is at
560 a reference level corresponding to the lowest point within the area. We apply forces
561 on top of this model to account for the topography. For the area of the quarry, the
562 topography is reconstructed from the topography of 1950 (Figure S8) and a
563 homogeneous additional layer is added corresponding to the volume extracted
564 between 1833 and 1950. The second step consists in modelling the effect of mass
565 withdrawal. To do this, the forces on top of the model are relaxed in the area of
566 the quarry. We have no detailed information on temporal evolution of the
567 topography, and only two periods are considered for the quarry extraction, before
568 and after 1950. The volume extracted for the first period 1833-1950 is not well
569 known and estimated by the quarry owner to be around $4.8 \times 10^6 \text{ m}^3$. The area of
570 the quarry is estimated by using the study of De Novellis *et al.*³⁴ and the volume
571 extracted is supposed evenly distributed on the whole surface. The volume
572 extracted for the second period corresponds to the difference between the

573 topography between 2019 and 1950 over the area of the whole quarry (Figure S8).
574 Using this observed map, our estimation of this volume is about $34 \times 10^6 \text{ m}^3$. The
575 density of the extracted mass is assumed 2500 kg/m^3 , corresponding to 12 and
576 85 million tons for the two periods, respectively. The Coulomb stress change is
577 given by $\Delta CFF = |\Delta\tau| - \mu(\Delta\sigma_n - \Delta P)$, where $\Delta\tau$ and $\Delta\sigma_n$ are the shear and normal stress
578 changes (positive in compression), μ the frictional coefficient (Table S2) and ΔP the
579 differential of pressure. The direction of $\Delta\tau$ is taken to the maximum shear stress
580 on the given fault geometry. The Coulomb stress change ΔCFF related to the mass
581 withdrawal is estimated from the difference between the two equilibrium steps.
582 The mass withdrawal generates a relaxing of normal stress on LRF as well as an
583 increase of shear stress.

584

585 *Seismological data analysis at Clauzel House (CLAU)*

586 The data recorded at Clauzel House (CLAU) are made available to the scientific
587 community by the quarry owner LAFARGE CEMENTS. The sensor is a three-
588 component, short-period seismograph (sampling rate at 1056.4 Hz), installed in a
589 private house to monitor the vibrations due the quarry blasts. The recorded data
590 of the mainshock include visually unnatural jumps in velocity and this leads to
591 unexpected level of acceleration. After visiting the station CLAU, we observed that
592 the station have not been correctly fixed on the house floor and probably may
593 have been impacted by the fall of miscellaneous objects around. Although the
594 whole waveform may not be exploitable, the first movement at the beginning of
595 the signals could be informative³⁵. In order to verify the correct polarity, we check
596 the blast signal of the 25th September 2019 for which the origin is known (Ev1 in
597 Figure 8). For the given records, we remove the linear trend, apply the Butterworth
598 bandpass filter (order of 8) between 1 and 10 Hz and integrate once using the

599 software SeisGram2K Seismogram Viewer v7.0.0X10 (www.alomax.net) for data
600 viewing and processing. Then, we exploit the particle motion for a selected time
601 window manually (Figure S9). We obtain a back azimuth of $N98^{\circ}E \pm 20^{\circ}$ for the
602 true value of $N111^{\circ}E$. Thus, the particle motion indicates approximatively the
603 event direction with a margin of error of around 15° . We thus use the data from
604 the same station to estimate the direction of the mainshock of the 11th November
605 2019 and its associated uncertainty.

606

607

608 **Data availability**

609 Acquisitions of Sentinel-1 satellite for DInSAR are provided by the European Space
610 Agency (ESA, <https://sentinel.esa.int/web/sentinel/sentinel-data-access>). The *in situ* soil
611 moisture data and SMOS surface soil moisture data are freely available on the web
612 site of the International Soil Moisture Network (ISMN,
613 <https://ismn.geo.tuwien.ac.at/en/>) and of the French ground segment for the Level 3
614 data (CATDS, <https://www.catds.fr/>), respectively. The datasets generated and/or
615 analyzed in this work are available from the corresponding author on reasonable
616 request.

617

618 **Code availability**

619 The code that is central to our conclusions is the multiphase flow simulator called
620 ComPASS. It is an open platform using state of the art numerical schemes to
621 discretize multiphase Darcian flows on generic unstructured meshes. The version
622 used is freely available at the GitHub platform (<https://github.com/BRGM/ComPASS>).

623

624

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626

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793 fluid pressure perturbations in a slipping fault. *Geophysical Research Letters* **42**,
794 3197–3203 (2015).
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799 **Acknowledgments**

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801 and the quarry owner LAFARGE CEMENTS (grants CF19DRP21 and CF21DRP01).
802 We thank LAFARGE CEMENTS to make available the extracted volumes of rocks
803 from Le Teil quarry during the period 1850-2019 and the data of the SC03
804 geotechnical borehole drilled in 2016. A.Bu warmly thanks his former PhD
805 supervisor Laurent Charlet for the field visit looking for possible water sinkholes
806 around the epicenter location and the visit of his nearby house at Saint-Thomé
807 damaged by the earthquake.

808

809 **Authors contributions**

810 A.Bu and H.A wrote the main manuscript. A.Bu conceived the hydraulic study,
811 performed the SMOS and Berzème station data processing and contributed to the
812 overall interpretation. A.A.L performed the 3D hydraulic model with the ComPASS
813 version developed by S.L and the post-processing with Paraview with the support
814 of P.PB. M.F performed the overall SAR data processing with Gamma and D.R
815 interpreted the unwrapped interferogram. J.M performed the mechanical 3D model
816 with 3-DEC with the contribution of T.G and contributed with H.A and B.B.S to the
817 interpretation of the mechanical results. A.Bi and F.P contributed respectively to
818 the retreatment and interpretation of the seismic M201 profile. C.A performed the
819 geological data analyses and construct the 3D structural model at regional scale.
820 M.D, P.D and H.A performed the processing of the signal acquired by the vibration
821 sensor CLAU. B.B.S conceived the global study. All authors contributed to the text
822 and reviewed the manuscript.

823

824 **Ethics declarations**

825 The authors declare that they have no competing interests as defined by Nature
826 Research. The research support of LAFARGE CEMENTS to BRGM (grants
827 CF19DRP21 and CF21DRP01) did not include any role in the conceptualization,
828 study design, data analysis, decision to publish, or preparation of the manuscript.

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830 **Supplementary information**

831 Suppl_Info_V5

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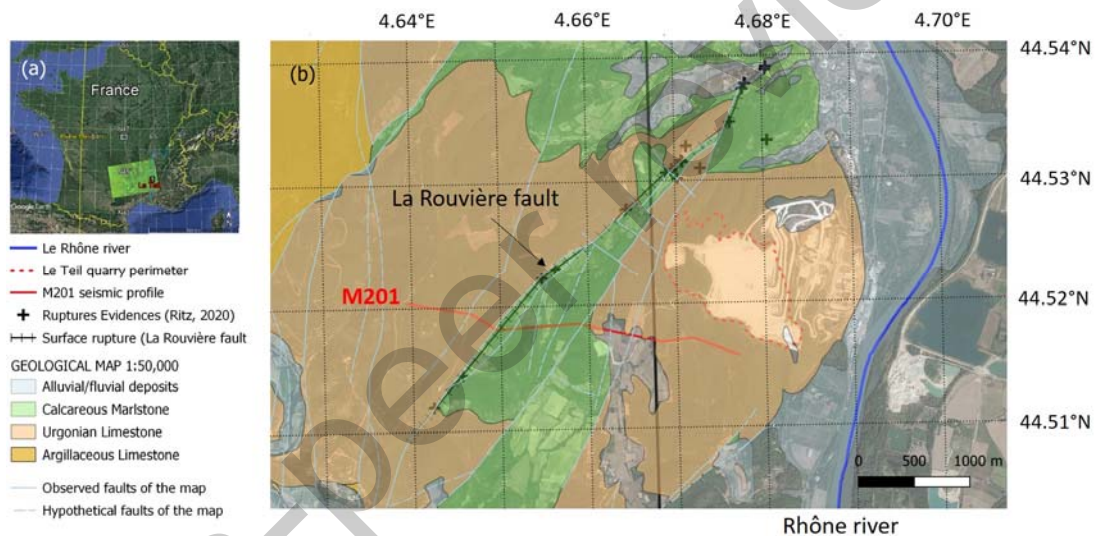
833 Table and Figures

834

835 Table 1 Hydraulic model simulations (parameters and results)

	Ref16	Ref20	Ref21
Soil moisture	SM30 (Berzème, 30 cm depth)	SM30 (Berzème, 30 cm depth)	SSM (SMOS ASC, 3 days)
Matrix Porosity w_m	0.2	0.2	0.2
Matrix Permeability K_m	10^{-18} m^2 in Apto-albien 10^{-16} m^2 elsewhere	10^{-16} m^2	10^{-18} m^2 in Apto-albien 10^{-16} m^2 elsewhere
Fault Porosity w_f	0.1	0.1	0.1
Fault Permeability K_f	10^{-11} m^2	10^{-11} m^2	10^{-11} m^2
Fault Width W	20 m	20 m	20 m
Maximum differential of pressure (ΔP) along the intersection LRF / BRF	9.82 bar	9.75 bar	9.03 bar

Figure 1: Map of the studied area. (a) Location of the studied area near Le Teil city in the southeastern France. Data are combined on Google map, Landsat/Copernicus, SIO, NOAA, US Navy, NGA and GEBCO and include one Copernicus Sentinel image (2019) that contains the 25 km SMOS L2 cell of the EASE equal-area grid (black square). (b) Simplified bedrock geology modified from the BRGM geological map at the 1:50,000 scale (Kerrien *et al.*, 1989) showing the observed faults (light blue solid lines) and hypothetical faults (light blue dashed lines). The surface trace of La Rouvière fault (LRF) (black line) is the black line joining the ruptures evidences (black crosses) of Ritz *et al.* (2020). Also shown the M201 seismic cross-section (solid red line), Le Teil quarry perimeter (dotted red line) and the north-south axis at around 4.67°, which is the boundary between L1 and L2 SMOS cells.



