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## Mechanical instability induced by water weakening in laboratory fluid injection tests

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10  
11 **Abstract**

12 To assess water-weakening effects in reservoir rocks, previous experimental studies have  
13 focused on changes in the failure envelopes derived from mechanical tests conducted on rocks  
14 fully saturated either with water or with inert fluids. So far little attention has been paid to the  
15 mechanical behavior during fluid injection under conditions similar to enhanced oil recovery  
16 operations. We studied the effect of fluid injection on the mechanical behavior of the weakly  
17 consolidated Sherwood sandstone in laboratory experiments. Our specimens were  
18 instrumented with 16 ultrasonic P-wave transducers for both passive and active acoustic  
19 monitoring during loading and fluid injection to record the acoustic signature of fluid  
20 migration in the pore space and the development of damage. Calibration triaxial tests were  
21 conducted on three samples saturated with air, water or oil. In a second series of experiments,  
22 water and inert oil were injected into samples critically-loaded up to 80% or 70% of the dry or  
23 oil-saturated compressive strength, respectively, to assess the impact of fluid migration on  
24 mechanical strength and elastic properties. The fluids were injected with a low back pressure  
25 to minimize effective stress variations during injection. Our observations show that creep

26 takes place with a much higher strain rate for water injection compared to oil injection. The  
27 most remarkable difference is that water injection in both dry and oil-saturated samples  
28 triggers mechanical instability (macroscopic failure) within half an hour whereas oil injection  
29 does not after several hours. The analysis of X-ray CT images of post-mortem samples  
30 revealed that the mechanical instability was probably linked to loss of cohesion in the water  
31 invaded region.

32

### 33 **1. Introduction**

34 It has long been recognized that the nature of the fluid present in the pore space of a reservoir  
35 rock can have a significant influence on its mechanical behavior. Water weakening is a well-  
36 known phenomenon that has been recognized in several geological settings, affecting  
37 different rock types, like sandstones and carbonates. For example Risnes et al. [2005] focused  
38 on the mechanical behavior of chalk to highlight the importance of water-weakening effects in  
39 the subsidence observed during the production and stimulation of the Ekofisk hydrocarbon  
40 reservoir in the southern part of the North Sea. They showed that the failure envelope for  
41 Ekofisk chalk samples depends on the nature of the saturating fluid, and that the chalk is  
42 significantly weaker when water is saturating the rock pore space than for any other saturating  
43 fluid. Different weakening mechanisms can operate when rocks exhibit water sensitivity,  
44 among them chemical and stress effects on mineral solubility (especially calcite) [Risnes et  
45 al., 2005], stress corrosion effects permitting easier crack propagation [Atkinson and  
46 Meredith, 1987; Zhu and Wong, 1997], adsorption effects at grain surfaces [Orowan, 1944;  
47 Rehbinder et al., 1948; Baud et al., 2000], water-clay mineral interactions and capillary  
48 effects [Schmitt et al., 1994]. To study water weakening in the laboratory, a classical method  
49 is to compare the mechanical behavior of rocks with different saturating fluids in standard  
50 triaxial tests under comparable effective confining pressure, and to infer the failure envelopes.

51 Doing so, Baud et al. [2000] found for several sandstones that water weakening affects both  
52 the strength (i.e. low mechanical strength in water-saturated rocks) and the elastic moduli (i.e.  
53 low elastic moduli in water-saturated rocks).

54 Little attention has been paid so far to fluid substitution processes in a reservoir at depth and  
55 the resulting consequences in terms of mechanical stability. This issue is crucial for the  
56 development of enhanced oil recovery strategies in partially depleted reservoirs. Indeed a  
57 widespread method to maintain reservoir pressure during production is to inject water into the  
58 reservoir [Donnez, 2012]. Nevertheless injecting water can have a strong impact on the  
59 reservoir mechanical stability: a good example of problems that might occur is the increase of  
60 subsidence rate observed for the Ekofisk reservoir when water was injected to recover its  
61 original pore pressure [Doornhof et al., 2006]. Therefore an integrated study combining  
62 mechanical characterization and fluid migration monitoring in porous rocks is desirable. The  
63 idea is to isolate the water weakening effect during fluid injection from any other, especially  
64 effective stress variations. In contrast to former experimental studies on water weakening  
65 based on triaxial testing on fluid saturated rocks, our approach - partly inspired by Stanchits et  
66 al. [2011] - consists in injecting water in reservoir rocks with minimum perturbation of the  
67 stress, to analyze how weakening effects progressively affect their mechanical integrity under  
68 conditions similar to fluid injection/withdrawal in real reservoirs. One key question is to  
69 understand the damage that water weakening produces and if it can lead to localized  
70 deformation structures like shear fractures or compaction bands. Another key question is  
71 whether continuous acoustic monitoring is capable of recording the fluid substitution process  
72 and the associated damage when water weakening is active in rocks. To answer these  
73 questions, we developed an original experimental protocol designed to highlight the  
74 weakening effects of fluid injection.

75

## 76 **2. Petrophysical and mechanical properties of the selected rock**

77 We selected for our study the weakly-consolidated Sherwood sandstone, also named Otter  
78 Sherwood sandstone, a fairly good analog for an actual reservoir rock. The Sherwood  
79 sandstone formation is produced at a depth of approximately 1500 m in the Wytch Farm Oil  
80 Field, the only onshore oil field operated in the UK. The Sherwood sandstone outcrops in  
81 South-West of England and was sampled directly at the Ladram Bay cliffs. Quartz and  
82 Felspar are the major minerals in the rock composition, with also a significant amount of  
83 detrital clays (**Table 1**, see also Nguyen et al., 2014). The Sherwood sandstone has a mean  
84 porosity of 30%, an average grain diameter of 120  $\mu\text{m}$  and an anisotropic permeability, with  
85 200 mD and 350 mD normal and parallel to the bedding, respectively. The Sherwood  
86 sandstone is poorly consolidated and needs to be handled with care during coring and  
87 preparation for laboratory experiments.

88 The hydro-mechanical behavior of the Sherwood sandstone was investigated thoroughly by  
89 Nguyen et al. [2014] in triaxial experiments with controlled stress paths. The failure envelope  
90 [Wong et al., 1997] for water-saturated samples was obtained under drained conditions and  
91 the onset of grain-crushing and pore collapse occurs at a critical pressure of  $P^*=40$  MPa as  
92 determined by Nguyen et al. [2014]. In addition to its low mechanical strength, we also  
93 selected this rock because of its sensitivity to water: for example the critical pressure  $P^*$  is  
94 much higher for the dry Sherwood sandstone ( $> 60$  MPa) than for the water saturated rock.

95 The P wave velocity anisotropy was investigated at room conditions through measurements  
96 for ray paths with different angle with respect to the bedding. The dry Sherwood sandstone  
97 exhibits a significant velocity anisotropy (about 15%) with a minimum velocity for P-waves  
98 travelling perpendicular to the bedding (1250 m/s) and a maximum velocity for travel paths  
99 parallel to bedding (1470 m/s). This anisotropy vanishes when the rock sample is saturated  
100 with water, and velocity for all travel paths shows a fairly similar value ( $\sim 2000$  m/s). This

101 contrast in anisotropy can be explained by pore shape anisotropy as shown by Louis et al.  
102 [2003]: when saturated with water the pores with anisotropic shape become stiffer and have a  
103 smaller effect on the overall elastic anisotropy. We have also measured the evolution of P-  
104 wave velocity for partially saturated samples and found that in the low water saturation range  
105 ( $S_w < 55\%$ ) the P-wave velocity is lower than that of the dry rock, then increases to a higher  
106 value close to full saturation. P-wave velocity anisotropy and variation with saturation need to  
107 be taken into account for the understanding and modeling of the injection experiments  
108 reported below.

109

### 110 **3. Experimental approach**

#### 111 *3.1. Experimental set-up*

112 Series of mechanical tests were conducted at the CSIRO's rock mechanics laboratory (Perth,  
113 Australia) using a Sanchez Technologies triaxial rig [Sarout et al., 2010; Sarout et al., 2014]  
114 on rock specimens with 38 mm nominal diameter and 80 mm nominal length. All samples  
115 were cored in a direction perpendicular to the bedding. During each mechanical test, the mean  
116 axial strain is measured and averaged over the sample length through three external  
117 displacement sensors, and the local radial strain by an internal cantilever sensor attached at  
118 mid-height to the sample. The average volumetric strain is computed from axial and radial  
119 strains. All of the mechanical parameters are controlled and monitored in real time on a  
120 computer with a LabVIEW interface. A special jacket design is used to isolate the sample  
121 from the confining fluid, with provision for attaching 16 piezoelectric sensors directly to the  
122 sample's surface and distributed on four different planes. In our experiments only P-wave  
123 transducers, with a diameter of 9 mm and a mean resonant frequency of 0.5 MHz, were used.  
124 They are connected to an Applied Seismology Consultants ultrasonic monitoring system  
125 which can work in two different modes: in the passive mode the system records all micro-

126 seismic events (above a pre-defined energy threshold) which occur in the sample during  
127 loading; in the active (or survey) mode the system works in a transmitter-receiver  
128 configuration, with each transducer successively pulsing while the others record the  
129 transmitted signal. In the active mode, a velocity survey is typically run every minute and the  
130 flight times of P-waves can be extracted and converted into velocity knowing the distance  
131 between source-receiver pairs. In the passive mode, we can analyze the acoustic emission  
132 (AE) activity during the experiment. We can also locate the micro-seismic events using a  
133 model of the velocity field in the rock sample inferred from the velocity surveys (active  
134 mode), but the results of this analysis will not be reported here.

135

### 136 *3.2. Experimental protocols*

137 In contrast with previous studies based mainly on triaxial testing to assess mechanical water-  
138 weakening effects in reservoir rocks, we promote an experimental protocol based on fluid  
139 injection, adapted from the work of Stanchits et al. [2011]. Three different fluids were used:  
140 air, water and oil. In the last case, we used Fluorinert oil, a fully-fluorinated liquid (no  
141 oxygen) which has at 25°C a density  $\rho_o=1940 \text{ kg/m}^3$ , a dynamic viscosity  $\mu_o=0.024 \text{ Pa.s}$  and a  
142 surface tension  $\gamma_o=0.018 \text{ N/m}$  (for comparison, water properties are  $\rho_w=1000 \text{ kg/m}^3$ ,  
143  $\mu_w=0.00088 \text{ Pa.s}$  and  $\gamma_w=0.072 \text{ N/m}$ ). The mechanical tests were run under a controlled  
144 temperature of 25°C.

145 Three types of experiments were carried out (**Figure 1**). All three were performed on pre-  
146 consolidated samples, i.e. hydrostatically loaded up to 25 MPa (well below the critical stress  
147  $P^*$ ) and unloaded down to 5 MPa. This pre-consolidation (step I in **Figure 1**) is applied to  
148 minimize the effect of variations in initial crack content and promotes a better reproducibility  
149 of the mechanical behavior from sample to sample. The three experimental protocols consist  
150 of:

151            a) Triaxial tests: We first performed a standard characterization of P-wave velocity  
152 and compressive strength sensitivities to the different fluids through standard triaxial tests  
153 (**Figure 1a**). For the dry test, the sample is kept at 5 MPa confining pressure and axial stress  
154 is increased up to failure at constant strain rate of  $10^{-5} \text{ s}^{-1}$  (step IV). For the tests with water  
155 and oil as pore fluid, we first evacuated the dry pre-consolidated sample for a couple of hours  
156 to remove the air from the pore space, then we injected the fluid at the bottom end of the  
157 sample with a controlled fluid pressure of 0.5 MPa until at least one pore volume of fluid bled  
158 through the top pore fluid line (step II). We achieve full saturation by increasing both the pore  
159 pressure to 2 MPa and the confining pressure to 7 MPa (step III) to dissolve any residual air  
160 trapped in the pores and ensure full saturation of the samples while keeping the same effective  
161 confining pressure as in the dry test. Finally, the axial stress was increased at a constant strain  
162 rate ( $0.5 \cdot 10^{-5} \text{ s}^{-1}$ ) up to failure (step IV) while the confining pressure and pore pressure were  
163 kept constant. In the following, we will refer to these tests as TRX-a, TRX-o and TRX-w  
164 when the saturating fluid was air, oil or water, respectively.

165            b) Fluid injection tests into dry samples: These tests are designed to highlight the  
166 effect of fluid injection in a dry rock under constant triaxial stress (creep condition). At a  
167 confining pressure of 5 MPa, a dry sample is axially loaded to a differential stress level  
168 corresponding to 80% of the dry compressive strength (**Figure 1b**). At this constant stress, the  
169 sample is evacuated for 15 minutes at its top end and then either water or oil is injected at the  
170 bottom end with a controlled injection pressure of 0.5 MPa. In the following, we will refer to  
171 these experiments as INJ-wa and INJ-oa for water and oil injection into a dry sample  
172 respectively.

