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# 3D geometries of normal faults in a brittle-ductile sedimentary cover: Analogue modelling

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## Abstract

It is well known that ductile layers play a major role in the style and location of deformation. However, at the scale of a single normal fault, the impact of rheological layering is poorly constrained and badly understood, and there is a lack of information regarding the influence of several décollement levels within a sedimentary cover on the single fault geometry under purely extensive deformation. We present small-scale experiments that were built with interbedded layers of brittle and ductile materials and with minimum initial constraints (only a velocity discontinuity at the base of the experiment) on the normal fault geometry in order to investigate the influence of controlled parameters such as extension velocity, rate of extension, ductile thickness and varying stratigraphy on the 3D fault geometry. These experiments showed a broad-spectrum of tectonic features such as grabens, ramp-flat-ramp normal faults and reverse faults. Forced folds are associated with fault flats that develop in the décollement levels (refraction of the fault angle). One of the key points is that the normal fault geometry displays large variations in both direction and dip, despite the imposed homogeneous extension. This result is exclusively related to the presence

25 of décollement levels, and is not associated with any global/regional variation in extension direction  
26 and/or inversion.

27

28 *Keywords: analogue modelling; décollement level; extensional forced fold; ramp-flat-ramp normal*  
29 *faults*

30

## 31 **1. Introduction**

32 In extensional basins, the deformation style is largely influenced by the rheology of the different  
33 deposits filling it. This is well-known in large-scale objects such as the lithosphere (e.g. Davy et al.,  
34 1995; Dauteuil et al., 2002), or even at a smaller scale such as the interaction between a sediment  
35 cover and basement faults (Vendeville, 1987; Withjack et al., 1990; Stewart et al., 1996; Hardy and  
36 McClay, 1999; Withjack and Callaway, 2000; Richardson et al., 2005; Fossen and Rotevatn, 2016).  
37 However, at the scale of a single fault, the impact of rheological layering is poorly constrained and  
38 poorly understood; only layer rotation around vertical fault overlap zones (Rykkelid and Fossen,  
39 2002), or small-scale relay zones between normal faults (Kristensen et al., 2008) have been  
40 considered. Field examples show the influence of a layered system on the pattern of faults with a  
41 flat-ramp fault geometry at both the thin-section scale (Fig. 1a) and outcrop scale (Fig. 1b). Few  
42 seismic examples associate small zones of flat normal fault geometry with the presence of salt (Fig.  
43 1c). In general, normal faults associated with a décollement level present a decrease in dip at depth,  
44 with development of a wide flat, and are considered as listric faults. This typical geometry is  
45 identified and studied at the seismic scale (Fig. 1d), and reproduced through sandbox modelling  
46 (Fig. 1e). Previous works, especially using analogue modelling, have investigated the impact of a  
47 pre-cut flat-ramp fault geometry on deformation (McClay and Scott, 1991; McClay, 1990) as well  
48 as the effect of a single décollement layer at the base of the experiments (Higgins and Harris, 1997;

49 Withjack and Callaway, 2000; Withjack et al., 1990). This analogue modelling did not investigate  
50 the initiation of the flat geometry of the normal fault during extension.

51 The aim of this paper is to study the geometry of normal faults at a local scale, created in pure  
52 extension context, when cutting potential décollement layers. It is critical to know how to identify  
53 reverse faults or folds created during pure extensional deformation as observed in the field (Sharp et  
54 al., 2000) or analogue modelling (Horsfield, 1977; Vendeville, 1987; Withjack et al., 1990; Ge and  
55 Jackson, 1998; Withjack and Callaway, 2000; Dooley et al., 2003; Soto et al., 2007) in order to  
56 avoid interpreting these structures as related to inversion or strike-slip movement.

57 Here, we present a series of small-scale physical experiments that were built with interbedded  
58 layers of brittle and ductile materials and without any initial constraints on the normal fault  
59 geometry. In addition, the fault geometries observed at the final stage of deformation are only  
60 related to the rheology of the layers. We used analogue modelling to study the impact of several  
61 ductile layers on deformation (geometry of the layers and faults) as well as mechanical parameters:  
62 rate and amount of extension, ductile thickness, and varying stratigraphy (Table 1) followed by a  
63 3D geometrical model built from the results of one of our experiments (experiment 3). Our results  
64 show that the specific pattern of normal faults with a ramp-flat-ramp geometry of the associated  
65 reverse faults are only related to pure extension and not associated with any global/regional  
66 variation in extension direction and/or inversion.