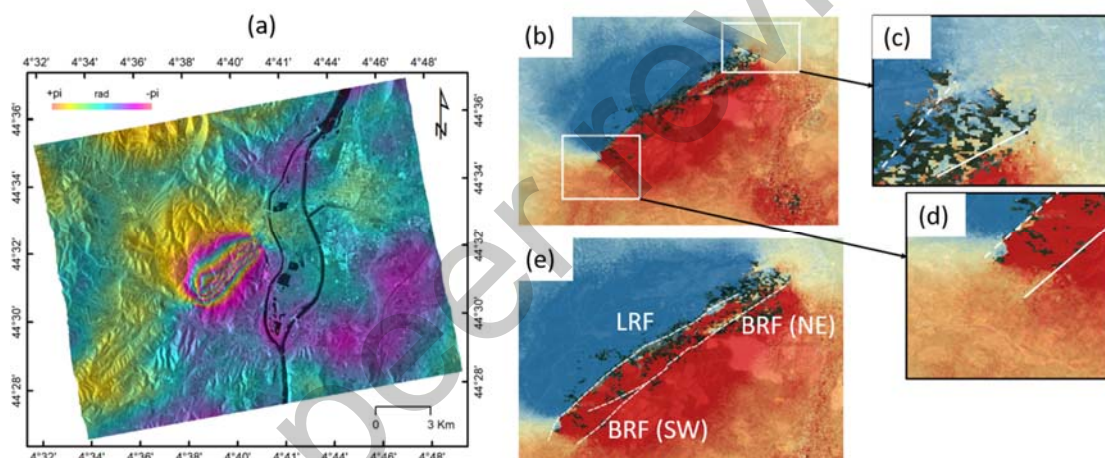
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Figure 2. Double surface rupture using Sentinel-1 synthetic-aperture radar data. (a) A059 (Ascending mode) interferogram (wrapped phase) showing a fringe (phase variation of 2π) corresponding to a surface displacement of 28 mm in line of sight (LOS). The total movement is about 5.5 fringes (about 15 cm in LOS). (b) The unwrapping of A059 allows to convert the phases in LOS displacement of the Sentinel-1 satellite (viewing angle of 43.7°). The black pixels corresponding to pixels with insufficient coherence and are masked during the unwrapping process. (c)(d) Zooms on both extremities of the detected surface rupture (white lines). (e) Double surface rupture (white lines) of the main fault (La Rouvière; LRF) and the secondary fault (Bayne Rocherenard fault; BRF) including the new position of the North-East part (NE).

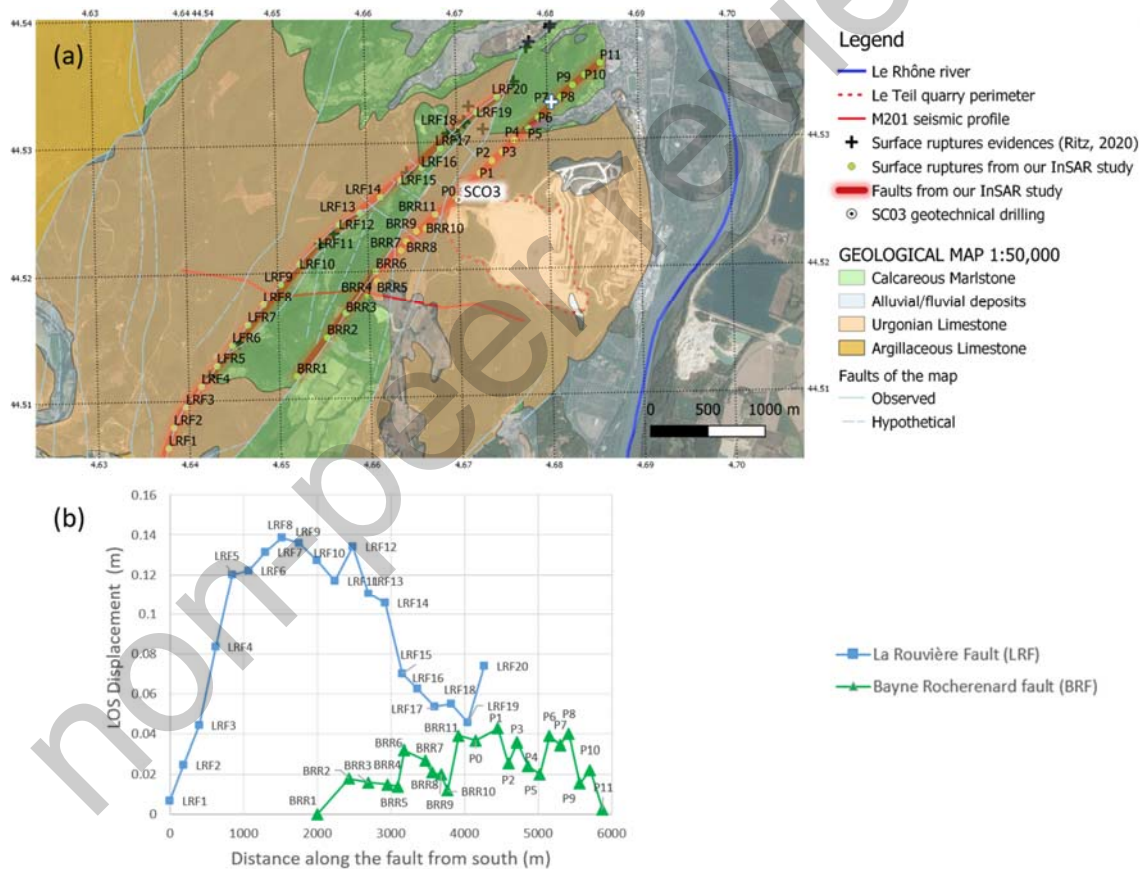


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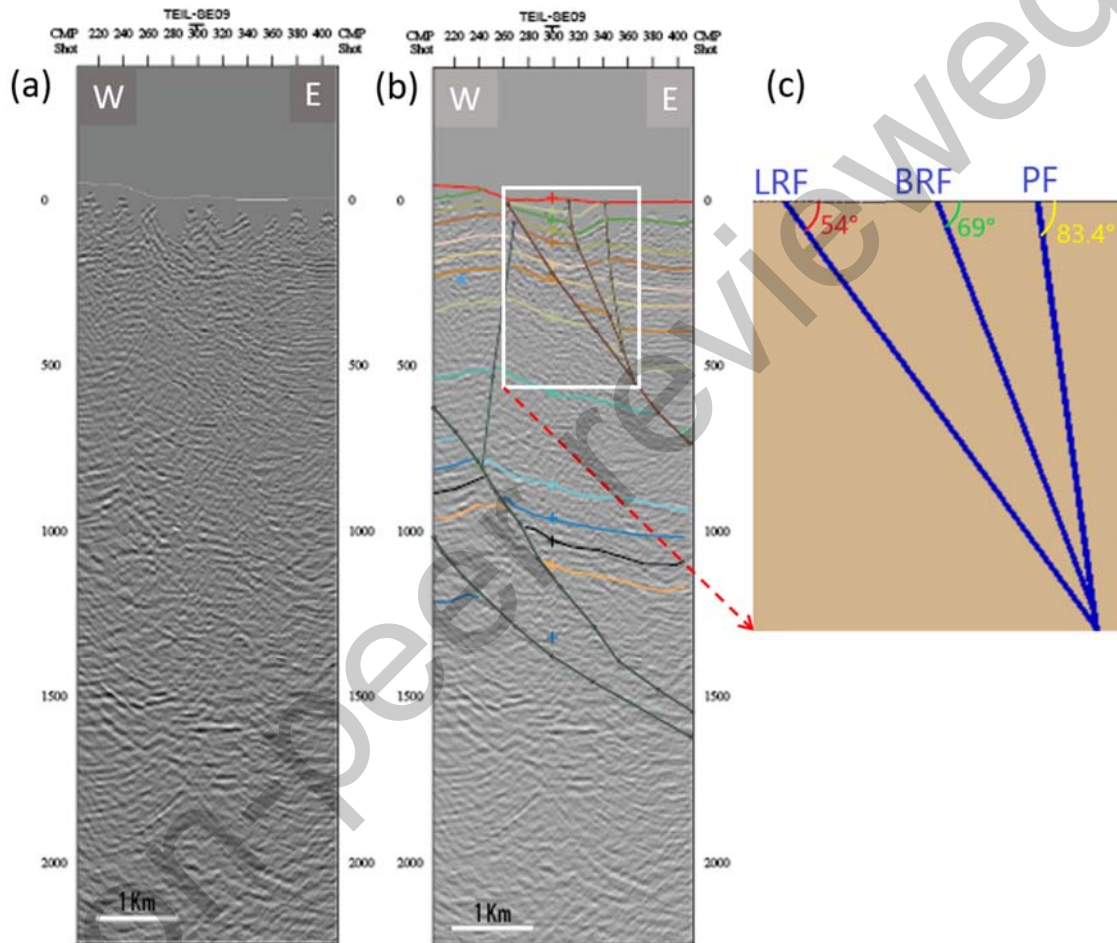
Figure 3: Distribution of surface displacements along the main and secondary faults. (a) Position of the surface rupture points (yellow circles and red shaded line) and interpretation in terms of fault traces showing two co-seismic rupture lines roughly parallel: the main La Rouvière fault (LRF between LRF1 and LRF20) and the secondary Bayne Rocherenard fault (BRF between BRR1 and BRR11, continuing farther between P0 and P11). Also shown are the previously mapped faults (Kerrien *et al.*, 1989) and the rupture evidences observed by Ritz *et al.* (2020). (b) Comparison of Line of Sight (LOS) displacements for LRF and BRF faults (starting points of both profiles are the most southwestern points LRF1 and BRR1, respectively).