173            c) Fluid substitution tests: We inject water into an oil-saturated sample under constant  
174 triaxial stress; a test aimed at mimicking Enhanced Oil Recovery operations by water flooding  
175 an oil-saturated reservoir (**Figure 1c**). The oil saturation of the sample was achieved



176 according to step II of the triaxial test at a confining pressure of 5 MPa. We aimed initially at  
177 conducting the fluid substitution under conditions similar to step III in the other injection  
178 tests, i.e. at stress level corresponding to 80% of the dry strength. However, doing so led to  
179 the premature failure of several samples before the targeted critical load of 80% was reached.  
180 Thus we targeted a lower value of differential stress of 13 MPa, corresponding to 70% of the  
181 oil-saturated strength derived from TRX-o test. In addition, water injection into the oil-  
182 saturated sample was carried out at a constant flow rate from the bottom end, while  
183 maintaining a back pressure of 0.35 MPa at the top end of the sample. This modification of  
184 the protocol was implemented to ensure that the sample was fully oil-saturated prior to  
185 injecting water, which was not an issue for INJ-wa and INJ-oa. We selected an injection rate  
186 ( $30 \text{ cm}^3/\text{h}$ ) at the bottom end of the sample so that the fluid pressure there never exceeded 1  
187 MPa. Although the bottom end fluid pressure was not controlled in this test, the selected  
188 injection rate there and the back-pressure applied at the top end must have generated only a  
189 relatively small pore pressure gradient across the sample (0.65 MPa across 80 mm). In the  
190 following, we will refer to this experiment as INJ-wo.

191

#### 192 **4. Results of the triaxial tests**

193

194 During the saturation stage prior the triaxial tests, a striking difference was found between  
195 water injection and oil injection in the dry samples. The passage of the water near the planes  
196 where the ultrasonic sensors are located (**Figure 2a**) induces a decrease in P-wave velocity for  
197 water injection (**Figure 2b**), whereas for oil injection we observe an increase (**Figure 2c**).

198 During the pre-consolidation stage, the reproducibility is not ideal when looking at the strain  
199 at maximum pressure and after unloading down to 5 MPa (**Figure 3a**) which is probably due  
200 to (i) the initial stiffness of the samples at room pressure being significantly different, (ii) the

201 different amount of time the samples were allowed to rest (creep) at the highest pressure (25  
202 MPa) and/or (iii) the heterogeneous nature of the studied rock. However the stiffness of the  
203 samples at high pressure is relatively similar as suggested by the slope of the pressure-strain  
204 curve during unloading. As the pre-consolidation stage was aimed at minimizing the effect of  
205 sample heterogeneity, we consider that for each sample the final strain after unloading down  
206 to confining pressure of 5 MPa corresponds to a reference state with respect to which further  
207 triaxial deformation and weakening effects are evaluated. Therefore, the initial axial strain in  
208 the triaxial loading stage was set to zero.

209 During the triaxial loading, the mechanical behavior of the Sherwood sandstone is clearly  
210 controlled by the nature of the fluid saturating the pore space because both the peak stress and  
211 the static elastic moduli are different in the three triaxial tests conducted under similar  
212 effective pressure conditions (**Figure 3b, Table 2**). The lowest peak stress is found for the  
213 water-saturated sample TRX-w (14.1 MPa), much lower than for the dry sample TRX-a (20.2  
214 MPa). Sample TRX-o has an intermediate peak stress value (18.5 MPa). Clearly water has a  
215 strong weakening effect not only on the mechanical strength of Sherwood sandstone but also  
216 on its elastic moduli, if we compare the Young's moduli for TRX-a (4.3 GPa), TRX-o (4.1  
217 GPa) and TRX-w (3.5 GPa). No change in Poisson's ratio between dry and water-saturated  
218 samples (0.3) is observed (**Table 2**), but a significant reduction is recorded for the oil-  
219 saturated samples (~0.2). The results on the mechanical strength and elastic parameters of the  
220 three samples suggest that oil has also moderate weakening effects, not as pronounced as  
221 water. All the samples failed in the brittle regime as expected at such low confining pressure,  
222 with post-failure stress-drop, onset of dilatancy near the peak stress and shear localization.

223

224

225

## 226 **5. Results for fluid injection tests**

227

228 This section reports the details of the injection stage (step III in **Figure 1b** or V in **Figure 1c**)  
229 after the rock samples experienced a pre-consolidation cycle and were critically loaded to 70-  
230 80% of their compressive strength.

231

### 232 *5.1. Water injection into a dry sample*

233 Different stages in the strain response of sample INJ-wa can be observed (**Figure 4**):

234 \* Stage (P): in the preliminary stage, the rock is dry and water has not yet reached the bottom  
235 end of the sample. As a high differential stress is applied, creep is taking place.

236 \* Stage (I): rapid creep starts as soon as water reaches the bottom end of the sample,  
237 accompanied by a sharp increase in AE activity. As usually observed in creep experiments,  
238 stage I corresponds to primary creep with a concave downward curvature of the strain vs. time  
239 plot. From this stage on, the volume of injected water (plotted as a fraction of pore volume in  
240 **Figure 4**) increases almost linearly.

241 \* Stage (II): the strain response of the sample moves to secondary creep with a constant rate  
242 for almost 25 minutes, accompanied by a non-negligible increase in AE activity. The  
243 volumetric strain first increases (compaction), then reaches a plateau. Note that there is some  
244 uncertainty in defining the limits of stage (II).

245 \* Stage (III): a clear acceleration of the axial strain typical of tertiary creep occurs, but  
246 without any significant increase in AE activity.

247 \* Stage (F): a simultaneous sharp acceleration of the strains and the AE activity is observed,  
248 probably indicating the failure of the rock. We define this event as a mechanical instability  
249 leading to very large strains, both axial (shortening) and volumetric (compaction).

250 **Figure 5** presents the evolution of stress-strains and acoustic emission activity for the total  
251 duration of experiment INJ-wa with the sample response after the development of mechanical  
252 instability and a 3D reconstruction obtained from X-ray CT images of the sample after the  
253 test. The strong acceleration of the strain for sample INJ-wa (**Figure 5a**) was accompanied by  
254 a drop in the differential stress with a magnitude of several MPa because the actuator was  
255 unable to maintain the target 16 MPa differential stress after the occurrence of the mechanical  
256 instability. This differential stress drop is accompanied by an increase of the AE rate, which  
257 tends to reach a plateau when the sample shortening is about 8% (**Figure 5b**). The volumetric  
258 strain data suggests that the sample initially compacted before dilating at the very end of the  
259 experiment. However the volumetric strain should be considered with caution: indeed the  
260 axial strain is averaged over the total sample length while the radial strain is a local  
261 measurement in the central part of the sample. The upper part of the sample shows no sign of  
262 damage (**Figure 5c**), and the bedding is still visible and undisturbed, whereas the lower part  
263 has experienced intense damage through the development of conjugated shear bands. Cross-  
264 sections through planes 1 to 4 confirm this observation (**Figure 5c**). The arrival of water at the  
265 altitude of a given ultrasonic ray path results in a decrease of the corresponding P-wave  
266 velocity (**Figure 6**). Note that the oblique ray paths between Planes 1 and 2 are affected soon  
267 after the beginning of the injection. At the onset of the mechanical instability, a sharp drop in  
268 P-wave velocity is observed in Plane 2 and along the oblique ray path between Planes 2 and 3,  
269 suggesting that significant damage is located between these two planes in agreement with the  
270 post-mortem CT images (**Figure 5c**). Interestingly, the velocities above the plane 3 are not  
271 affected by the water migration while the mechanical instability develops; the velocity  
272 decrease associated with the arrival of the water at the level of this plane is identified after 90  
273 minutes of injection. Our results show that mechanical instability occurred when the volume

274 of injected water was equivalent to only 15% of the pore volume (**Figure 3**) when the upper  
275 part of the sample is still free of water.

276

### 277 *5.2. Oil injection in a dry sample*

278 Compared to test INJ-wa, the time scale of the test INJ-oa is much longer and covers several  
279 hours (**Figure 7**), because of the higher viscosity of Fluorinert compared to water, which  
280 requires a lower injection rate to maintain a similar fluid pressure of 0.5 MPa. No acoustic  
281 emissions have been recorded during oil injection (Macault, 2013). We can also identify  
282 different stages during the oil injection experiment:

283 \* Stage (P): the rock is dry and oil has not yet reached the sample, small creep takes place.

284 \* Stage (I): primary creep with a noticeably larger strain rate starts when the oil reaches the  
285 bottom end of the sample.

286 \* Stage (II): there is no clear transition between stage (I) and (II) and a rather constant creep  
287 rate is observed for about 4 hours. The volumetric strain is monotonically increasing and the  
288 rock is compacting.

289 \* Stage (III): a slow increase in strain rate typical of tertiary creep is observed but with no  
290 significant AE activity. As the experiment was stopped after 8 hours when oil started to flow  
291 out of the top end of the sample, it is not possible to extrapolate if this acceleration of the  
292 strain rate would have led to mechanical instability and failure.

293 The P-wave velocity evolution in test INJ-oa is similar in its kinetics to the one observed in  
294 INJ-wa, except that velocity rather increases when the oil reaches a plane where ultrasonic  
295 sensors are located, in agreement with the saturation stage in TRX-o (**Figure 2**). When  
296 comparing both injection experiments, it is clear that the nature of the injected fluid has a  
297 strong influence on the mechanical behavior of the rock and on its elastic response.

298

299 *5.3. Fluid substitution test*

300 The third injection experiment was designed to mimic a scenario commonly used during  
301 secondary oil recovery by water flooding in hydrocarbon reservoirs (Bertauld, 2014). After  
302 the pre-consolidation stage we saturated the sample with Fluorinert and then injected water  
303 (see protocol in **Figure 1c**).

304 \* Stage (P): the rock is oil-saturated and water has not yet reached the sample (**Figure 8**).  
305 Creep takes place and, in contrast with tests INJ-wa and INJ-oa, stage (P) extends after the  
306 water starts invading the oil-saturated sample at time  $t=0$ .

307 \* Stage (I): the onset of faster creep is delayed and becomes noticeable 6 minutes after water  
308 first enters the sample. In contrast with classical primary creep curves, creep in INJ-wo  
309 exhibits a concave upward curvature.

310 \* Stage (II): again there is no clear transition between stages (I) and (II), and in both stages  
311 the strain vs. time plot exhibits a concave upward curvature instead of the classical linear  
312 evolution characterizing secondary creep. In stage (I) and beginning of stage (II) the  
313 volumetric strain increases then starts to decrease during stage (II) suggesting a transition  
314 from compaction to dilation. Note however that because the radial strain measurement is  
315 local, this transition might as well be linked to the arrival of the water at the sample mid-  
316 height where the radial strain is monitored: dilation may have started earlier in the lower part  
317 of the sample.

318 \* Stage (III): the axial strain rate increases faster while the volumetric strain is decreasing, as  
319 expected during tertiary creep. Few acoustic emissions are recorded near the end of stage  
320 (III).

321 \* Stage (F): a very sharp increase in acoustic AE activity and strain rates occurs during this  
322 stage, which is probably related to the development of a mechanical instability. The final axial  
323 strain reached before unloading was 1.4%.

324 As for test INJ-wa, water seems to have a weakening effect on the Sherwood sandstone in this  
325 experiment, which eventually led to a mechanical instability when the volume of injected  
326 water was equivalent to 56% of the pore volume, compared to 15% for INJ-wa. However the  
327 time of occurrence (35-31 minutes) and the amount of axial strain (0.5-0.57%) at the onset of  
328 failure are comparable for both experiments. A sharp stress drop at the onset of the  
329 mechanical instability is also observed, accompanied by an increase in AE activity (**Figure**  
330 **9a**). On a 3D reconstruction of X-ray CT images of the sample post-mortem (**Figure 9c**),  
331 several fracture-like features resembling shear bands can be observed in the lower half of the  
332 sample. As for test INJ-wa (**Figure 5c**), radial damage patterns are observed on a cross  
333 section. A set of inclined fractures distributed axi-symmetrically around the injection point in  
334 the lower part of the sample is observed. When the water reaches the ray path of a given pair  
335 of ultrasonic sensors, the P wave velocity decreases (**Figure 10**), and at the onset of the  
336 mechanical instability an additional velocity decrease occurs for the sensors located in the  
337 lower half of the sample. In addition, the mechanical instability occurs when water is located  
338 well above the plane 3. The total velocity drop is smaller than in INJ-wa, probably because  
339 the velocity contrast between water and oil is much lower than between water and air.