67

## 68 **2. Experimental protocol**

### 69 *2.1. Analogue materials*

70 In this study, we used the classical techniques of analogue modelling applied for brittle/ductile  
71 experiments developed by the Experimental Tectonics Laboratory of Géosciences Rennes

72 (Université de Rennes 1, France). These techniques have been described in various previous works  
73 dealing with the use of a velocity discontinuity (VD; e.g. Malavieille, 1984; Balé, 1986; Ballard et  
74 al., 1987; Allemand et al., 1989), the use of silicone and sand as analogue materials (Faugère and  
75 Brun, 1984), as well as various scaling issues (Davy and Cobbold, 1991; Weijermars et al., 1993).  
76 In order to simulate the brittle behaviour of sedimentary rocks with Mohr-Coulomb properties, two  
77 materials were used: (i) dry Fontainebleau quartz sand (manufactured by SIBELCO France), with a  
78 mean grain size of approximately 250  $\mu\text{m}$ , an internal friction angle of 30-35° (Krantz, 1991) and a  
79 volumetric mass density ( $\rho$ ) of approximately 1500  $\text{kg/m}^3$ , (ii) microbeads (manufactured by CVP  
80 France) with a lower internal friction angle than sand of 20-22° and a volumetric mass density ( $\rho$ )  
81 of approximately 1480  $\text{kg/m}^3$  (Panien et al., 2006).

82 Silicone putty was used to simulate the ductile behaviour of viscous sedimentary rocks such as  
83 evaporite, or under compacted and over-pressured shale (e.g. Cohen and McClay, 1996; Wu and  
84 McClay, 2011). Given that weak sedimentary rocks have different strengths in nature, we used two  
85 silicone putties in order to represent décollement levels with different strengths in the same  
86 experiment. The strongest silicone is a pink silicone putty with a mean viscosity close to  $6 \cdot 10^4$  Pa.s  
87 at 20°C and a mean volumetric mass density of approximately 1300  $\text{kg/m}^3$  (Rhodorsil Gomme GS1  
88 RG 70 009 manufactured by Rhône-Poulenc, France). The weakest silicone is a transparent silicone  
89 putty with a mean viscosity close to  $3 \cdot 10^4$  Pa.s at 20°C and a mean volumetric mass density of  
90 approximately 970  $\text{kg/m}^3$  (silicone putty SGM 36, manufactured by Rhône-Poulenc, France).

## 91 2.2. *Experimental apparatus*

92 The experimental apparatus consists of a fixed wall screwed to a rigid and fixed basal plate, over  
93 which another wall is fixed to a thin mobile basal plate (Fig. 2). The mobile basal plate and wall are  
94 pulled at a constant rate perpendicularly to the wall. A 5 cm wide sand wall supports the two other  
95 sides; the first centimetres of the experiment near these sand walls, where there are significant

96 border effects, are not considered. The displacement of the basal mobile plate induces a velocity  
97 discontinuity (VD), which localises the deformation at the base of the experiment in the middle of  
98 the experiment (cf. Malavielle, 1984; Balé, 1986; Ballard, 1989). The experiment is set up in a 40  
99 cm wide and 60 cm long apparatus with a 12.5 cm thick stratigraphy (Fig. 2, Table 1) that is wide  
100 enough to allow the experiment to be cut into several vertical slices and studied outside the zone of  
101 the border effects.

102 From base to top, the reference stratigraphy of the experiments (e.g. experiment 3) was made up of  
103 (Fig. 2 and 3):

- 104 - 1 cm of light brown silicone layer, a rectangular band measuring approximately 5 cm wide,  
105 located all along the VD (basal silicone);
- 106 - 3.5 cm (2.5 cm above the basal silicone) of black and white coloured sand (sand 1);
- 107 - 0.5 cm of white microbeads (microbeads);
- 108 - 2.5 cm of black and white coloured sand (sand 2);
- 109 - 0.5 cm of pink silicone putty (lower Silicone);
- 110 - 2.5 cm of black and white coloured sand (sand 3);
- 111 - 0.5 cm of transparent silicone putty (upper Silicone), and
- 112 - 2.5 cm of black and white coloured sand (sand 4). Black sand was sprinkled in very thin layers at  
113 the top of the experiment.