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845 **Figure 4. Interpretation of the seismic profile M201.** (a) The data along the
846 cross-section M201 in the time domain (vertical scale is two-way travel time). (b)
847 Interpretation of the faults and geological layers on M201 consistent with our
848 updated geological model. (c) True dip angles of LRF (La Rouvière), BRF (Bayne
849 Rocherenard) and PF (Paurière) faults (see Supplementary information for our
850 calculation method, texts S1-S3).

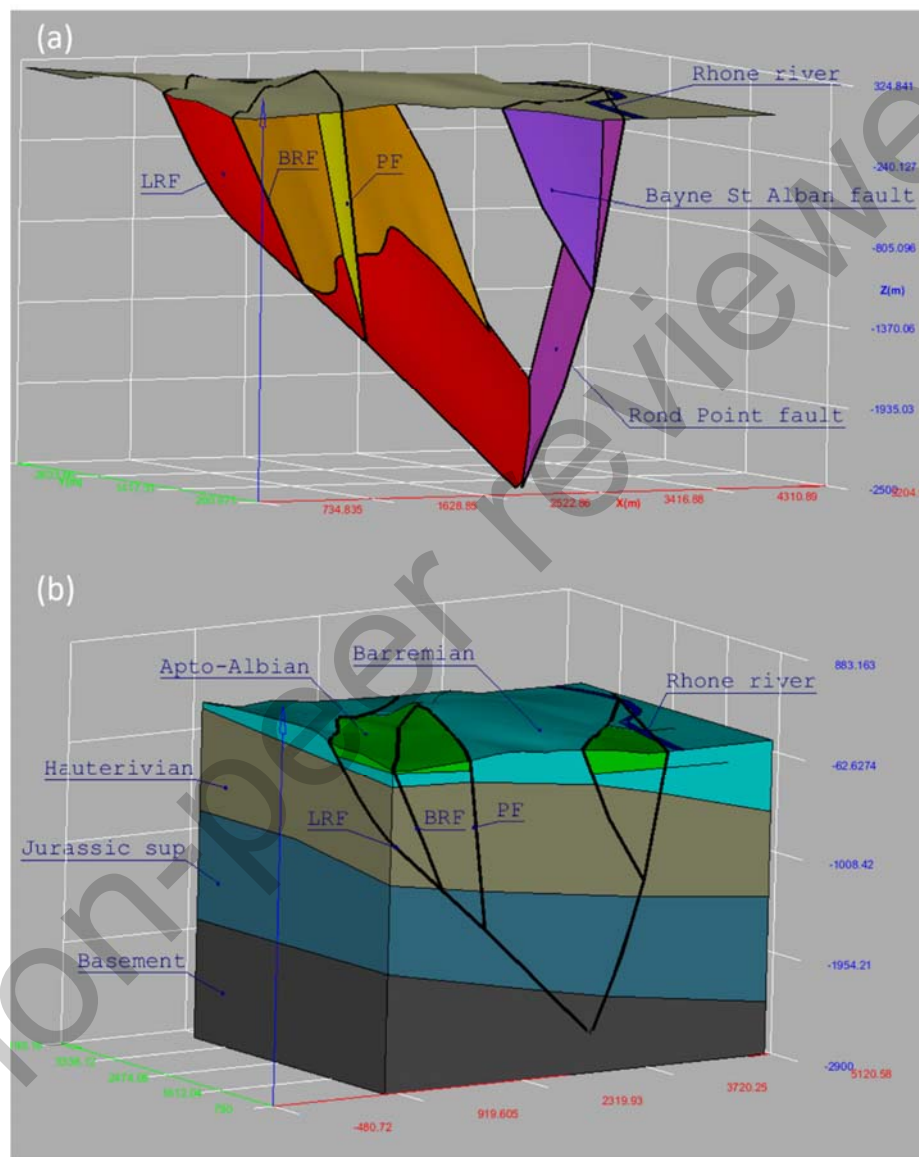


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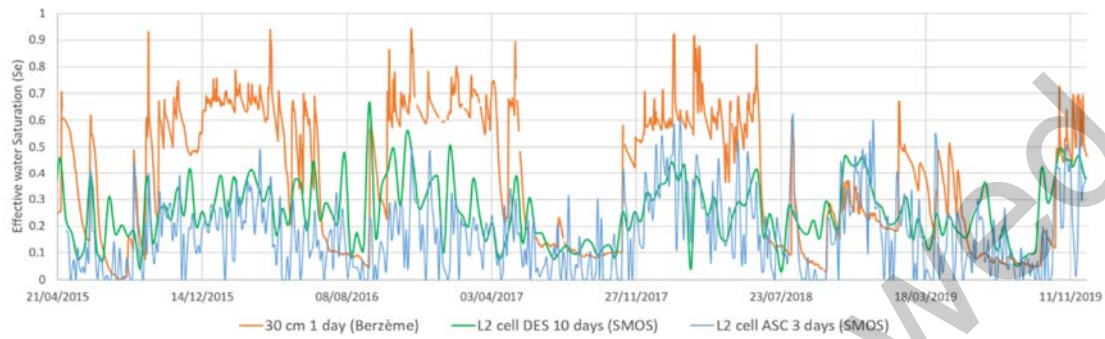
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854 **Figure 5. Mesh of the hydraulic model.** (a) Three-fault system consisting of
 855 LRF (La Rouvière), BRF (Bayne Rocherenard) and PF (Paurière) faults. Two other
 856 faults in the East are also included. Also shown is the topographic surface with the
 857 Rhône river. (b) Matrix including, among other layers, the surface layer
 858 characterized by the Apto-Albian clay layer (green) and the Barremian limestones
 859 (the rest).



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862 **Figure 6. Surface boundary condition of the hydraulic model.** The effective
863 saturation S_e (also called normalized water content) is calculated using *in situ* soil
864 moisture at 30 cm depth (SM30) at Berzème or Surface Soil Moisture (SSM) every
865 3 days or 10 days acquired by SMOS in the L2 cell (method section).