340

## 341 **6. Discussion**

342 Water weakening has been evidenced in Sherwood sandstone through classical triaxial tests,  
343 and most importantly through injection tests aimed at mimicking more realistically the stress  
344 state, stress path and fluid-substitution scenarios experienced by an actual reservoir at depth.  
345 For the former type of tests it was found that at the selected confining pressure the  
346 compressive strength of the water-saturated rock was reduced by 30% compared to the dry  
347 rock, whereas a relatively smaller strength reduction of 8% is observed for the oil-saturated  
348 rock. For the latter type of tests we showed that water injection in the Sherwood sandstone

349 initially saturated with either oil or air and stable under a constant stress equivalent to 70-80%  
350 of its compressive strength triggers a mechanical instability leading ultimately to failure in a  
351 relatively short period of time (less than an hour). Such instability was not observed during oil  
352 injection after 8 hours of injection. For both water and oil injection, creep occurs during fluid  
353 substitution, with a much faster creep rate (more than an order of magnitude) when water is  
354 injected compared to oil.

355 Rock physics monitoring through the recording of AE activity and P-wave velocity evolutions  
356 was used to assess the development of damage and fluid substitution during the experiments.  
357 The P wave velocity decreases when water reaches the sensors planes (**Figure 2, 6 & 10**),  
358 whereas it increases for oil migration (**Figure 2**). We relate this observation to the contrasting  
359 wetting characteristics of the fluids, i.e. water is expected to be wetting while oil is expected  
360 to be non-wetting. When water invades the pore space, capillary forces enhance the driving  
361 force in addition to the applied injection pressure, and this potentially leads to trapping of the  
362 non-wetting phase and heterogeneous distribution of fluids. As mentioned in Section 2, the  
363 velocity of Sherwood sandstone at low water saturation is smaller than that of the dry rock.  
364 The elastic weakening mechanism reported by Pimienta et al. [2014] linked to the adsorption  
365 of water molecules at grain surfaces is possibly another explanation for the P wave velocity  
366 decrease in water injection tests. On the other hand, for oil injection capillary driving force  
367 does not pull up the oil into the sample during injection, and we expect less air trapping.  
368 However the estimation of the actual water or oil saturation in the injection experiments is not  
369 straightforward. The evolution of velocity informs us on the approximate location of the fluid  
370 front, but not on the geometry of the invaded region. A piston-like fluid front propagation  
371 would induce a sharp decrease or increase of the velocity when water or oil is injected,  
372 respectively. Based on the progressive evolution of the velocity measured along a given plane,  
373 we can rather expect a more complex geometry. Furthermore the fluid is injected at the



374 bottom of the sample through a hole in the bottom platen, and a “plume”-like fluid migration  
375 in the pore space is expected and would give a better description of the injection process.  
376 Concerning the passive monitoring, less acoustic emissions were recorded in the water  
377 injection experiments when oil was used as the starting pore fluid (**Figure 9a**) compared to air  
378 (**Figure 5a**) and we can only speculate possible explanations: (i) an enhanced attenuation of  
379 wave amplitudes associated with the higher viscosity of Fluorinert; (ii) a shift in the dominant  
380 frequency of the radiated waves outside the sensitivity range of the ultrasonic transducers (~  
381 0.5 MHz).

382 The following sections will focus on specific aspects of the observations reported in the  
383 previous sections in an attempt to shed light on the mechanisms taking place during these  
384 experiments, namely, the stability of the experimental conditions and stress paths during the  
385 injection; the variations in creep rates and evidence of fluid-induced weakening; the final  
386 macro-structure of the damaged samples.

387

#### 388 *6.1. Stability of the experimental conditions and stress paths during the injection tests*

389 The objective of the fluid injection protocol was to highlight specifically the effects of  
390 physico-chemical interactions between the pore fluid and the mineral matrix of the rock,  
391 while minimizing the influence of well-known mechanical effects associated with changes in  
392 effective stress. In this regard, the main feature of this protocol is to carry out a fluid  
393 injection/substitution with a fluid pressure as small as possible so that during the injection: (i)  
394 the average effective confining pressure in the sample is not significantly affected; and (ii) the  
395 contrast in effective confining pressure between the fluid-invaded and the dry parts of the  
396 sample at any given time is minimized so that the stress heterogeneity remains low. Doing so,  
397 effective stress variations are not expected to be the major factor triggering the observed

398 mechanical instability, and therefore the observed weakening can reliably be attributed to the  
399 nature of the injected fluid.

400 Stanchits et al. (2011) in their study on the Flechtingen sandstone, which has a higher  
401 compressive strength than the Sherwood sandstone, applied higher injection pressures  
402 between 5 and 30 MPa. In these conditions, a concomitant effect of water weakening and  
403 stress-induced damage may be expected. In contrast, in both INJ-wa and INJ-oa, the fluid  
404 pressure at the bottom of the sample was maintained at a low value of 0.5 MPa during the  
405 injection (**Figure 11**), which induces a very small contrast in effective pressure between the  
406 dry and the fluid-invaded part of the sample (10% change). In INJ-wo the bottom pore  
407 pressure during injection raised up to about 1 MPa, while the back-pressure at the top end was  
408 maintained at 0.35 MPa. Note however that changing the injection protocol for the  
409 experiment INJ-wo resulted in a significant difference in fluid injection rate ( $30 \text{ cm}^3/\text{h}$ )  
410 compared to INJ-wa and INJ-oa ( $3\text{-}4 \text{ cm}^3/\text{h}$ ) while the impact of the injection rate on the  
411 damage induced by water weakening remains unknown. As in both water injection  
412 experiments failure occurred at a similar time, more water was present in the oil-saturated  
413 sample (**Figure 8**) than in the dry sample (**Figure 4**) when the mechanical instability and the  
414 resulting failure developed. In a sense water was more efficient in destabilizing the rock  
415 during the test INJ-wa than during the test INJ-wo.

416 To assess a potential role of effective pressure variation on the sample failure, we use the  
417 failure envelope obtained by Nguyen et al. [2014] for the water saturated Sherwood  
418 sandstone, which can be fitted by the cap model of Wong et al. [1997] (**Figure 12a**). Our  
419 results, in terms of followed stress paths and associated peak stresses, have been  
420 superimposed on the same plot. The failure stress for TRX-w is in good agreement with the  
421 data reported by Nguyen et al. [2014]: for sake of simplicity the failure envelope at low mean  
422 effective stress can be approximated by a straight line obtained by the least-squares best fit on

423 the three data points available for the water-saturated Sherwood sandstone (**Figure 12a**). We  
 424 assume that a straight line with equal slope but different intercept (i.e. pore-fluid dependent  
 425 cohesion) is also a good approximation for the failure envelope of the dry and oil-saturated  
 426 Sherwood sandstone (**Figure 12b**). For the dry rock, this assumption seems to be fairly good:  
 427 indeed the green solid circle in **Figure 12b**, corresponding to the failure stress reported by  
 428 Nguyen [2012] for a triaxial test at 2 MPa confining pressure on a dry Sherwood sandstone  
 429 sample, is in good agreement with the estimated straight line. Starting from the stress states at  
 430 which the injection experiments have been performed (dashed lines), we report the stress  
 431 paths associated with the fluctuation of pore pressure (**Figure 11**) imposed or induced during  
 432 these tests; we obtain the orange and green horizontal paths in **Figure 12b**, respectively. We  
 433 can see that both stress paths do not intercept the corresponding failure envelopes, which  
 434 means that the observed mechanical instability was likely triggered by fluid weakening effects  
 435 and not by the pore pressure change. This conclusion, drawn from the worst-case scenario  
 436 where the failure envelopes are linear at low stresses, would be even stronger if one takes into  
 437 account the curvature of the failure envelopes (**Figure 12a**) commonly observed in porous  
 438 rocks [Wong et al., 1997].

439

#### 440 *6.2. Variation in creep rates and evidence of fluid-induced weakening*

441 Water injection resulted in faster creep rates compared to oil injection (**Figure 13a**). Before  
 442 the arrival of the injected fluid into the rock sample, creep rates are systematically small,  
 443 comprised between  $3.9$  and  $5 \cdot 10^{-8} \text{ s}^{-1}$  (**Table 3**). The largest rate was recorded during the  
 444 injection of water in the oil-saturated sample (INJ-wo). During the oil injection test (INJ-oa),  
 445 a moderate increase in creep rate is observed (from  $3.9$  to  $4.4 \cdot 10^{-8} \text{ s}^{-1}$ ), whereas an increase by  
 446 more than one order of magnitude occurred during the water injection test INJ-wa. For INJ-  
 447 wo, the creep rate is accelerating continuously and a real secondary creep stage or a primary

448 creep with a concave downward curvature is absent. Therefore the values reported in **Table 3**  
 449 for this test are approximations. The time at the onset of tertiary creep is comparable for both  
 450 water injection tests, but much smaller than for the oil injection test (**Table 3**). For all three  
 451 experiments the strain increment (measured strain minus strain at the beginning of creep) is  
 452 almost the same, so that the onset of accelerated creep occurs more or less at the same level of  
 453 damage accumulated in the early creep stages, as previously reported by Heap et al., 2009.  
 454 During primary and secondary creep the strain vs. time plots for INJ-wa and INJ-oa are  
 455 almost linear in logarithmic scale with a similar slope (**Figure 13b**). A power-law with a  
 456 similar exponent must thus fit our results for these two experiments. The best fit creep law in  
 457 stages I and II is given in **Table 3** for INJ-wa ( $\varepsilon(t) = 0.199 t^{0.84}$ ) and for INJ-oa ( $\varepsilon(t) = 0.0187$   
 458  $t^{0.92}$ ). The creep behavior for INJ-wo exhibits a transition from a slow creep at early times,  
 459 similar to that observed in experiment INJ-oa, to a faster creep at larger times typically  
 460 observed in experiment INJ-wa (**Figure 13b**). The sharp creep acceleration in INJ-wo seems  
 461 to be similar in nature to that observed in INJ-wa, but occurs with a time delay. This transition  
 462 phase occurs at a rate nearly double compared to that observed for both other tests.  
 463 Tentatively we interpret this observation as a transition from a behavior dominated by oil-wet  
 464 to a behavior dominated by water-wet solid surfaces during test INJ-wo, and this evolution  
 465 does not follow the classical transition from primary to secondary creep. The results for water  
 466 and oil injection in the dry samples display a similar behavior, which can be fitted by a single  
 467 scaled creep law

$$\left(\frac{\varepsilon}{\varepsilon_t}\right) = \left(\frac{t}{t_t}\right)^{0.9}, \quad (1)$$

469 whereas the results for test INJ-wo clearly follow a different trend involving a time delay and  
 470 significantly higher exponent

$$\left(\frac{\varepsilon}{\varepsilon_t}\right) = \left(\frac{t}{t_t}\right)^2 - \tau^2, \quad (2)$$

472 in which  $\tau = 0.2$  corresponds approximately to the (normalized) delayed time when  
473 accelerated creep starts in this particular experiment (**Figure 13c**). In both equations, strain  
474 and time are normalized to their respective values  $\varepsilon_t$  and  $t_t$  at the onset of tertiary creep (**Table**  
475 **3**). Equation (1) holds for both fluids injected in the dry sandstone: fluid weakening appears to  
476 be a scaling process for which water, compared to oil, enhances the magnitude (by a factor  $\varepsilon_t$ )  
477 and the rate (by a factor  $t_t$ ) of the strain experienced by the rock, probably without  
478 intrinsically changing the micro-mechanisms of the deformation. Note however that  $t_t$  for INJ-  
479 oa is about 15 times larger than for INJ-wa; and that the  $\varepsilon_t$  values are similar for both  
480 experiments. This suggests that the large-time magnitude of strain associated with weakening  
481 due to water and Fluorinert are in fact similar in the dry Sherwood, but to reach this  
482 asymptotic strain magnitude it would take 15 times longer with Fluorinert than with water. In  
483 other words, if we had carried on with the test INJ-oa for a longer time ( $> 8$  hours), the  
484 sample would probably have reached failure.

485 In contrast, when water is injected in the oil-saturated sandstone a very different creep law  
486 applies suggesting that the operating mechanisms leading to macroscopic creep might be  
487 different. Brantut et al. [2013] argue on the basis of the work by Main [2000] that secondary  
488 creep is in fact an intermediate transient stage between primary creep dominated by crack  
489 propagation with a negative feedback between crack length and  $K_I$ , the stress intensity factor  
490 in mode I, and tertiary creep where a positive feedback leads to accelerated creep and failure.  
491 Apparently this does not hold for the water into oil injection test where negative feedback  
492 seems to be missing. So far we have no definitive answer for such a contrasting behavior.