114 The basal silicone is located above the VD in order to distribute the deformation and generate a  
115 larger zone of deformation with the clearly separated normal fault. The sand layers represent brittle  
116 pre-kinematic formations with Mohr-Coulomb behaviour. The lower and upper silicone layers  
117 represent potential décollement layers with ductile behaviour, while microbeads represent a level  
118 with Mohr-Coulomb behaviour with a lower internal friction angle than sand. Part of the sand was  
119 coloured black in order to construct the experiment in layers and to make it easier to observe the

120 deformation in the cross-sections; the colouration does not influence the mechanical properties of  
121 the sand.

122 This reference stratigraphy was used for most of the experiments (experiments 1 to 8). In order to  
123 analyse the effect of the thickness of the ductile layers, we tested an experiment (experiment 9) with  
124 half the thickness of the ductile layers. In order to test the stratigraphic organisation of the ductile  
125 layers, we inverted the upper transparent silicone with white microbeads in one experiment  
126 (experiment 10).

127 This mechanical layering can be used to vary the mechanical behaviours in a heterogeneous system  
128 through a saw tooth strength profile (Fig. 2), thereby causing a broad variability in normal fault  
129 geometries.

### 130 *2.3. Experimental deformation process*

131 In the first set of experiments, the deformation was achieved by pulling the mobile basal plate  
132 perpendicularly to the VD at a defined and constant velocity (ranging from 0.25 cm/h to 4 cm/h) in  
133 order to generate 1 cm of pure extension.

134 In the second set of experiments, the deformation was achieved by pulling the mobile basal plate  
135 perpendicularly to the VD at a defined and constant velocity of 1 cm/h (like reference experiment  
136 3), but with a varying amount of displacement (ranging from 0.5 cm to 4 cm).

137 In the third set of experiments, the deformation was achieved by pulling the mobile basal plate  
138 perpendicularly to the VD at a defined and constant velocity of 1 cm/h (like reference experiment  
139 3), but with a variation in the stratigraphic setup of the ductile layers.

140 Photographs of the top surface of the experiment were taken every 1 mm of extension. At the end of  
141 the experiment, white sand was sprinkled in a thick layer to preserve the surface deformation of the  
142 experiment surface, and then humidification was performed in order to cut the experiment



143 perpendicular to the VD. The cross-sections were made every 2 cm through the central part of the  
144 experiments giving twelve sections. The photographs of the cross-sections record the final  
145 deformation state throughout the experiments highlighted by the colours of the layers.

146

### 147 **3. Experimental results**

#### 148 *3.1. General features*

149 The main structural features encountered in most of the experiments are two major normal faults  
150 connected at depth to the borders of the basal silicone sheet (Fig. 3). These faults may or may not  
151 show a flat within the lower and upper silicone layers (Fig. 3). Flats in the upper transparent  
152 silicone layer are wider and more common than in the pink lower silicone layer. Associated with the  
153 flat, the ductile layers are thinned as a consequence of pure shear deformation that accommodates  
154 extension in the ductile layer. Above the flat, the sand layers may display a continuous deformation  
155 represented by an accommodation extensional fold (e.g. Schlische, 1995; Withjack and Callaway,  
156 2000; also see Cosgrove and Ameen, 2000 and references therein) (Fig.3b). Above the flat, the sand  
157 layers also display a graben above the silicone layer as observed previously in analogue modelling  
158 (e.g. Vendeville, 1987; Nalpas et al., 1995; Brun and Nalpas, 1996; Withjack and Callaway, 2000;  
159 Dooley et al., 2003). The major border normal fault, affecting the upper sand layer, may also evolve  
160 as a reverse fault upward.

161 Between the two major normal faults, minor normal faults affect the brittle layers under the lower  
162 silicone layer and cut the microbeads without creation of a flat.