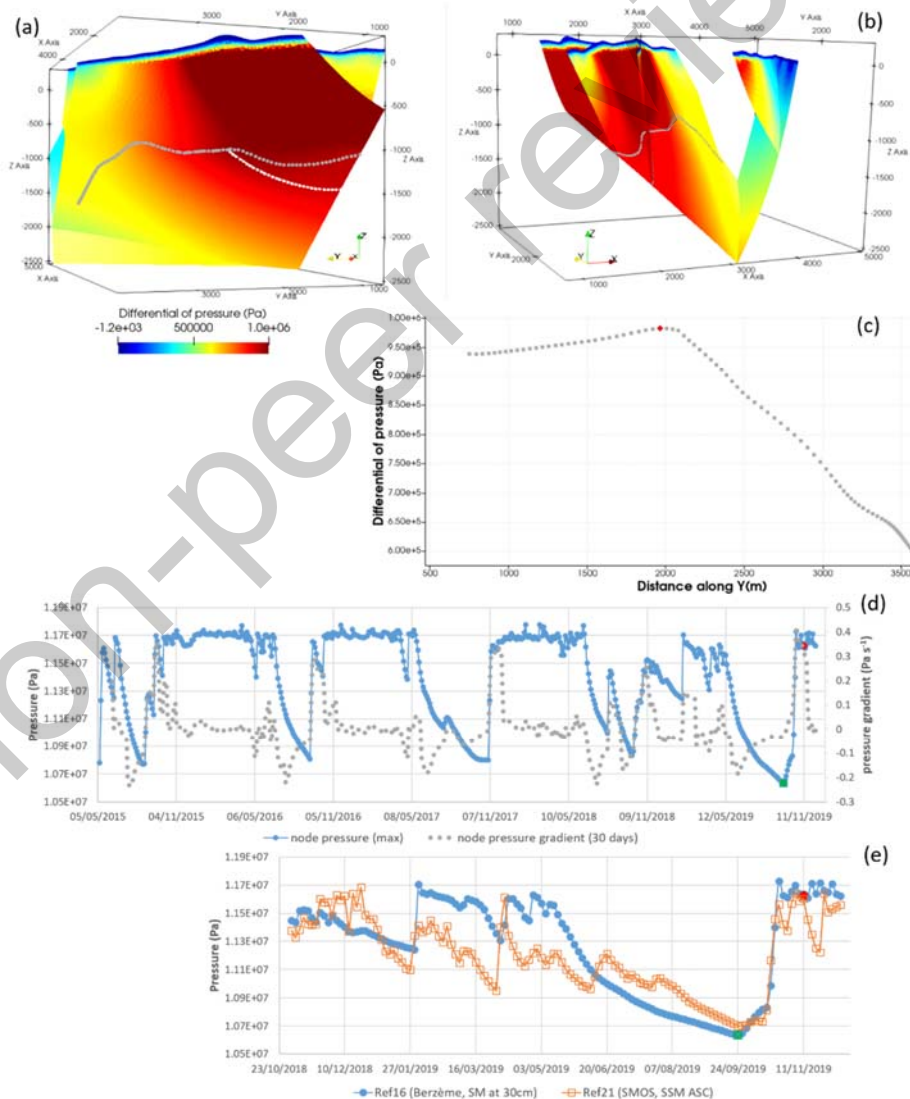
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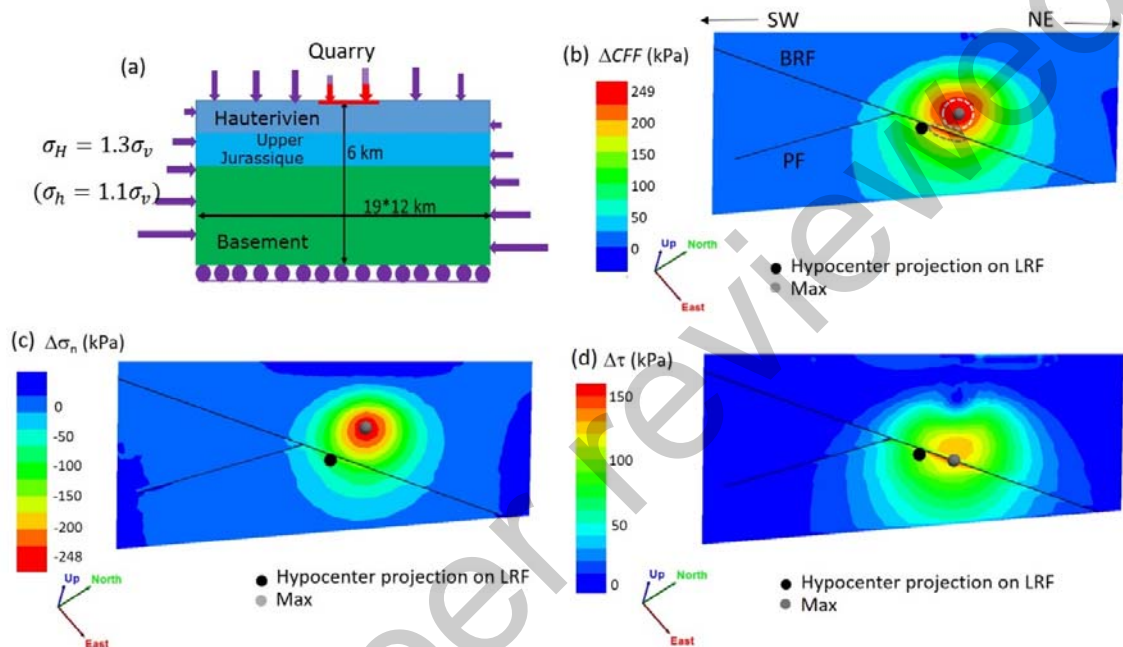
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870 Figure 7. Simulation result for the reference case using the soil moisture
 871 at 30 cm (Ref16). (a) Differential of pressure (ΔP) on LRF between 11th
 872 November 2019 and 24th September 2019. The intersection of BRF (or PF) with
 873 LRF is indicated by a grey (or white) dotted line. (b) ΔP on the local fault system
 874 (same view as in Figure 5). (c) Spatial variation of ΔP along the intersection line
 875 between LRF and BRF. Red diamond is the position of the node along this line
 876 where ΔP is maximum. (d) Temporal pressure variation between 2015 and 2019
 877 at the node where ΔP is maximum (blue line) and the pressure gradient for the
 878 previous 30 days (dotted grey line). The filled green square indicates the relative
 879 pressure minimum on 24th September 2019. The filled red circle indicates the
 880 pressure on 11th November 2019. (e) Zoom of (d) during the year 2019. Also
 881 shown is the result of the Ref21 case using the surface soil moistures (SSM).



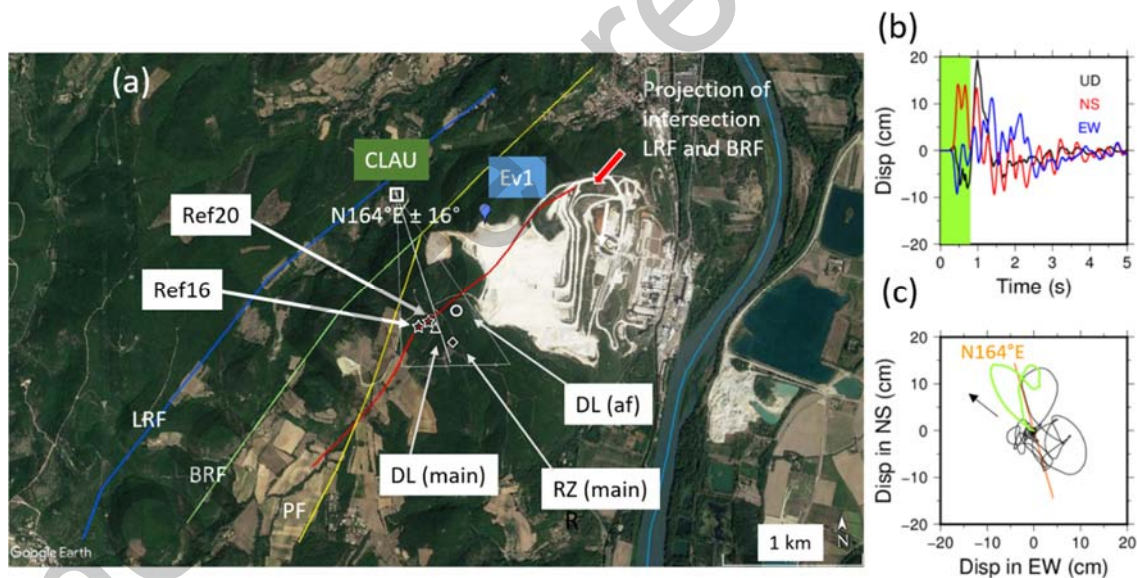
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884 **Figure 8. Mechanical simulation by 3DEC™.** (a) Conception of the mechanical
 885 model (change of the topography is given by a change of force on the ground
 886 surface). (b) Coulomb stress change (ΔCFF) on LRF related to mass withdrawal.
 887 Two areas of peak are identified as highlighted by broken lines. (c) Normal stress
 888 change on LRF. (d) Shear stress change on LRF. Grey point indicates maximum
 889 stress change. Black point indicates the projection of hypocenter location
 890 determined by Delouis *et al.* (2021) on LRF.



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894 **Figure 9. Comparison of different epicenter locations of Le Teil**
 895 **earthquake.** (a) Ref16 and Ref20 (stars) are the locations of maximum
 896 overpressures calculated by both reference cases Ref16 and Ref20. The red line
 897 represents the surface projection of the intersection at depth between LRF and
 898 BRF. Ev1 is the location of the blast event of 25th September 2019 in the quarry
 899 that is used in the analyses (Method section). DL (main): Epicenter location
 900 (triangle) of the mainshock suggested by Delouis et al. (2021). RZ (main):
 901 Epicenter location (losange) suggested by Ritz et al. (2020). DL (af): Epicenter
 902 location (circle) of the aftershock (MI 2.8) of the 23 November 2019 suggested by
 903 Delouis et al. (2021). Also shown is the sensor at the private Clauzel house (CLAU)
 904 located between LRF and BRF. (b) Waveforms in displacement of the earthquake
 905 event recorded by the sensor CLAU (integrated once from original record in
 906 velocity). The three components are displayed (NS, EW, UD). (c) Horizontal
 907 particle motion for the selected time window of the beginning of the signals (shown
 908 in panel (b) with green color) and associated polarity (orange line).