493 Water injection resulted in catastrophic failure in both experiments INJ-wa and INJ-wo but  
494 not in INJ-oa, confirming our conclusions from triaxial testing that fluid sensitivity and water  
495 weakening need to be taken into account in the mechanical behavior of Sherwood sandstone,  
496 effective pressure effects put aside. Baud et al [2000] analyzed the effect of water weakening

497 on the mechanical behavior of a set of sandstones with various degrees of quartz and clay  
 498 contents: using fracture mechanics concepts they showed that the strength reduction in the  
 499 presence of water can be linked to a decrease in surface energy  $\gamma$  which lowers both the  
 500 fracture toughness  $K_{IC}$  (or equivalently the fracture energy  $G_C$ ) and the friction coefficient  $\mu$ ,  
 501 thus facilitating crack propagation and sliding. They argue that the strength decrease due to  
 502 fluid weakening is controlled by the strength reduction parameter  $\lambda = \gamma'/\gamma = (K'_{IC}/K_{IC})^2$ , where  
 503 primed symbols correspond to the parameters in presence of water. Water weakening will also  
 504 induce a reduction in the critical pressure such that  $P^{*'}/P^* = \lambda^{3/2}$ . Applying this relationship to  
 505 their tested sandstones, Baud et al [2000] found a strength reduction parameter  $\lambda$  in the range  
 506 0.79 to 0.97. For the studied Sherwood sandstone we only know the critical pressure  $P^{*'} = 39.5$   
 507 MPa for water saturated conditions [Nguyen et al., 2014]. We can calculate  $\lambda$  from the  
 508 strength reduction found in our set of triaxial experiments (**Figure 3** and **Table 2**).  
 509 Comparison of strength reductions from dry to water-saturated and dry to oil-saturated  
 510 conditions yields  $\lambda_{wa} = 0.70$ , and  $\lambda_{oa} = 0.91$ , respectively. These values allow for the prediction  
 511 of the critical pressure for the dry rock ( $P^* = 67.4$  MPa) and for the oil-saturated rock ( $P^* = 45.5$   
 512 MPa). Due to the limitation of the used experimental rig, Nguyen et al. [2012] could not load  
 513 dry Sherwood sample above 60 MPa and no evidence for onset of pore collapse was recorded  
 514 at such confining pressure. The derived dry  $P^*$  is in agreement with this result. The reduced  
 515 surface energy contrast when water substitutes oil in the pore space  $\gamma'/\gamma_o = \lambda_{wa} / \lambda_{oa} = 0.77$  may  
 516 explain the delayed creep acceleration in test INJ-wo but not the highest creep rate once it  
 517 started. Our understanding of the deformation mechanisms during the injection tests is far  
 518 from being sufficient, in particular because it was not possible to do post-mortem  
 519 microstructure analyses (the samples could not be retrieved without complete loss of  
 520 cohesion). One question that needs addressing in future studies is the specific role of clays in  
 521 the weakening process.

522

523 *6.4. Strain localization patterns*

524 For both water injection experiments, we investigated the post-mortem damage patterns using  
525 X-ray tomography techniques. For the test INJ-wa, a 3D reconstruction of the sample has  
526 already been presented in **Figure 5c**: whereas the upper part of the sample did not show any  
527 visible sign of deformation, the lower part has experienced important damage. For this  
528 experiment, the overall axial strain at the end of the test was close to 10%. On a horizontal  
529 section through the damaged zone, we observe numerous dark spots (low density, probably  
530 large pores/discontinuities) as well as a pattern of bright radial linear structures (high density  
531 zones) (**Figure 14a**). To our knowledge such radial features have not been observed in triaxial  
532 loading experiments in consolidated rocks, but similar features were observed in triaxial tests  
533 on unconsolidated granular materials. For example a CT scan image of sand packs loaded  
534 under triaxial conditions shows similar patterns [Batiste et al., 2004] (**Figure 14b**). Similar  
535 features have also been found experimentally by Desrues et al. [1996] and were reproduced  
536 by Fazekas et al. [2006] using DEM numerical simulation on unconsolidated granular media.  
537 This striking similarity provides new insight onto the damage mechanisms that occurred in  
538 test INJ-wa. Due to the water invasion from the bottom, we think that a complete or partial  
539 loss of cohesion between grains occurred in the lower part of the sample, while the upper part  
540 remained mechanically stable. Looking at the curved interface between the damaged and the  
541 intact zones in **Figure 5c**, it seems that the cohesive upper part of the sample acted as a hard  
542 indenter on the cohesion-less lower part.

543 On the 3D reconstruction for test INJ-wo (**Figure 9c**), several shear bands, oblique and radial,  
544 as well as axisymmetric circular features were observed. For this experiment, we recall that  
545 the axial strain at the end of the test was lower than for INJ-wa, close to 1%. Again the  
546 damage was concentrated in the lower part of the sample, while the upper part was virtually

547 undamaged. Based on the threshold of the CT scan images, we propose a 3D reconstruction of  
548 the damaged zone shown in **Figure 14c**: we can see that the damaged zone has a conical  
549 shape. The cone base corresponds to the bottom end of the sample and oblique shear fractures  
550 radiate from the center. Again there is a striking similarity with what has been observed by  
551 Desrues et al. [1996] in triaxial experiments on sand packs: a sketch of the deformation  
552 patterns found by these authors is shown in **Figure 14d**, with a central cone and V shaped  
553 fractures radiating from the cone surface. As stated by Desrues et al. [1996], such  
554 axisymmetric features are likely to develop in unconsolidated materials due to higher degrees  
555 of freedom in un-cemented grain packs compared to cemented sandstones. Like for the other  
556 water injection test INJ-wa, we suspect that the sample has experienced a loss of cohesion.  
557 Water seems to confer the properties of unconsolidated sand upon the invaded part of the  
558 sample. One may argue that these deformation patterns could be influenced by local stress  
559 variations due to friction between the sample and the piston: such effects can hardly be  
560 avoided in mechanical testing. However, damage was observed only in the region where  
561 water was injected and not near the top end of the samples, where friction effects also exist.  
562 This confirms that damage is primarily linked to fluid weakening.

563 Our data set is far from being exhaustive: only one rock type has been tested so far, under a  
564 single stress configuration and limited structural study could be achieved on the deformed  
565 samples. More work will be necessary to highlight the effect of fluid chemistry (especially  
566 salinity which has an important effect on swelling properties of clay minerals), temperature  
567 and stress state in order to get closer to realistic in situ reservoirs conditions.

568

## 569 **7. Conclusions**

570



571 We studied fluid-weakening effects on the weakly-consolidated Sherwood sandstone by  
572 conducting standard triaxial tests and fluid injection tests on critically loaded samples. Water  
573 weakening resulted in a 30% decrease of the compressive strength when comparing the results  
574 of triaxial tests on dry and water-saturated samples, at low effective confining pressure (5  
575 MPa). Oil has also a weakening effect but with moderate amplitude (8% decrease in strength).  
576 Water weakening leads also to accelerated creep when injecting water into dry and oil  
577 saturated samples loaded up 70 to 80% of the compressive strength. Eventually tertiary creep  
578 is followed by the onset of a mechanical instability linked to the development of intense  
579 damage and loss of cohesion in the region where water has invaded the rock. In the injection  
580 tests the injection pressure was kept to a low value in order to minimize the effect of effective  
581 stress variations, so that the mechanical response could primarily be linked to the physico-  
582 chemical effect of the invading fluid. One major conclusion of our work is that water  
583 weakening is able to trigger mechanical instabilities under static loading. Active acoustic  
584 monitoring allowed us to follow the migration of the fluid front. Another article devoted to  
585 the detailed analysis of the velocity field variation and the location of acoustic events during  
586 fluid substitution is currently in preparation. We believe that experimental studies like the one  
587 presented here can have a strong impact for 4D seismic monitoring strategies during enhanced  
588 oil recovery operations at the reservoir scale and for a better understanding of the mechanical  
589 response and the micro-seismicity associated with water weakening effects.

590

591

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597 significantly the paper.

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### Figure and Table captions

**Table 1:** Mineralogical content and petrophysical properties of the Sherwood sandstone. For the mineralogy, the range of volumetric fraction and mean value are given, for the petrophysical properties, the average properties and standard errors from measurements on several rock samples are given.

**Table 2:** Description and results of the triaxial (TRX) and injection (INJ) tests.

**Table 3:** Analysis of creep parameters for the three injection tests. The starred values are given with caution (no real secondary creep for test INJ-wo).

**Figure 1:** Experimental protocol for a) triaxial tests, b) fluid injection tests in dry samples, and c) fluid substitution test.

**Figure 2:** a) Map of the 16 ultrasonic transducers distributed on 4 planes, b) P-wave velocity evolution during the saturation stage, normalized to the value in dry conditions for test TRX-w (water injection and c) for test TRX-o (oil injection).

**Figure 3:** Results from the triaxial tests. a) Hydrostatic pre-consolidation stage on three dry samples. b) Triaxial loading on the same samples saturated with water, air and oil respectively.

719

720 **Figure 4:** Results for the water injection test INJ-wa in a critically loaded dry sample. Time  
721 zero corresponds to the moment when the injected fluid starts to flow into the rock  
722 sample from the bottom at constant pressure (0.5 MPa).

723

724 **Figure 5:** Evolution of a) differential stress  $Q$ , acoustic emission activity and b) axial ( $\epsilon_a$ ),  
725 radial ( $\epsilon_r$ ) and volumetric ( $\epsilon_v$ ) strains for the whole experiment INJ-wa. The grey  
726 bar corresponds to the time interval in Figure 4. c) 3D reconstruction of the sample  
727 after test from X-ray CT images and cross-section images of the four ultrasonic  
728 sensors planes.

729

730 **Figure 6:** P-wave velocity evolution (normalized to the velocity before injection) vs. time  
731 during water injection in test INJ-wa. The vertical dashed line corresponds to the  
732 onset of the mechanical instability.

733

734 **Figure 7:** Results for the oil injection test INJ-oa in a critically loaded dry sample.

735

736 **Figure 8:** Results for the fluid substitution test INJ-wo with injection of water into a critically  
737 loaded sample saturated with oil.

738

739 **Figure 9:** Evolution of a) differential stress  $Q$ , acoustic emission activity and b) axial ( $\epsilon_a$ ),  
740 radial ( $\epsilon_r$ ) and volumetric ( $\epsilon_v$ ) strains for the whole experiment INJ-wo. c) 3D  
741 reconstruction of the sample after test from CT-scan images and cross-section  
742 images of the four ultrasonic sensors planes.

743

744 **Figure 10:** P-wave velocity evolution (normalized to the velocity before injection) vs. time  
745 during the fluid substitution test INJ-wo.

746

747 **Figure 11:** Evolution of pore pressure, confining pressure, differential stress, mean effective  
748 stress and injection rate during the three injection tests.

749

750 **Figure 12:** a) Failure envelope for the water saturated Sherwood sandstone: the experimental  
751 data (open squares) from Nguyen et al. [2014] can be modeled using the cap model  
752 (solid and dashed brown lines) of Wong et al. [1997]. The red dashed line is the  
753 triaxial stress path followed in our study, the stars correspond to the peak stress for  
754 the TRX experiments shown in Figure 3 and the blue line is a linear approximation  
755 of the failure envelope. b) Closer view on the stress paths followed during pore  
756 pressure build-up in the injection tests. The failure envelopes for each saturating  
757 fluid are approximated by straight lines. An additional data point (green solid  
758 circle) from Nguyen [2012] has been added.

759

760 **Figure 13:** Comparison of creep plots for all three injection tests. a) Incremental strain vs.  
761 time in linear coordinates. The inserted figure is a close-up on the water injection  
762 tests. b) Same plot in logarithmic coordinates. c) Scaled creep plot with time and  
763 strain normalized by the respective values at the onset of tertiary creep.

764

765 **Figure 14:** Damage patterns induced by mechanical instabilities. a) Cross-cut in the damaged  
766 zone for test INJ-wa. b) CT-scan image of a sand pack sheared in a triaxial  
767 experiment (adapted from Batiste et al. [2004]). c) 3D reconstruction of the radial  
768 and conical fracture patterns in test INJ-wo. d) Sketch of the deformation patterns



769 observed in sand packs sheared in triaxial experiments (adapted from Desrues et al.  
770 [1996]).