#### 163 *3.2. Influence of extension rate*

164 Five cross-sections from different experiments (experiments 1 to 5; Table 1) with the same standard  
165 layering illustrate the influence of extension rate (from 0.25 to 4 cm/h) and consequently  
166 mechanical behaviour in the ductile layers of the final deformation after 1 cm of extension (Fig. 4).

167 For the highest extension rate (4 cm/h - Fig. 4a, experiment 5), two normal faults affect the whole  
168 experiment with the major one located on the left side. No observable flat is present associated with  
169 either the lower silicone layer or reverse fault. A graben, associated with a flat, accommodates the  
170 flexural deformation of the upper sand layer on the right side of the experiment above the upper  
171 silicone layer. Several normal faults affect the lower sand layers and microbeads below the lower  
172 silicone layer.

173 For intermediate rates of 1 or 2 cm/h (Fig. 4b and c, experiments 3 and 4, respectively), two major  
174 faults are refracted in the silicone layer, and develop a ramp and flat geometry when crossing  
175 silicone layers. This ramp-flat-ramp geometry may evolve in two ways: either as a fault lens (Fig.  
176 4b zoom) or as a flat with an extensional forced incipient fold (Fig. 4c zoom). In the case of a fault  
177 lens (Fig. 4b zoom), the sand layers (sand 3) are deformed by translation along the faults without  
178 rotation. In the case of a flat (Fig. 4c zoom), the sand layers (sand 3) are deformed by flexure, with  
179 creation of an extensional forced fold, affecting the hanging wall only above the flat. Note that this  
180 incipient fold, created only in extension, corresponds to an anticline fold in the hanging wall of the  
181 normal fault, while drag folds (more hanging-wall synclines) develop generally along normal faults  
182 when there is no flat.

183 For the lowest rate of 0.5 and intermediate rates of 1 or 2 cm/h (Fig. 4b, c and d, experiments 2, 3  
184 and 4 respectively), the major faults (red bold line in figures) evolve near the surface in the sand  
185 layers (sand 4) from a normal fault to a reverse fault (Fig. 4d zoom).

186 For the lowest rates of 0.25 or 0.5 cm/h (Fig. 4d and e, experiments 1 and 2, respectively), only one  
187 major fault cuts the whole stratigraphic pile that concentrates the deformation and one or two

188 antithetic normal faults below the lower silicone layer. With a very low velocity of extension 0.25  
189 cm/h (Fig. 4e, experiment 1), only one antithetic normal fault is located near the major normal fault,  
190 which produces a narrow deformed zone, and the associated subsidence above the lower silicone  
191 layer is accommodated by a flexural deformation of the sand layers. The ramp-flat-ramp fault  
192 geometry is emphasised for a very a low velocity (0.25 cm/h, Fig. 4e zoom). The global  
193 deformation of the sand layers in the hanging wall between the two silicone layers corresponds to a  
194 faulted evolved extensional forced anticline fold. Note that the flats are best developed in the last  
195 experiment with a very low rate of extension.

196 Even though the extension direction is the same for all experiments, note that the major normal fault  
197 is sometimes located on the right side (experiments 1, 3 and 5) and sometimes on the left side  
198 (experiments 2 and 4). That means that the basal silicone layer decreases the initial constraints  
199 created by the velocity discontinuity situated at the base of the experiment. Similarly, the fault  
200 geometry and associated deformation are neither symmetric nor cylindrical, as can be seen on the  
201 top view of the final state of experiment 3 (Fig. 3). The left side of the experiment shows numerous  
202 closely spaced normal faults and a curved reverse fault. The right side of the experiment shows not  
203 straight normal faults that resemble an “en échelon” pattern. Note that the reverse fault and "en  
204 échelon" fault created here both result from pure extension.

### 205 *3.3. Non-homogeneous geometries illustrated by the 3D model of experiment 3*

206 As suggested by Figure 3, even though the applied displacement and the building of the experiment  
207 are homogeneous, the final deformation is neither symmetric nor cylindrical. Thus, in order to  
208 further investigate the lateral variations of both fault shapes and layer geometries, a 3D model was  
209 built using the gOcad modeller (Mallet, 2002) from twelve cross-sections of experiment 3 (Fig. 5).