909

Supplementary Information to “Double surface rupture and hydraulic recharge of a three-fault system during the Mw 4.9 earthquake of 11 November 2019 at Le Teil (France)”

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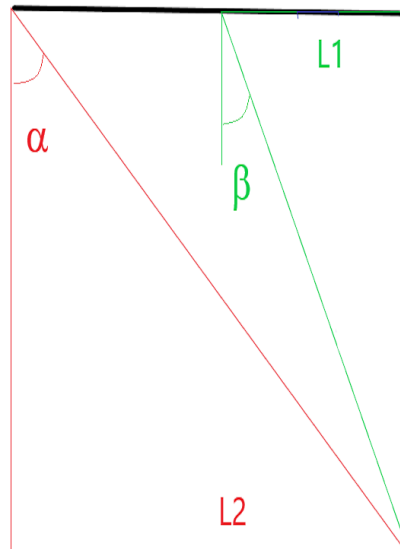
This file contains:

Texts S1-S3,

Tables S1-S4,

Figures S1-S9.

Text S1: Geometry of a two-fault system using a seismic profile.



The Two-way travelttime (TWT) result of a seismic profile is often not adequate to measure the true dip angle of one single fault due to the variations of the velocity with depth. If the lateral velocity variations are small compared to the variations with depth, we can use the ratio of apparent dip angles of a two-fault system in order to calculate both true dip angles.

Alpha (α) and Beta (β) are the supposed constant deviation to the vertical of La Rouvière fault (LRF) and Bayne Rocherenard fault (BRF), respectively.

L1 (and L2) is the horizontal distance between the projection of the intersection point of both faults and the intersection of LRF (and BRF) with the ground surface.

There is a simple trigonometric relationship between these four parameters:

$$\frac{\tan \beta}{\tan \alpha} = \frac{L1}{L2} \quad (1)$$

The equation to solve is therefore:

$$\frac{\tan x}{\tan \mu * x} = \lambda \quad (2)$$

With :

- the unknown x that is the deviation to vertical of BRF
- μ (μ) the ratio between alpha and beta
- λ (λ) the ratio between L1 and L2

We develop a python program using the Newton algorithm to resolve this equation for a couple of values (μ , λ) given by the seismic M201 profile (see Figure 4).

If $\mu = 4$, there is an explicit solution:

$$(\tan x)^2 = 3 - 2\lambda - 2\sqrt{1 + (\lambda - 1)^2} \quad (3)$$

If μ value is less than 4, the Newton method is applied using a first estimate corresponding to the explicit solution obtained with $\mu = 4$ (see text S2).

Text S2: Python script to resolve the equation (2)

```
#!/usr/bin/env python3

"""
:author: André Burnol
:date: 08 avril 2021
"""

from math import tan, atan, cos, sqrt, pi

def beta4rad(l):
    """fonction inverse de  $l = \tan(x)/\tan(4x)$ 

    x=0 if l=1/4
    """
    return atan(sqrt(3 - 2 * l - 2 * sqrt(l**2 - 2 * l + 2)))

def beta4(l):
    """fonction inverse de  $l = \tan(x)/\tan(4x)$ 

    x=0 if l=1/4
    """
    return 180 * beta4rad(l) / pi

def betarad_from_mu_lambda(mu, l):
    """fonction inverse de  $l = \tan(x)/\tan(\mu * x)$ 

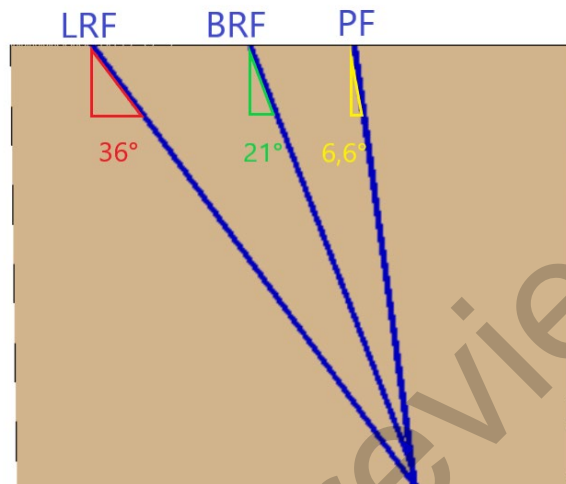
    x=0 if l=1/mu
    """
    x0 = 4/mu * beta4rad(mu * l/4)
    x = x0
    epsilon = 1e-14 # objectif en erreur relative
    delta = - (tan(x)-l*tan(mu*x))/(1/cos(x)**2-mu*l/cos(mu*x)**2)
    while abs(delta) > epsilon * abs(x):
        x = x + delta
        # méthode de Newton pour résoudre  $\tan(x) - l * \tan(\mu*x) = 0$ 
        delta = - (tan(x)-l*tan(mu*x))/(1/cos(x)**2- mu*l/cos(mu*x)**2)
    return x

def beta_from_mu_lambda(mu, l):
    """fonction inverse de  $l = \tan(x)/\tan(\mu*x)$ 

    if lambda=l=0.5128 and mu=1.76
    >>> beta_from_mu_lambda(1.76, 0.5128)
    20.55150781493907
    >>> beta_from_mu_lambda(1.76, 0.5128)*1.76
    36.170653754292765
    >>> beta_from_mu_lambda(1.76, 0.5128)/3.1
    6.629518649980345
    """
    return 180 * betarad_from_mu_lambda(mu, l) / pi
```

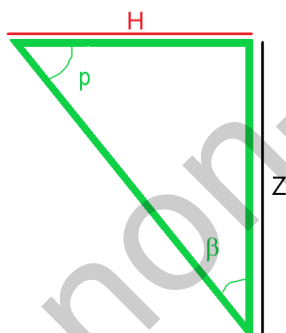
Text S3: Application to the three-fault system using M201 seismic profile and comparison with the observations of SC03 geotechnical drilling

From the M201 seismic profile (see Figure 4), we found $(\mu, \lambda) = (1.76, 0.5128)$ and the solution given by the $\beta_{\text{from_mu_lambda}}(\mu, \lambda)$ is $\beta = 21^\circ$ and therefore $\alpha = \mu * \beta = 36^\circ$. The same method is used for the Paurière fault (PF), we found using M201 profile a ratio of both angles of $\mu_2 = 3.1$ and therefore the deviation of PF to the vertical is $\beta / 3.1 = 6.6^\circ$.

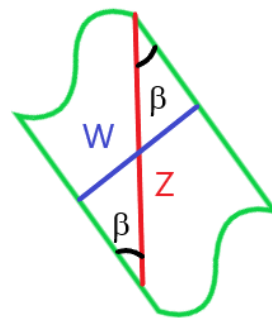


The corresponding dip angles of LRF, BRF and PF are therefore 54° , 69° and 83.4° (Figure 4c).

Another way to calculate the deviation to the vertical of BRF is to use the observations of SC03 geotechnical drilling conducted in 2016 by the quarry owner (see Figure S5 below):



$$\tan \beta = \frac{H}{Z} \quad (4)$$



$$Z \times \sin \beta = W \quad (5)$$

In Figure S5, the photo S5b of SC03 core reveals a natural sub-vertical fracture at 90.5m vertical depth (with calcite veins). By using $(H,Z) = (35.6 \text{ m}, 90,5 \text{ m})$, we found $\beta = 21.47^\circ$ using (4). Both values of the dip angle of BRF we found are therefore consistent and credible if it assumed that this dip angle is laterally and vertically constant. Using this β value, we can estimate the thickness of BRF noted W by supposing that the height Z of (5) is located between a depth of approximately 83 m to 115 m (see Figure S5): $W = 32 \text{ m} * \sin (21.47^\circ) = 11.7 \text{ m}$. Therefore, a range of values of the width between 10 m and 30 m can be used (see Tables 1 and S4).

- **Supplementary tables**

Table S1: Characteristics of the produced interferograms.

Track ID	Acquisition dates	Perpendicular baseline (m)	Time span (days)
059 (ascending)	6/11/2019 and 12/11/2019	13	6
161 (ascending)	7/11/2019 and 13/11/2019	92	6
037 (descending)	11/11/2019 and 17/11/2019	7	6
139 (descending)	6/11/2019 and 12/11/2019	51	6

Table S2: fault parameters after Derode et al (2015) used for 3DECTM simulation.

Parameters	Values
Normal stiffness k_n [GPa/m]	20
Shear stiffness k_s [GPa/m]	20
Friction coefficient μ	0.6

Table S1 : Model parameters of the medium for 3DECTM simulation. Thickness represent the value below le Teil. Each layer is inclined slightly of 3° to 5°.

Parameters	Value		
	Hauterivian	Upper Jurassic	Basement
Poisson ratio ν	0.24	0.27	0.3
Young modulus E [GPa]	42	16	61
Density [kg/m ³]	2500	2600	2690
Thickness [m]	420	780	-

Table S4: ComPASS results for a 10-fold decrease of the fault permeability and fault porosity compared to the reference cases (Table 1).