Mineralogical content		Petrophysical properties	
Quartz	26-44 % (30%)	porosity	30.2 ± 1.7 %
Felspar	13-26 % (18%)	bulk density	1800 ± 20 kg/m <sup>3</sup>
Detrital clays (mainly illite)	3-29 % (12%)	grain density	2590 ± 30 kg/m <sup>3</sup>
Mica	0-7 % (2%)	permeability // bedding (water flow method)	350 ± 70 10 <sup>-15</sup> m <sup>2</sup>
Heavy minerals	< 3 %	permeability perp. bedding (water flow method)	200 ± 30 10 <sup>-15</sup> m <sup>2</sup>
		Young's modulus (for dry rock)	4.6 ± 0.7 GPa

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**Table 1**

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Test name	Description	pore fluid in triaxial stage	Max. differential stress <i>Q<sub>max</sub></i> (MPa)	Young's modulus <i>E</i> (GPa)	Poisson's ratio <i>v</i>
<b>TRX-a</b>	Full triaxial on a dry sample	Air	20.2 ("Dry" peak stress)	4.3	0.30
<b>TRX-o</b>	Full triaxial on an oil-saturated sample	Oil (Fluorinert)	18.5 ("Oil" peak stress)	4.1	0.23
<b>TRX-w</b>	Full triaxial on a water-saturated sample	Water	14.1 ("Water" peak stress)	3.5	0.31
<b>INJ-wa</b>	Water injection into a dry critically loaded sample	Air	16 (80% dry peak stress)	4.7	0.30
<b>INJ-oa</b>	Oil injection into a dry critically loaded sample	Air	16 (80% dry peak stress)	3.9	0.30
<b>INJ-wo</b>	Water injection into an oil-saturated critically loaded sample	Oil (Fluorinert)	13 (70% oil peak stress)	5.8	0.19

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**Table 2**

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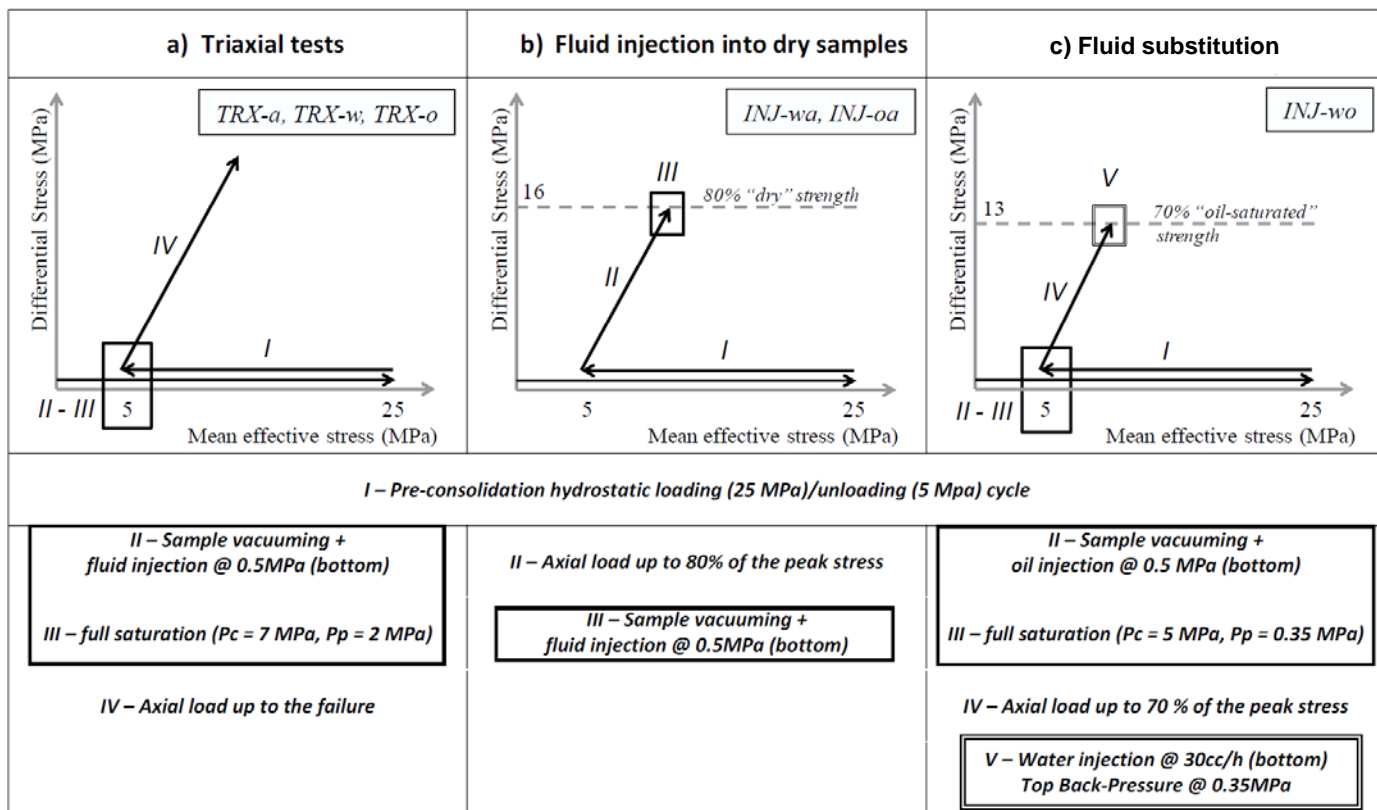
777

Test name	<i>INJ-wa</i>	<i>INJ-wo</i>	<i>INJ-oa</i>
<b>Load</b>	16 MPa (80% "dry" strength)	13 MPa (70% "oil" strength)	16 MPa (80% dry strength)
<b>Creep rate before injection (<math>s^{-1}</math>)</b>	$4.2 \cdot 10^{-8}$	$5.0 \cdot 10^{-8}$	$3.9 \cdot 10^{-8}$
<b>Creep rate during injection - stage II (<math>s^{-1}</math>)</b>	$5.8 \cdot 10^{-7}$	$1.2 \cdot 10^{-6}$ *	$4.4 \cdot 10^{-8}$
<b>Creep law in stage I + II</b>	$0.199 t^{0.84}$	-	$0.0187 t^{0.92}$
<b>Time <math>t_i</math> at onset of tertiary creep (min)</b>	28	22*	372
<b>Strain increment <math>\varepsilon_i</math> at onset of tertiary creep (%)</b>	0.11	0.094*	0.10
<b>Onset of mechanical instability</b>	yes	yes	no
<b>Time at the onset of mechanical instability (min)</b>	35	31	-
<b>Strain increment at the onset of mechanical instability (%)</b>	0.186	0.233	-
<b>injected volume / pore volume at the onset of mechanical instability</b>	15%	56%	-
<b>Comments</b>	standard creep (I, II, III), compaction	accelerated creep, compaction then dilation	standard creep (I, II, III), compaction, no AEs

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Table 3



**Figure 1**

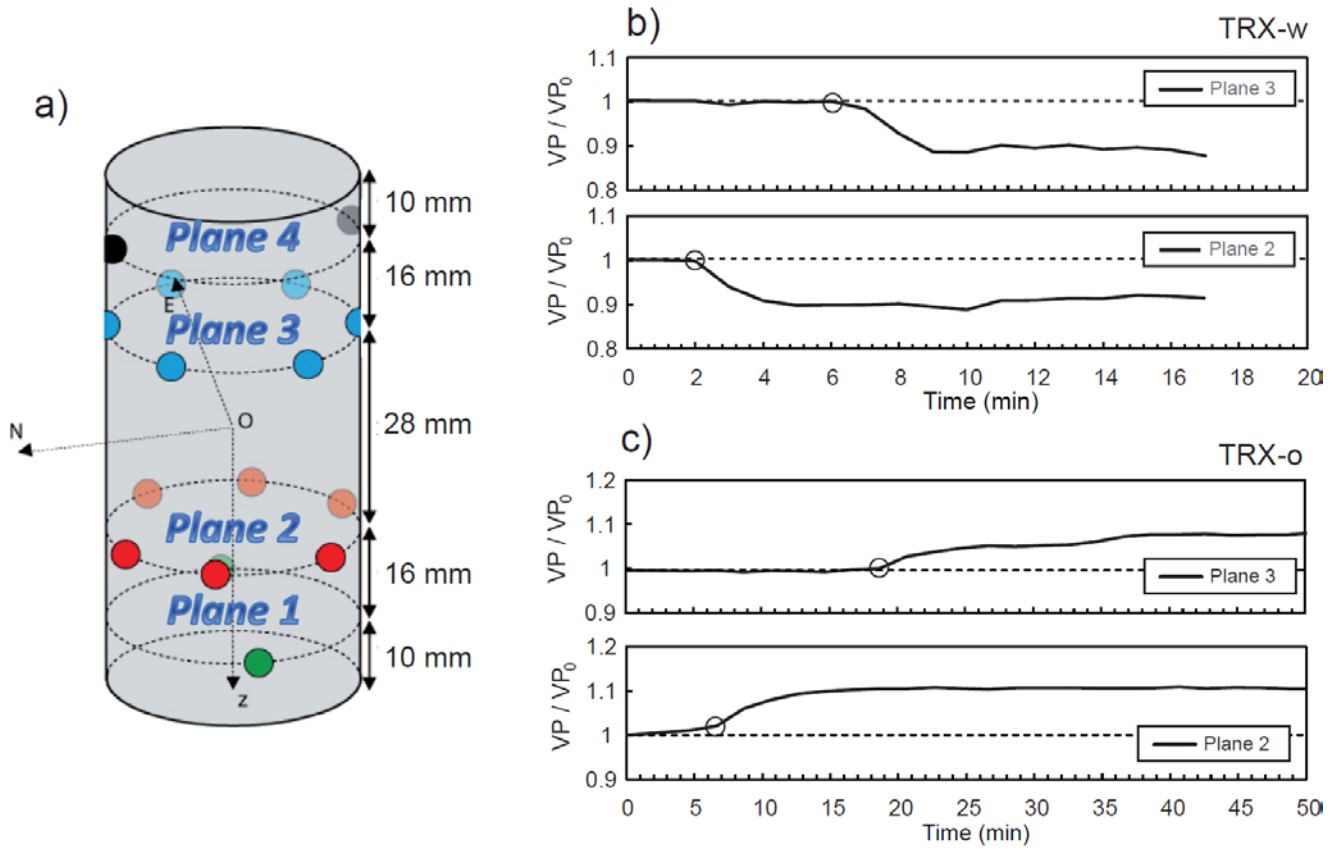
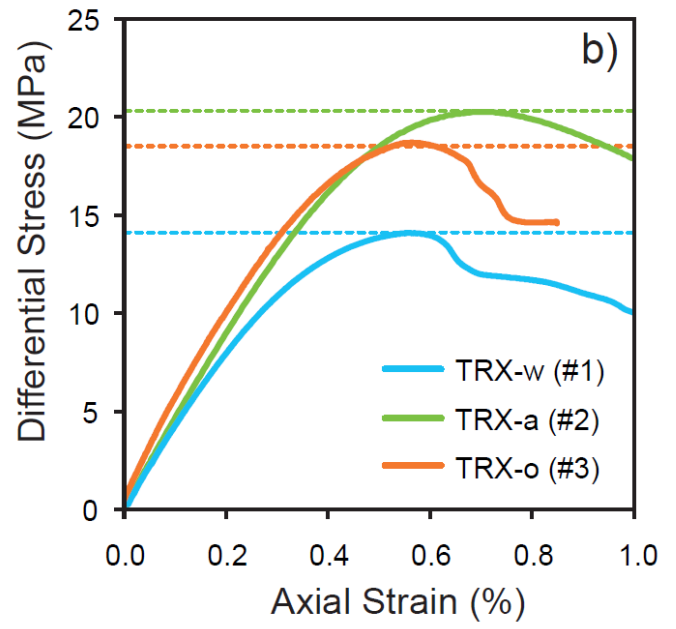
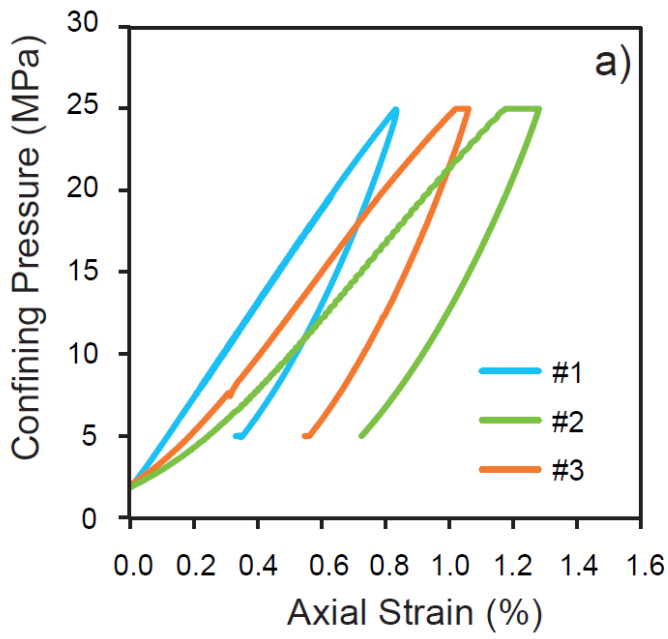
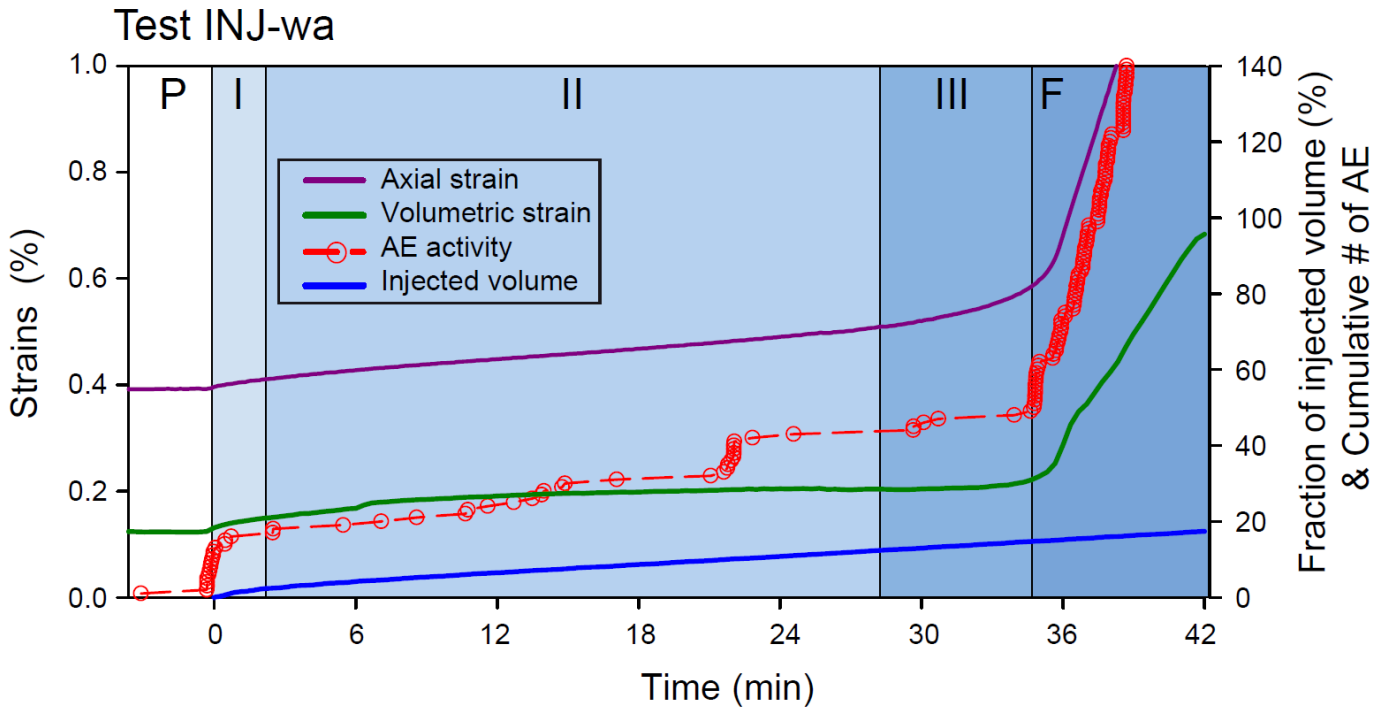