210 The model building comprises two steps:

211 - The integration of the 3D cross-section data and the correlation of the cross-sections  
212 amongst themselves (coherency must be checked). The cross-sections are then used as a base to  
213 model faults and horizons.

214 - The construction of the 3D structural model with faults and horizons following geological  
215 and geometrical coherency rules (Caumon et al., 2009). This construction is made from the twelve  
216 cross-sections of experiment 3 (see example in Le Carlier de Veslud et al., 2009) using the DSI  
217 interpolator (Discrete Smooth Interpolation, Mallet, 2002). Faults are built first, followed by the  
218 layers that are then made to be consistent with the faults according to their continuous versus  
219 faulted behaviour as seen in the cross-sections.

220 As previously mentioned, décollement levels within the system lead to a broad diversity in the  
221 extensional structures related to the normal faults. The 3D numerical model enables a better  
222 visualisation and understanding of these non-homogeneous geometries (Fig. 5):

- 223 - The geometry of the fault planes corresponds to an undulating surface.
- 224 - Fault surfaces are not necessarily continuous and are organised "en échelon".
- 225 - The flat parts of the normal faults are not continuous and vary laterally in width, but are  
226 systematically associated with décollement levels.
- 227 - Some faults present normal dip at depth and turn to reverse faults upwards.

228 It is not straightforward to obtain information from the top view (Fig. 3) where only fault traces are  
229 visible in the 3D fault network (Fig. 5). This example demonstrates that, in a multi-layered system  
230 with several décollement levels, surface data with one cross-section are simply not sufficient  
231 enough to thoroughly reconstruct the fault network in depth as the deformation is complex.

232 Moreover, a partial observation can be misleading since the faults on the right-hand side of Figure 5  
233 show an "en échelon" pattern that could suggest strike-slip movements whereas none are involved  
234 in our experiments at all.

235 *3.4. Influence of the extension amount*

236 Four cross-sections coming from four different experiments (experiments 3, 6, 7 and 8) carried out  
237 with the same standard stratigraphy and the same rate of extension of 1 cm/h illustrate the influence  
238 of the amount of extension from 0.5 to 4 cm (Fig. 6).

239 For an extension amount of 0.5 cm (Fig. 6a, experiment 6), the faults clearly cut the base layer of  
240 the experiment (sand 1, microbeads and sand 2) and are incipient in the middle part (sand 3); no  
241 faults affect the upper part of the experiment (sand 4). No variation in fault dip is observed. Flats  
242 are observed in the lower pink silicone, mainly on the right side of the cross-section. The  
243 deformation of the upper part of the experiment corresponds to a zone of subsidence limited by  
244 flexures situated above the two faults affecting the middle part of the experiment.

245 For an extension of 1 cm (Fig. 6b, experiment 3), which corresponds to the reference experiment  
246 with a standard stratigraphy as described previously (Fig. 4c), we observed the main characteristics  
247 with the creation of a graben, a normal fault to a reverse fault, and flat and fold related to the  
248 interaction between the sand and silicone layers during the extension. Note that the deformation  
249 affects all layers, with well-developed flats in the silicone layers.

250 For an extension of 2 cm (Fig. 6c, experiment 7), like FANEX 4, two major faults are developed  
251 with a ramp and flat shape when they cross the silicone layers. This ramp-flat-ramp geometry may  
252 evolve in two ways: either as a fault lens (Fig. 4b, right side) or as an overlap fault (Fig. 6c zoom).  
253 Above this overlap, the forced fold, affecting the hanging wall of the fault is partially faulted on its  
254 left side by a steep fault. The major fault evolves near the surface with an increase in the  
255 deformation of the upper sand layers (sand 4), with a graben on the platform border and a reverse  
256 fault in the direction of the subsidence zone. In the centre of the experiment between the two major  
257 normal faults, minor normal faults not only affect the brittle layers under the lower pink silicone  
258 layer but also the sand layer under the upper transparent silicone layer.

259 For an extension of 4 cm (Fig. 6d, experiment 8), the location of the structures is similar to the  
260 previous experiment, but the geometry is more complex, and the displacements and number of  
261 faults increase. In particular, the sand layers between the two silicone layers on the right side of the  
262 graben are deformed in the footwall of the normal fault associated with the gliding of the upper  
263 sand layer into the graben.