	Ref6	Ref19
Soil moisture	SM30 (Berzème, 30 cm depth)	SSM (SMOS DES, 10 days)
Matrix Porosity w_m	0.2	0.2
Matrix Permeability K_m	10^{-18} m^2 in Apto-albien	10^{-18} m^2 in Apto-albien
	10^{-16} m^2 elsewhere	10^{-16} m^2 elsewhere
Fault Porosity w_f	0.01	0.01
Fault Permeability K_f	10^{-12} m^2	10^{-12} m^2
Fault Width W	20 m	20 m
Maximum differential of pressure (ΔP) along the intersection LRF / BRF	9.6 bar	7.3 bar

- **Supplementary Figures**

Figure S1: position of our interpretation of the A059 interferogram on the 1:50 000 geological map (Kerrien et al., 1989). Black lines (solid and dotted): the position of the faults resulting from the geological map. Blue lines: our rupture lines based on the DInSAR results. Red dots: the observations of surface ruptures from Ritz et al. (2020).

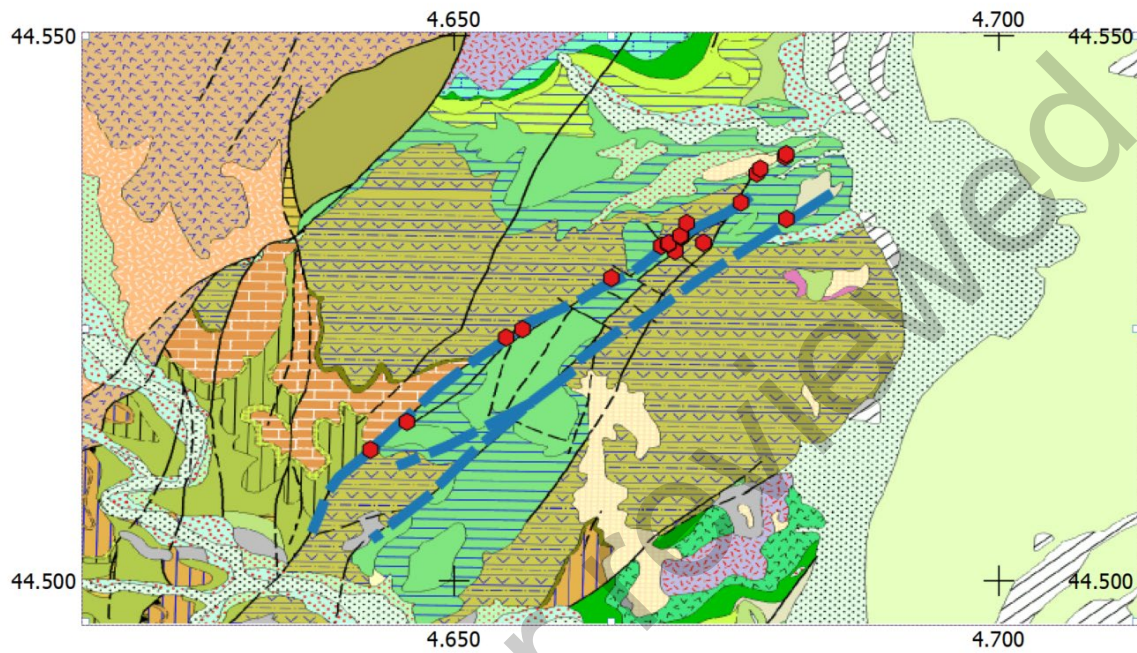


Figure S2: example of use of the Cosi-corr's profiles stacking tool. Left: interferogram A059 as represented in Cosicorr: red line fault "candidate" for LRF, yellow area containing the 10 profiles to be stacked (1500m X 150m). Right: stacked profile across LRF (position in pixels – i.e. 15m – displacement values in meters). Displacement on the fault is automatically computed as the difference at 0 position between the 2 green lines (linearly fitting the motion each side of the fault).

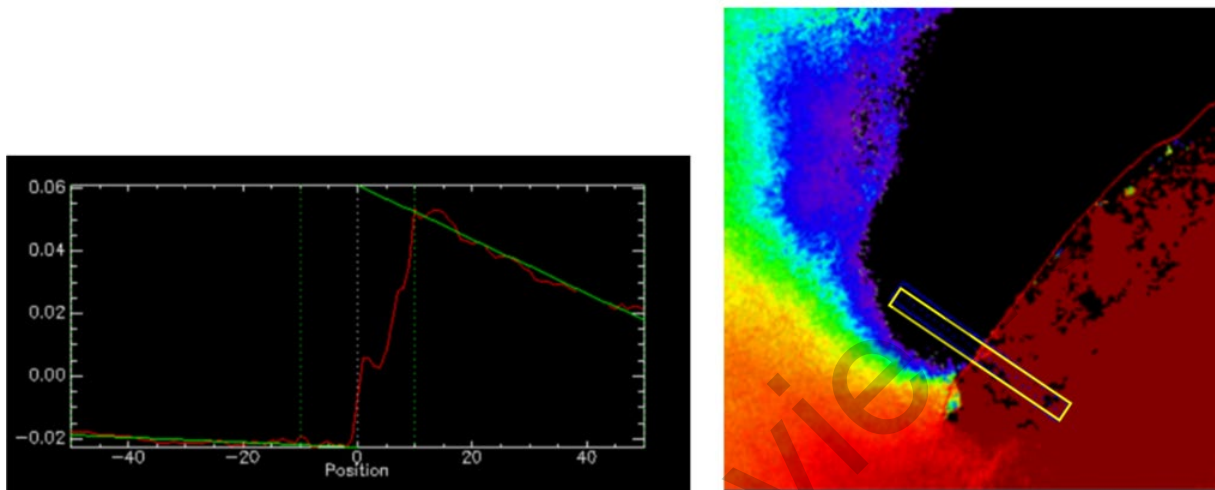


Figure S3: Diagram illustrating (in a very simplified way) a specific unwrapping issue due to two parallel jumps (in our case two surface ruptures represented by F1 and F2). Red line is a profile on the original wrapped interferogram. Assuming that the displacement should be zero at $\pm\infty$ left part of F1 and right part of F2 can be unambiguously unwrapped (blue dashed line). However between F1 and F2 the unwrapping solution results ambiguous: on solution a) all the displacement is on F2, on solution b) all the displacement is on F1, intermediary solutions are possible (e.g. c))

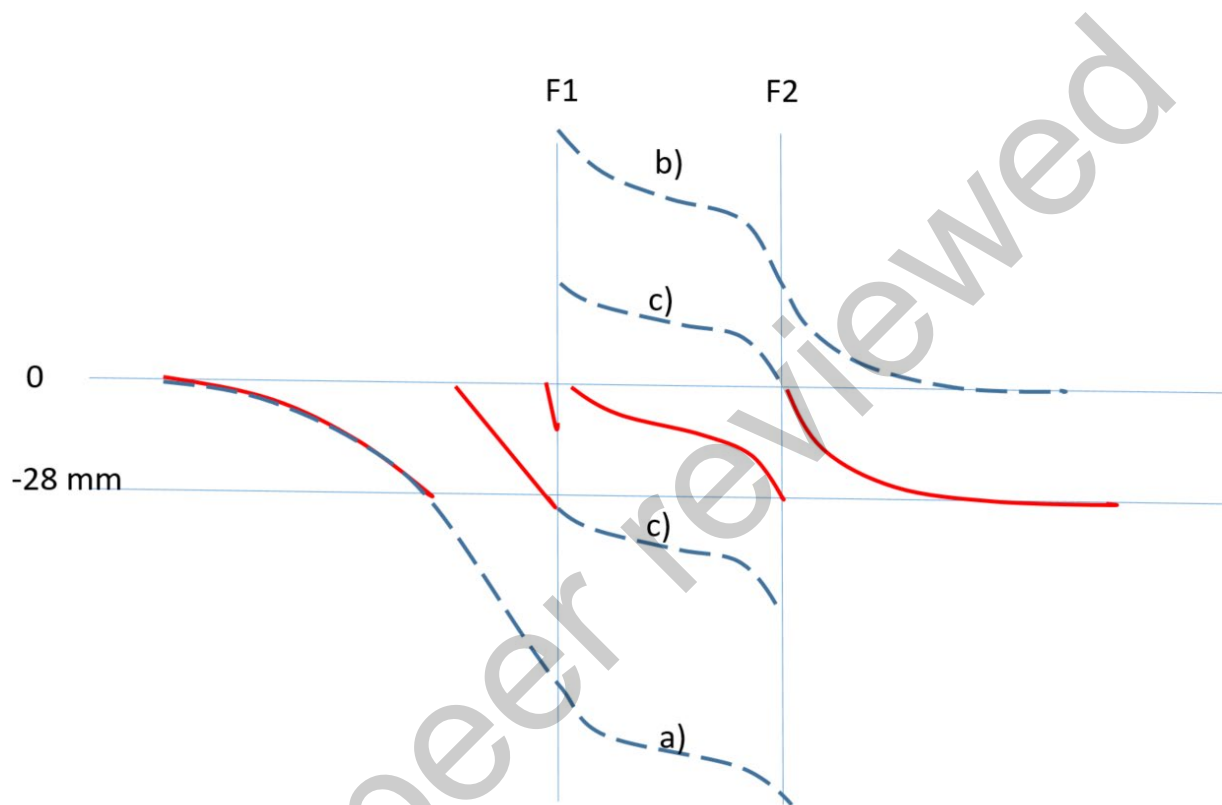


Figure S4: comparison of our unwrapped interferogram (A) with the figure (B) adapted from Ritz et al. (2020) on the North-East sector of the area of interest. We can observe that the unwrapping algorithms have distributed differently the slips between the two ruptures. For instance in Ritz et al. (2020) the LRF is locally locked suggesting a more complex behavior than in our interpretation (where this lock is not significant).