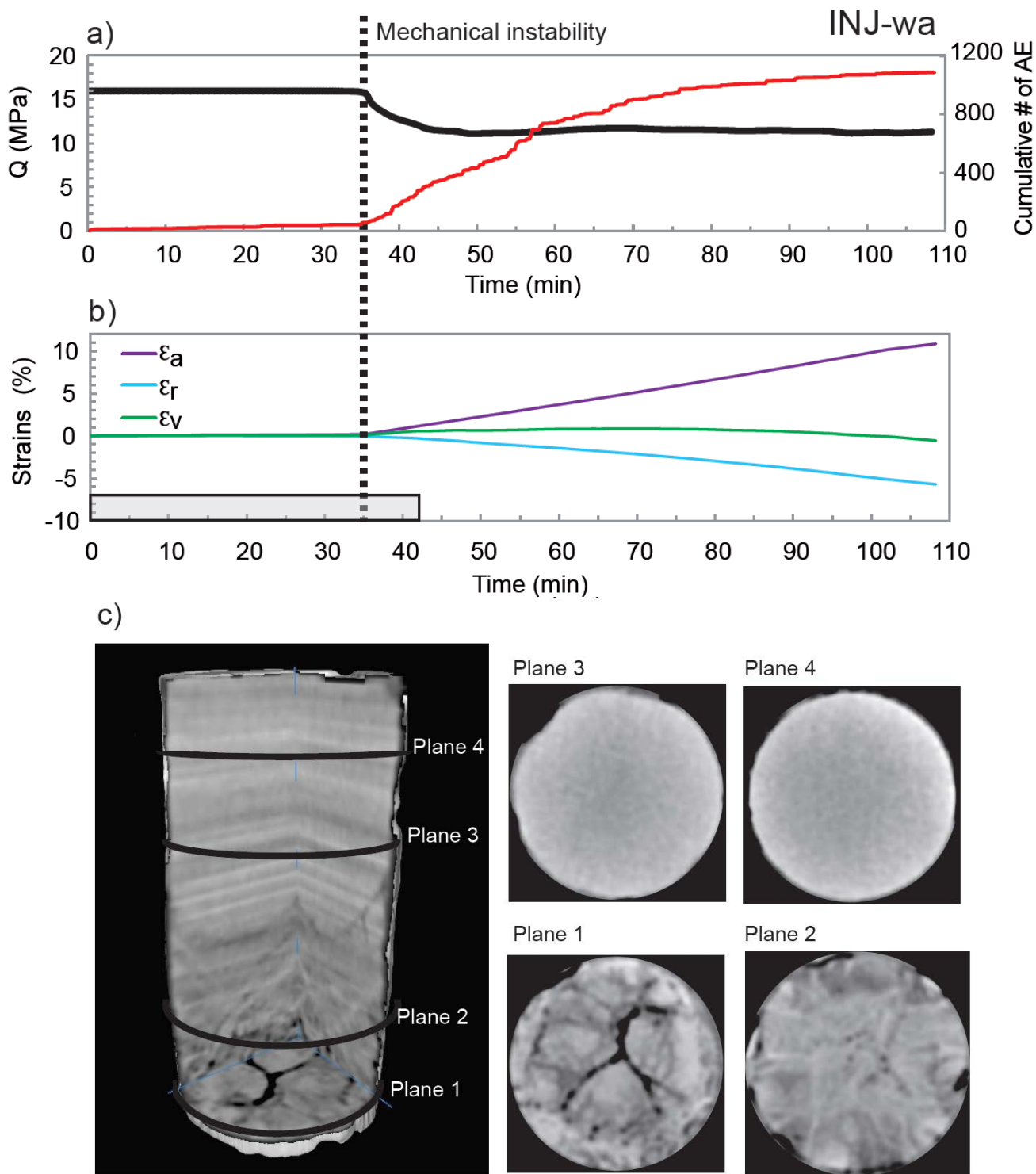
Figure 2



**Figure 3**

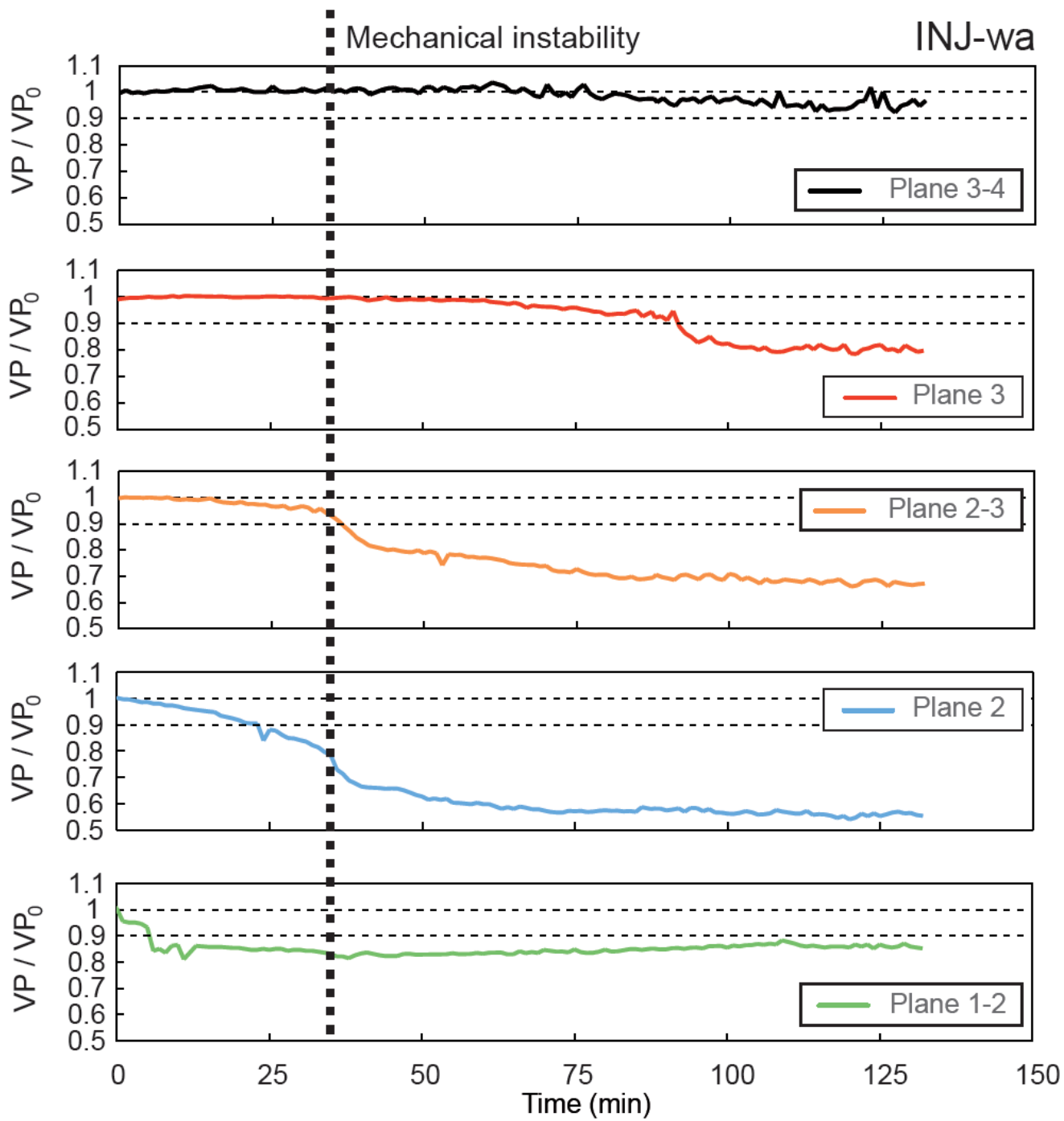


**Figure 4**

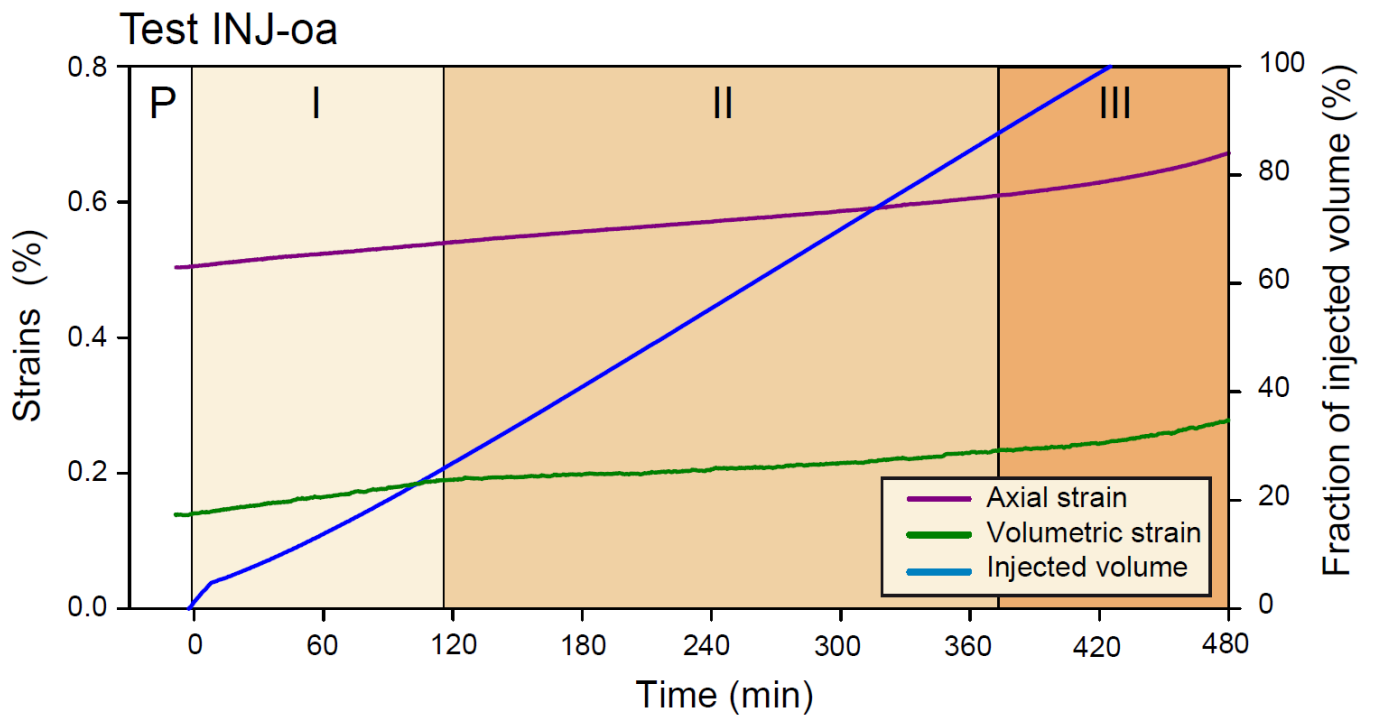