264 Note that, between the two normal faults created in the upper sand layers of the experiments, the  
265 subsidence zone is more developed (wider) when the upper sand over the transparent silicone is  
266 gliding in the direction of the central graben.

### 267 *3.5. Influence of the stratigraphy of the décollement layers*

268 Three cross-sections from three different experiments (experiments 3, 9 and 10) illustrate the  
269 influence of the mechanical layering (Fig. 7). Experiment 9 is built according to the same standard  
270 stratigraphy but the thicknesses of the silicone layers are roughly divided by two in experiment 9  
271 (see Table 1). In experiment 10, the transparent upper silicone layer is swapped with the microbeads  
272 layer compared to experiment 3 (see Table 1).

273 When the silicone layers are thinner than in the reference layering (Fig. 7a, experiment 9), the faults  
274 tend to cross the whole experiment straight forward, without dip variation. Only a fault lens  
275 develops on the right side of the experiment between the lower and upper silicone layers. No  
276 grabens, reverse faults, flats, with an associated fold, or flexures are observed in this experiment.  
277 Note that the geometry of the structures is close to the experiment with a high extension rate (Fig.  
278 4a, experiment 5).

279 When the silicone layers are in a reversed order (Fig. 7c, experiment 10), two normal faults, a major  
280 one (right side) and a minor one (left side), are developed in the upper sand layers of the  
281 experiments. The flat in the transparent silicone is wider than in experiment 3 and is associated with  
282 grabens between the silicone layers. As for experiment 9, no reverse faults are developed.

283 Note that, between the two normal faults created in the upper sand layers of the experiments, a  
284 subsidence zone develops and the width of this zone increases from experiment 9 to 10. In  
285 experiment 10, the major flats are developed in transparent silicone, which is located near the base  
286 of the experiment, resulting in a wider subsidence zone in the top; therefore, the deeper the flat, the  
287 wider the subsidence zone.

288

## 289 **4. Discussion**

### 290 *4.1. Mechanical layering effect*

291 The integration of a layer of microbeads, with a low internal friction angle, does not influence the  
292 geometry of the normal faults and their dip and therefore does not act as a décollement level (Fig.  
293 8). In extensional experiments, it seems necessary to associate a slope of the layers with fluid  
294 overpressure during extension to produce a flat fault in the microbeads (Lacoste et al., 2012). The  
295 effects of fluid overpressures and slope in the sand experiments have also been previously  
296 suggested to induce gravitational gliding (Mourgues and Cobbold, 2003). Thus in our modelling,  
297 the most important mechanical layers are the viscous layers, the location of which largely drives the  
298 deformation pattern (Fig. 8).

299 The development of the flats is related to the strength ratio between the sand and silicone layers; the  
300 higher the strength ratio, the wider the flats.

301 In experiment 3 (Fig. 4), the flats are more developed in the transparent silicone than in the pink  
302 silicone, because the transparent silicone is two times less viscous than the pink silicone, and  
303 therefore the strength ratio between the sand layer and silicone layers is larger. This is consistent  
304 with our observations related to a velocity effect where the flat is larger when the strain rate is  
305 lower.

306 In experiment 9 (Fig. 7), where the thicknesses of the lower and upper silicone layers are roughly  
307 divided by two, compared to experiment 3 (0.5 cm in experiment 3 and 0.25 cm in experiment 9,  
308 see Table 1), the flats are nearly inexistent due to the decrease in the strength ratio.

309 In experiment 10 (Fig. 7), where the upper transparent silicone layer replaces the microbeads layer,  
310 compared to experiment 3, the flats are more developed in the transparent silicone located deeper in  
311 the experiment because the strength ratio is much higher. Note that the amplification of the flat  
312 length at depth in the experiment induces an increase in the width of the zone of subsidence without  
313 an increase in the amount of extension (Fig. 7c).