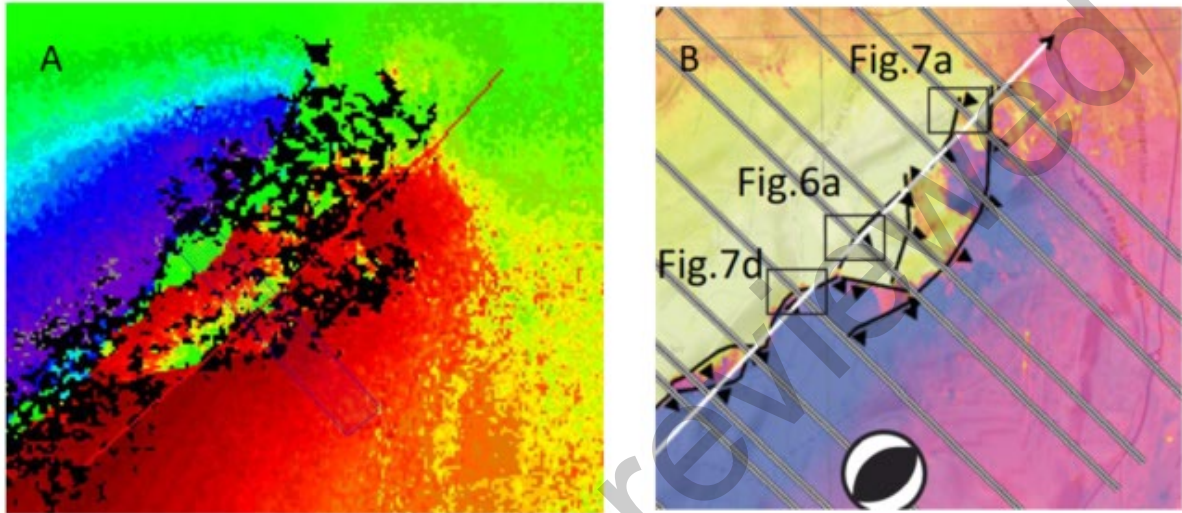
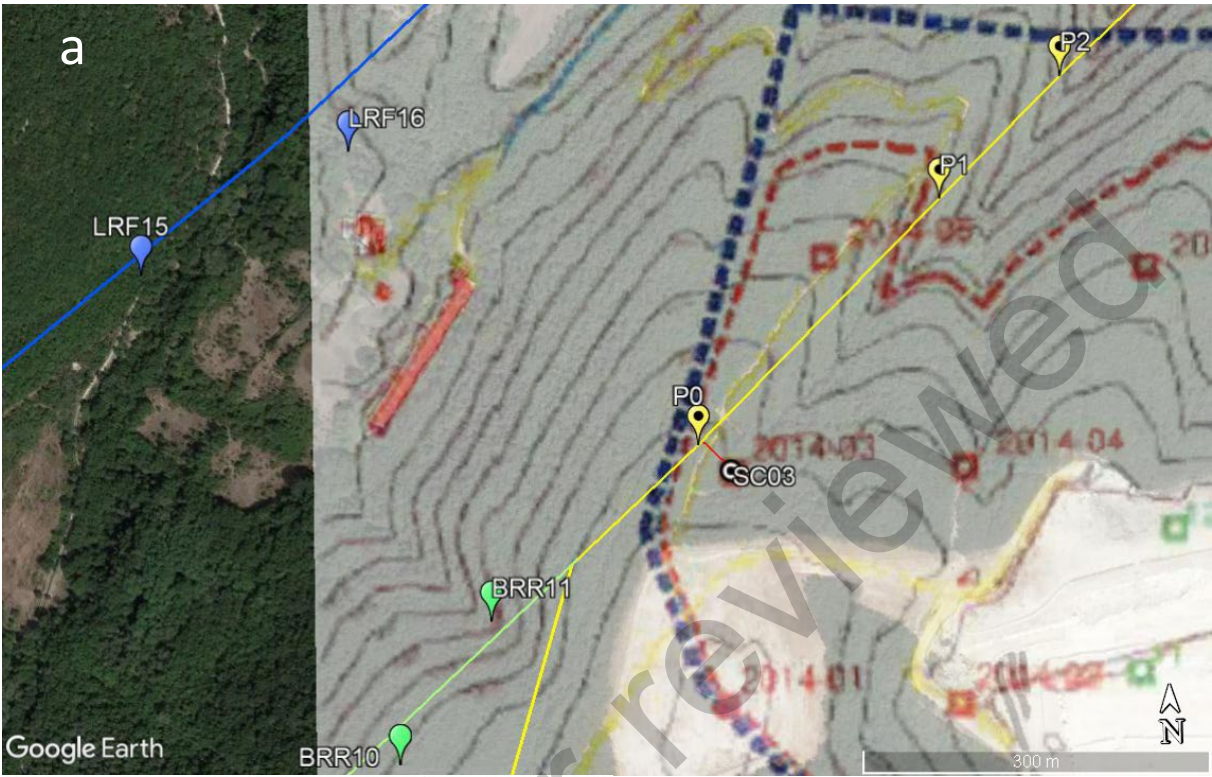


Figure S5: SC03 geotechnical drilling conducted in 2016 by the quarry owner: a) location of SC03 about 35.6 m (red line) southeast of Bayne Rocherenard fault (yellow line near P0) b) core samples at depth between 89 m and 92 m, c) core samples at depth between 112.5 m and 115.3 m.



Caisse n° 31 : Photo 15



Caisse n° 39 : Photo 23

Figure S6: (a) Regional setting with both SMOS cells L1 and L2 around Le Teil. The rainfall station is located in L2, the soil moisture station (Berzème) from the SMOSMANIA network in L1 and the Valvignères borehole in L1. The location and the date of all the seismic events in the area of 50 km x 25 km (L1 and L2) recorded by the French national catalogue (RéNaSS) are shown during the 2010-2019 period. (b) Comparison of the rainfall data with the Soil Moisture (SM) at Berzème (1 day) and the Surface Soil Moisture (SSM) acquired by SMOS (descending path, 10 days) during the 2010-2019 period. (c) Cell pressure (blue line) and cell pressure gradient (dotted green line) in the Ref19 case (Table S4) using the Surface Soil Moisture (SSM) acquired by SMOS (descending path, 10 days) during the period 2010-2019.