**Figure 5**





**Figure 6**



**Figure 7**

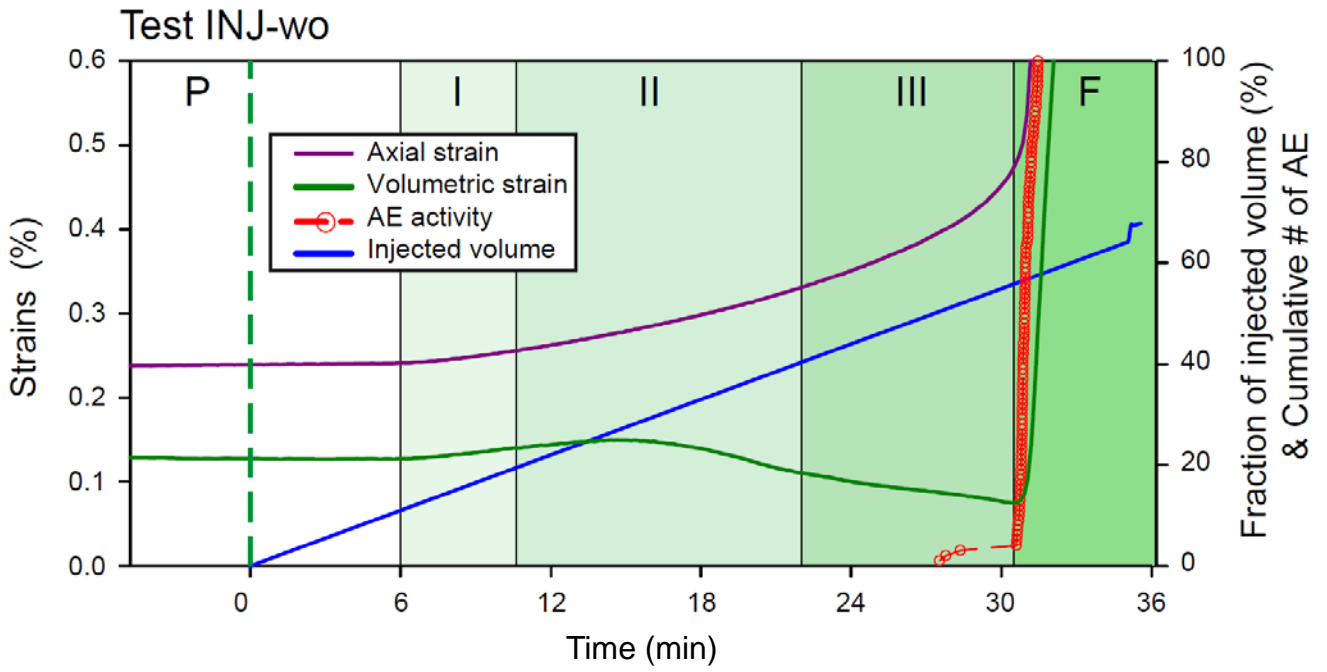
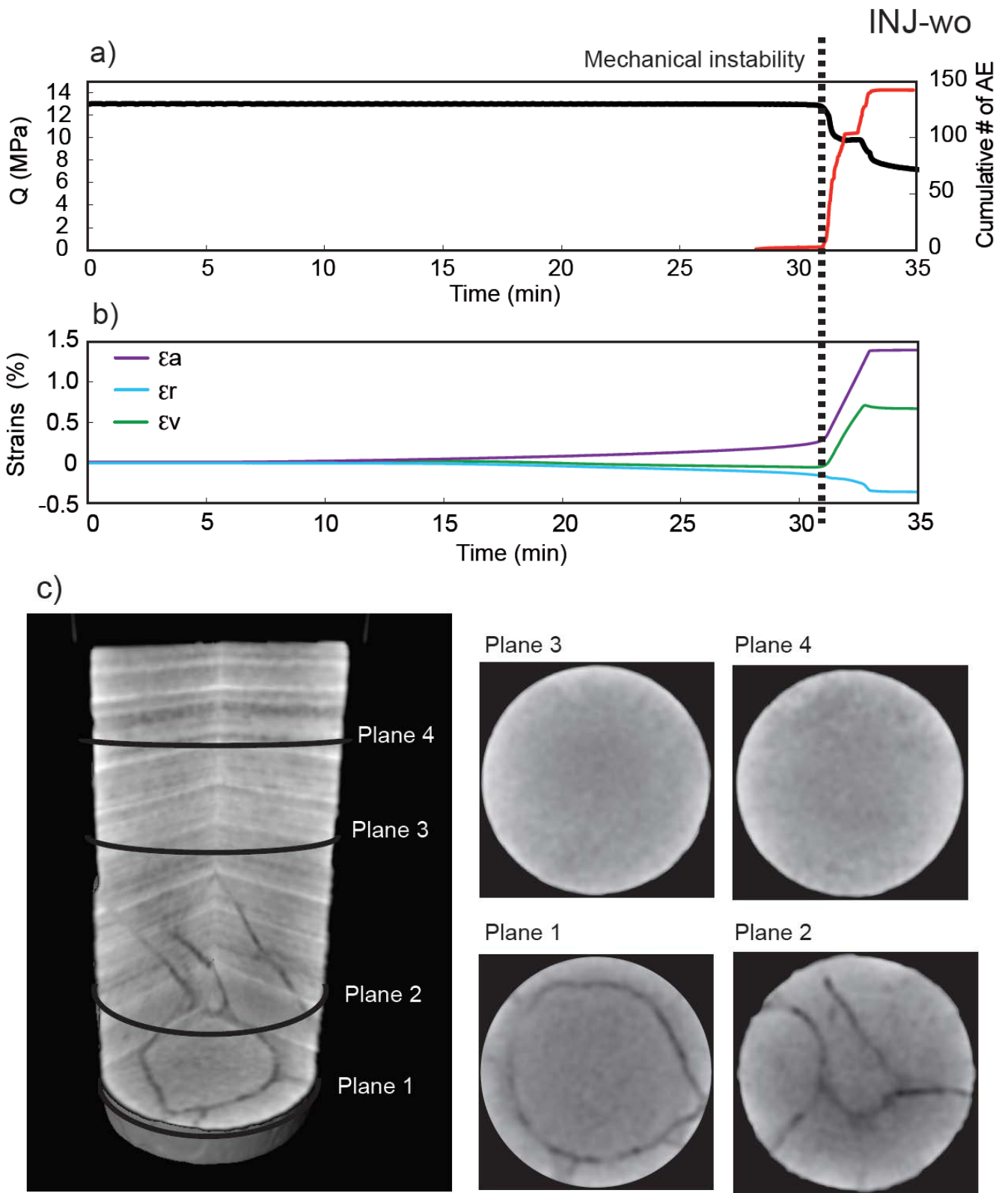
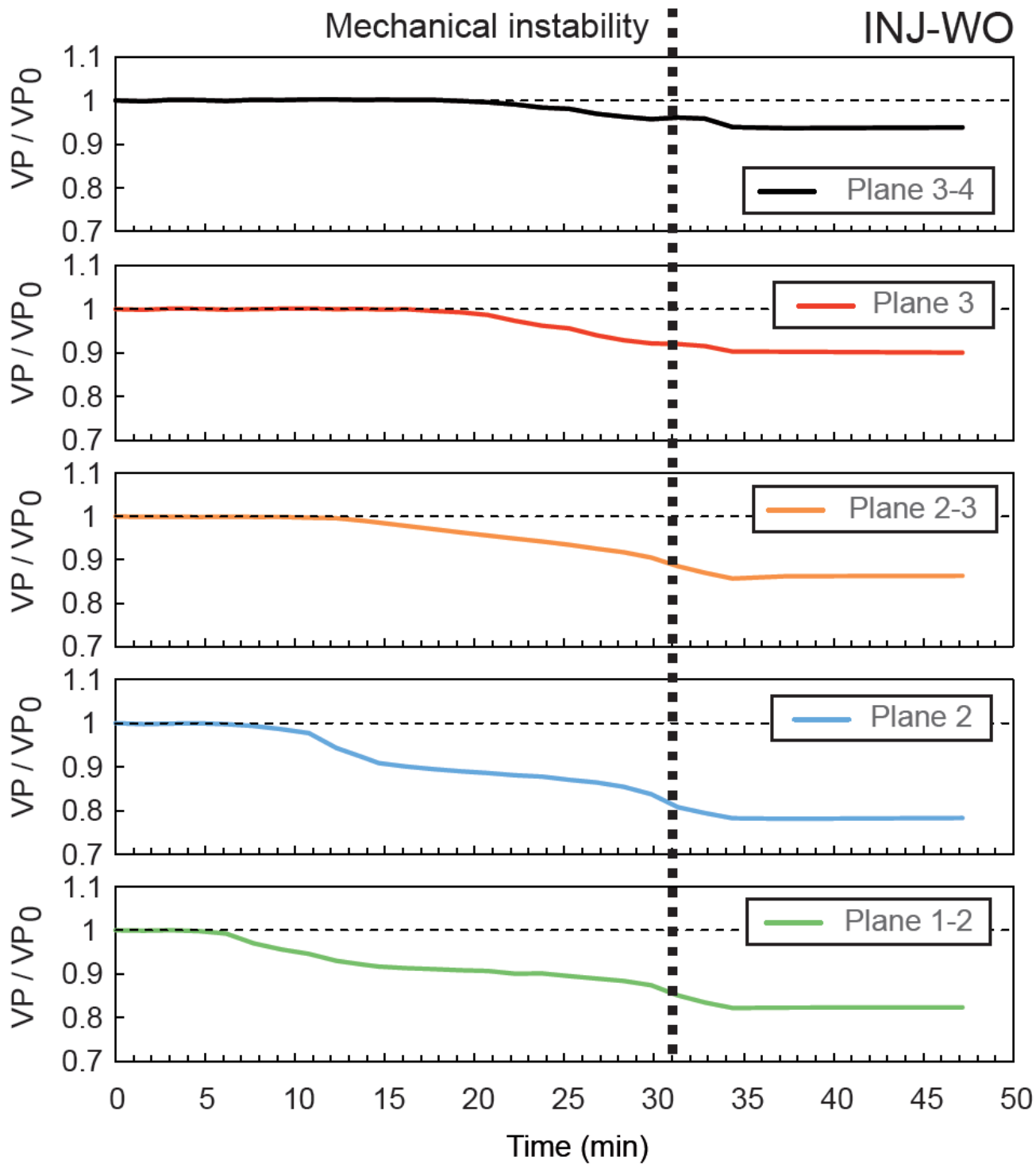