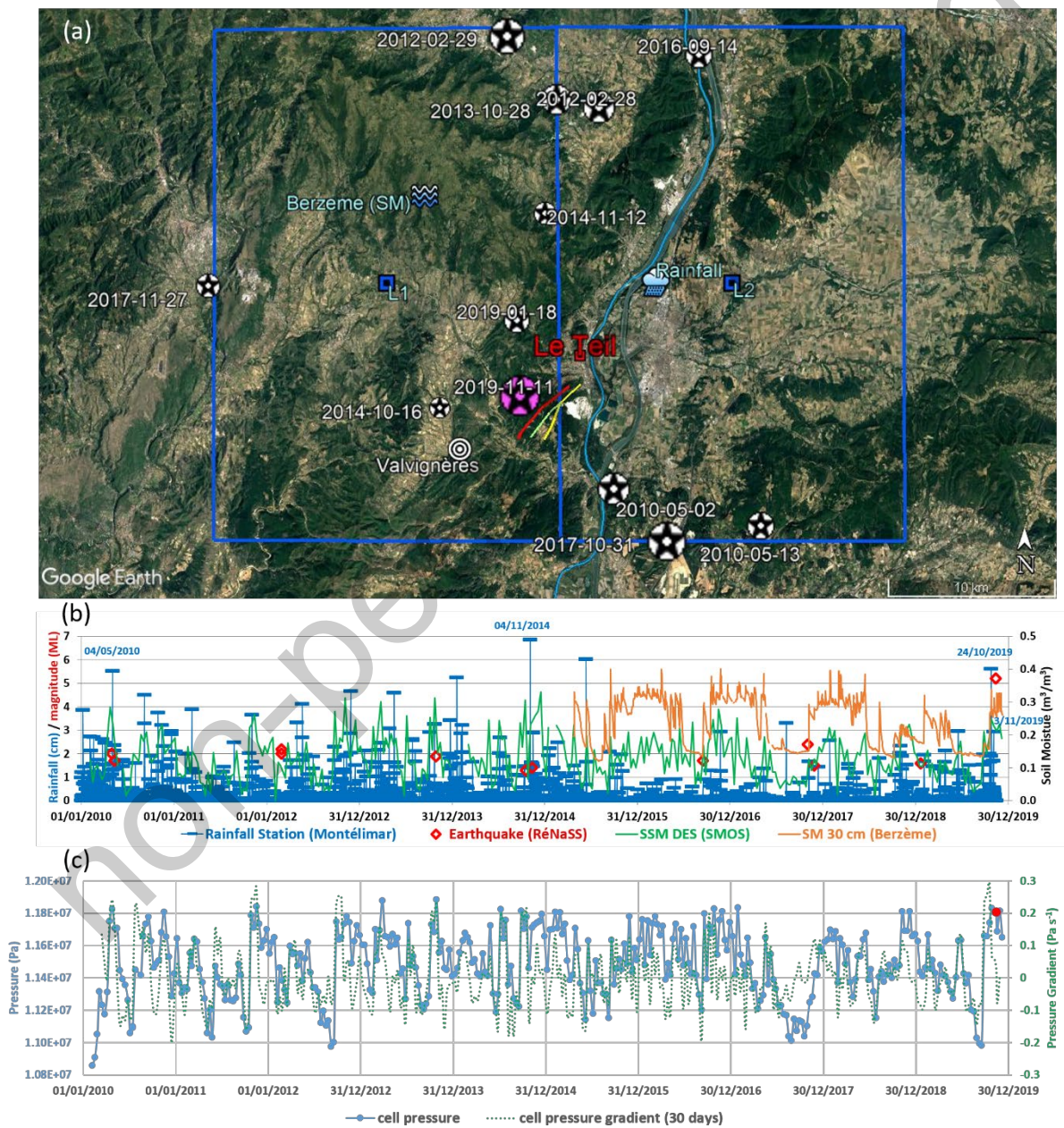


Figure S7: Fault models and numerical meshes in 3DEC simulations. The dimension (x,y,z) is 19 km (N110°E) x 12 km (N20°E) x 6 km (vertical). (a) Fault elements implemented in simulation. (2) A snapshot of simulation in a fault system with respect to the surface quarry. The color indicates the ΔCFF , whose color scale is indicative.

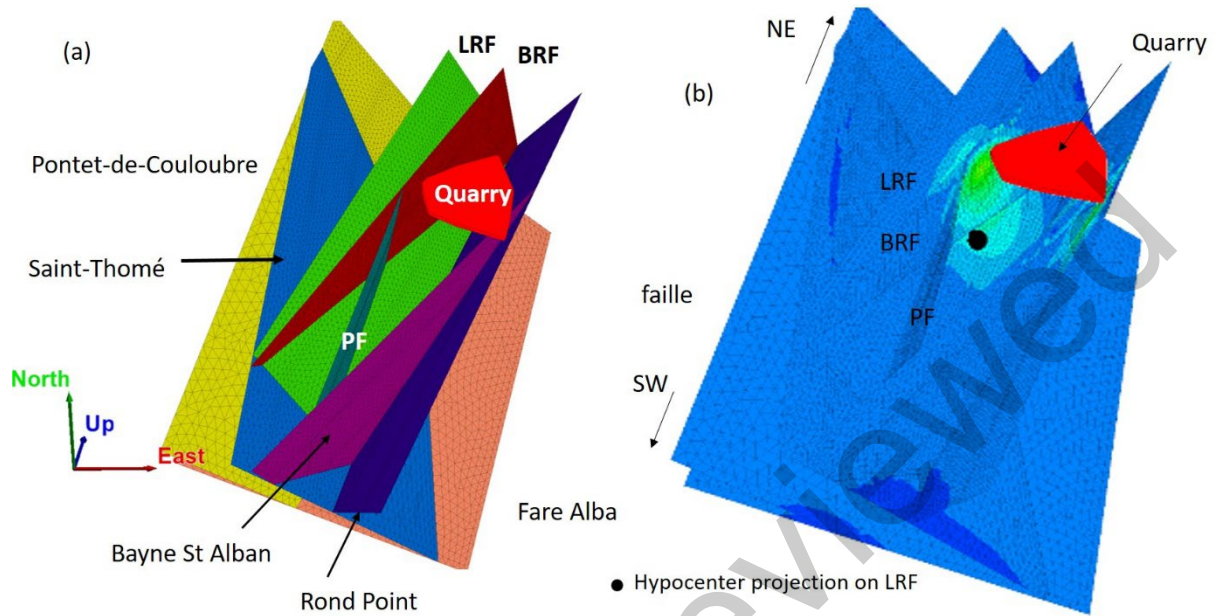


Figure S8: Estimated extracted area and topography change between 1833-2019. The earlier period before 1950 is based on the estimation of De Novellis et al. (2020) and the extracted volume is evenly distributed on the corresponding surface. The extracted volume during the second period after 1950 is estimated from the topography change observed on map.

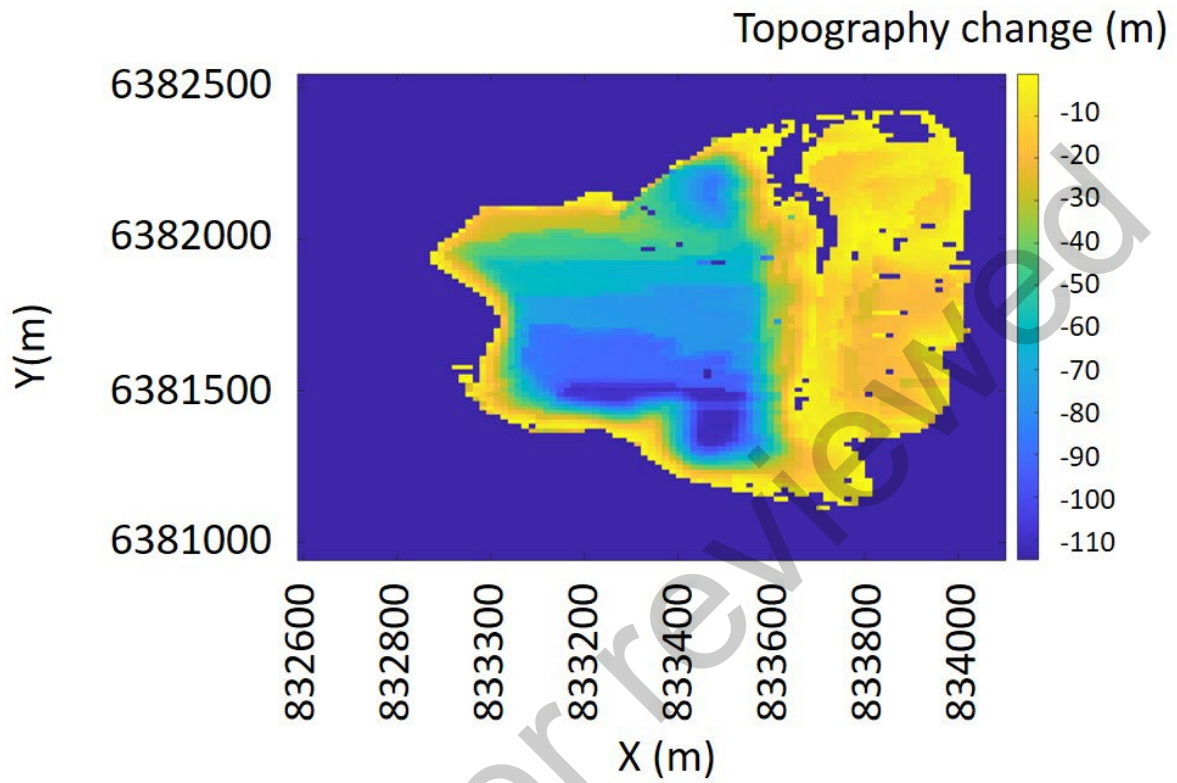
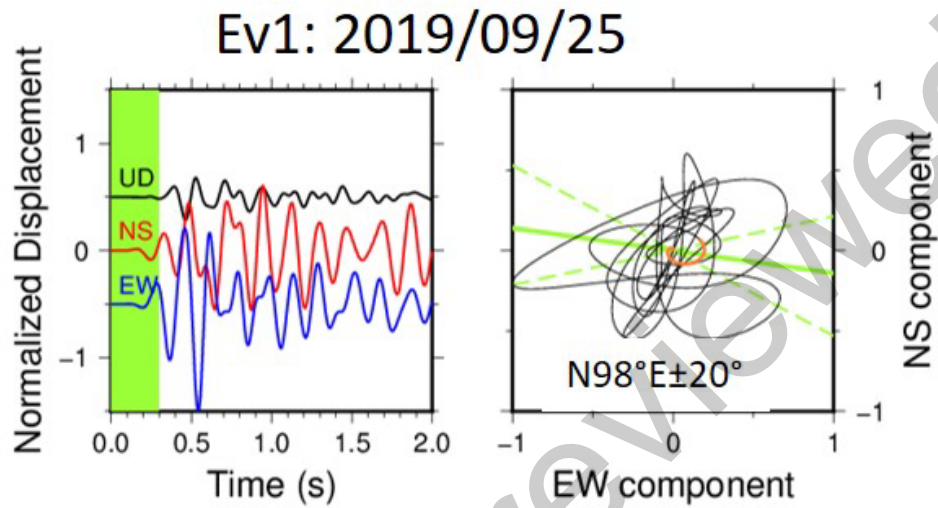


Figure S9: Ground motion recorded at Clauzel house (CLAU) for the blast event of the 25th September 2019. Filtered (1-10 Hz) and integrated seismograms in the left panel. The horizontal particle motion at the right. The first 0.3 second is highlighted as red line. The azimuth is estimated to $N98^{\circ}E \pm 20^{\circ}$ (green line with broken lines) with respect to the true value of $N111^{\circ}E$.



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