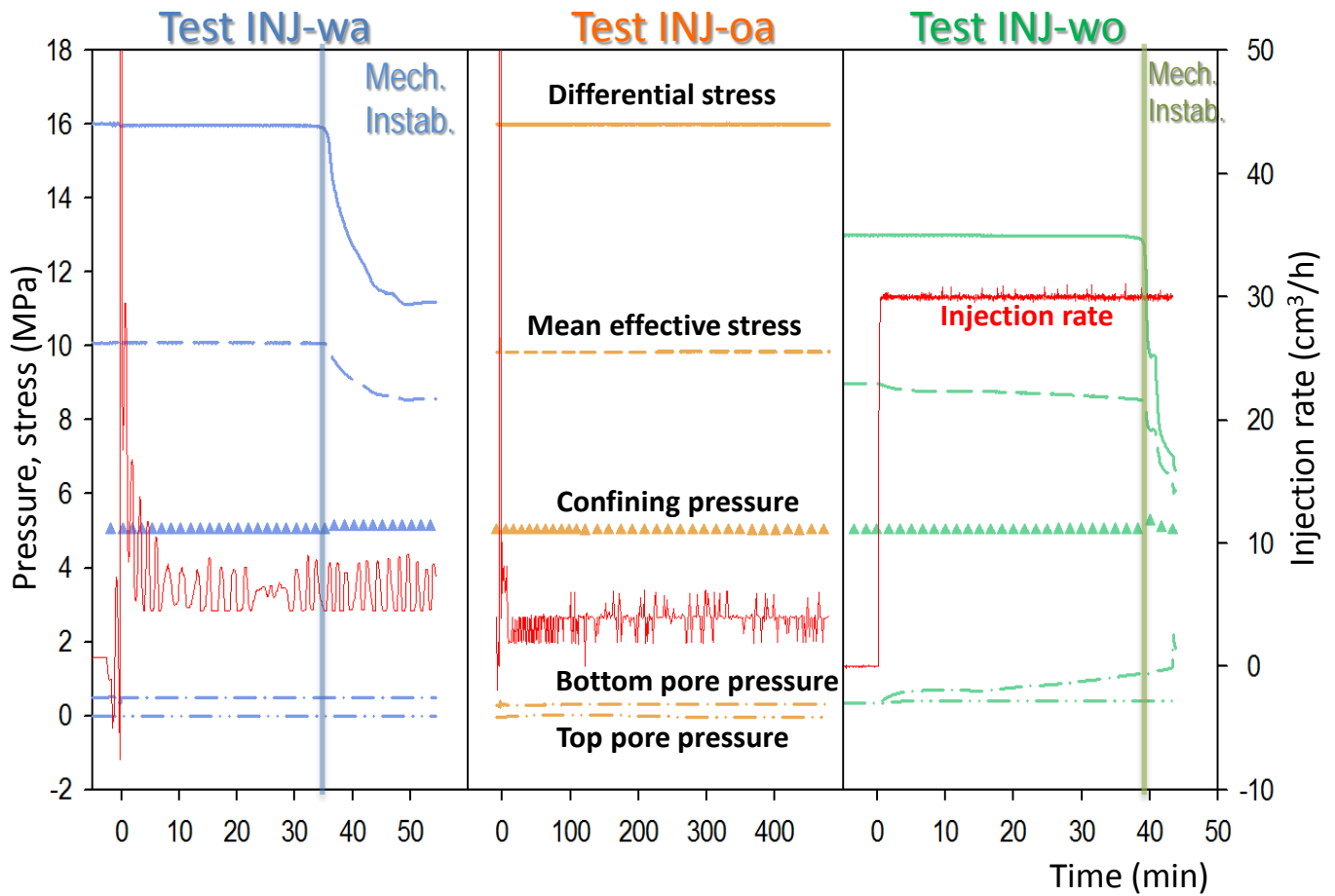
Figure 8



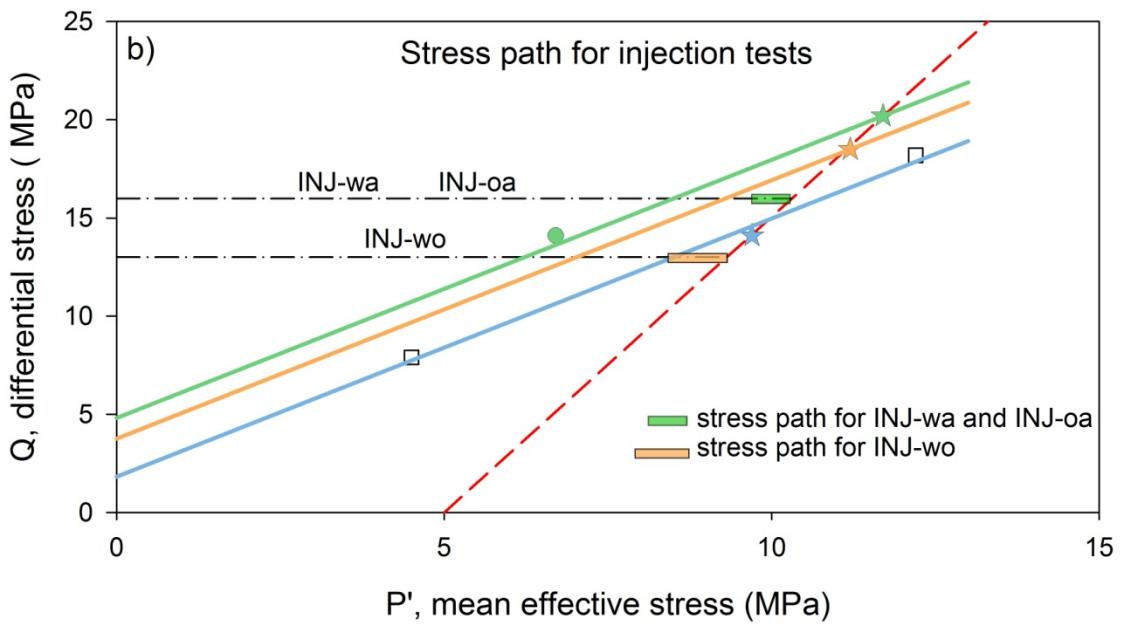
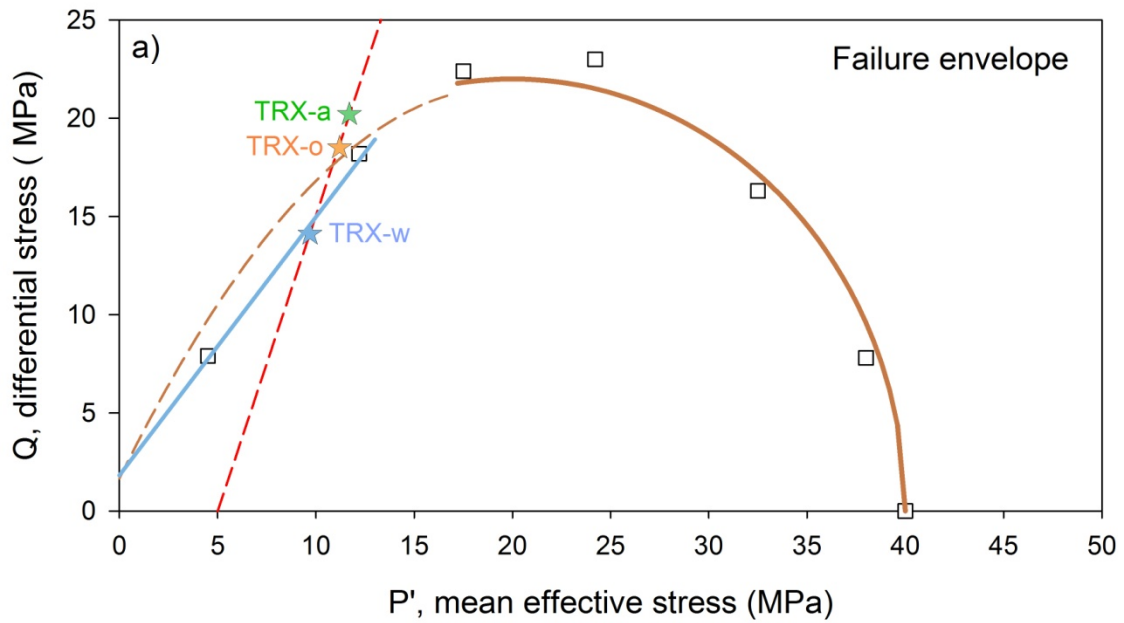
**Figure 9**



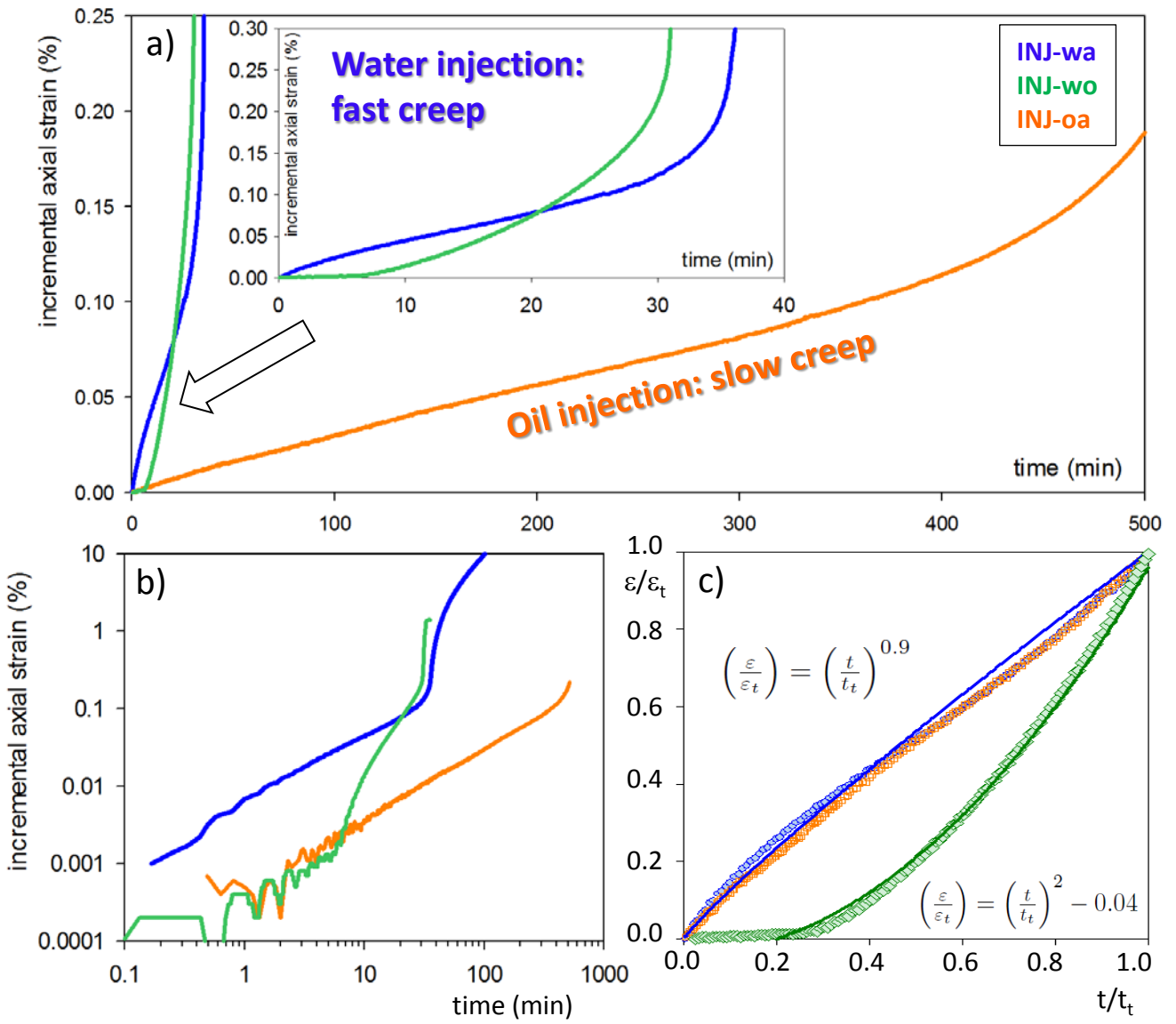
**Figure 10**



**Figure 11**



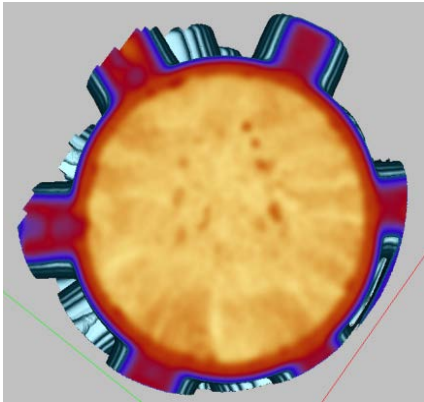
**Figure 12**



**Figure 13**

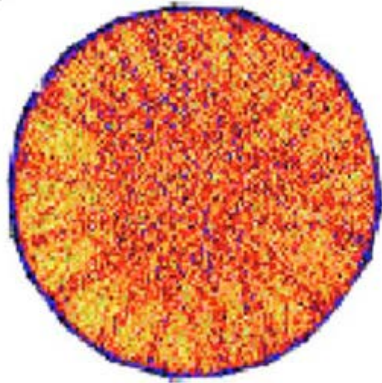


a)

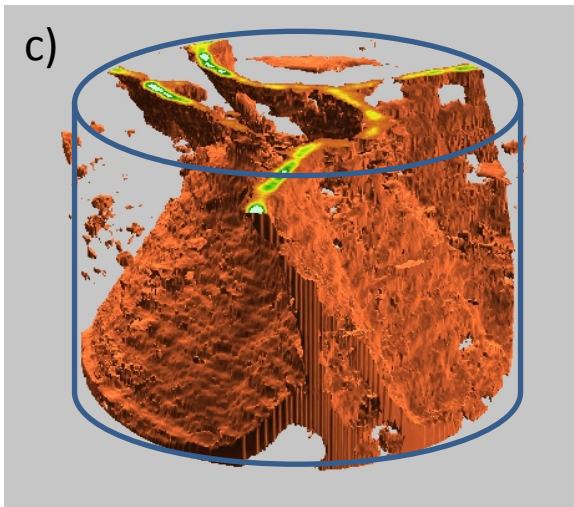


Test INJ-wa

b)



c)



Test INJ-wo

d)

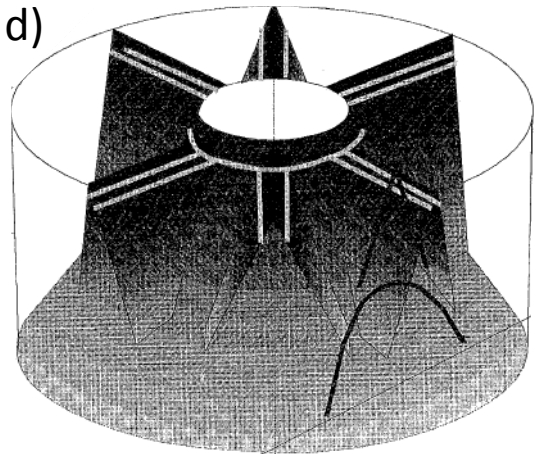


Figure 14