#### 314 *4.2. Strain rate effect*

315 The strain rate controls the strength of the viscous layer (silicone): the higher the rate, the higher the  
316 strength; therefore, variations in the strain rate may impact the fault pattern, particularly in terms of  
317 the number of faults and their organisation. When the strain rate is greater than or equal to 1 cm/h  
318 (Fig. 4a, b and c), two main faults develop from the basal silicone and cut the whole experiment on  
319 the right and left side. When the strain rate is less than 1 cm/h (Fig. 4d and e), only one main fault  
320 develops from the basal silicone and cuts the whole experiment on the right or left side. This means  
321 that when the strain rate is high, the global deformation is more distributed and controlled by the  
322 strength of the silicone layers whereas when the strain rate is low, the global deformation is more  
323 localised and controlled by the strength of the sand layers (e.g. Davy et al., 1995). When the strain  
324 rate is low (Fig. 4e), the strength of the silicone layers decreases and the silicone layers act more as  
325 a décollement level and the deformation of the sand layers is only concentrated in one major fault or  
326 deformation zone (localisation of the deformation in the brittle layers).

327 The second effect, related to the first one, is the increase in flat size, mainly in the experiment with  
328 the lowest strain rate (0.25 cm/h). The increase in flat size is consistent with the decrease in silicone  
329 strength associated with the low strain rate, which supports efficient décollement levels. The



330 creation of flats induces specific deformation of the layers in the hanging wall with the development  
331 of forced folds (e.g. Jackson and Rotevatn, 2013; Lewis et al., 2013) or reverse faults at the top of  
332 some experiments. The characteristic features of both folds and reverse faults result from pure  
333 extension and are not indicative of a strike-slip component, compression or inversion interpretation.

334 These forced folds are parallel to the border fault and only located in the hanging wall above a flat  
335 without any "en echelon" character. They result from differential subsidence in the hanging wall:  
336 along the normal fault and within the graben, the subsidence of the sand layers is larger than above  
337 the flat where the subsidence of the sand layers is lower (see the red arrows in Fig. 8). These forced  
338 folds correspond to the seismic example given in Figure 1c (Jackson and Rotevatn, 2013). In the  
339 cross-section, just above and below the folded layers, the layers are flat, which means that  
340 compression or inversion cannot be used to explain the geometry of these layers. Moreover, it is  
341 possible to generate shortening in a pure extensive context, related to a local layer reorganisation  
342 between faults, for example in a system where the layers cannot move laterally. Similarly, "en  
343 échelon" structures can be observed locally, as in Figure 5, just in order to accommodate a local  
344 organisation of the deformation of the layers, without this making sense on a global scale.

#### 345 *4.3. Effect of the amount of extension*

346 The first effect on the fault pattern is the number of faults generated inside the experiment. When  
347 the extension amount increases (Fig. 6), the two border main faults become more and more complex  
348 upward, in particular with a gliding amplification of the upper sand layer (sand 4) towards the  
349 graben (Nalpas and Brun, 1993). At the same time, the genesis of secondary conjugate normal faults  
350 between the two major border faults, in the centre part of the graben, produces a complex  
351 deformation of the lower and middle sand layers (sand 1, 2 and 3). In contrast, in the centre of the  
352 graben, the upper sand layer (sand 4) accommodates the deformation only by homogeneous  
353 subsidence. This is related to the decoupling between sand 4 and the lower layers allowed by the

354 upper silicone layer. As a result, the increase in the amount of extension is distributed along more  
355 faults, in the centre of the graben in lower layers and on the borders of the graben in upper layers.

356 The second effect is related to the flat genesis: the size of the flats located in the lower and upper  
357 silicone layers are not the same. For the lower silicone layer, the flat is not conserved during  
358 extension and an overlap, between normal faults affecting sand 2 and sand 3, is created in relation  
359 to the huge vertical throw of the fault (Fig. 6c). For the upper silicone layer, the subsidence between  
360 the two major faults, affecting the sand 1, 2 and 3 layers, induces a wide flat that results in the  
361 layers of sand 4 gliding above the upper silicone layer (see also Nalpas et al., 1993; Withjack and  
362 Callaway, 2000). This wide flat increases the zone of subsidence related to extension (Fig. 6a to d).

363 The third effect is both the creation and amplification of the movement of the upper reverse faults,  
364 affecting sand 4, associated with differential subsidence (Fig. 6). These faults have been previously  
365 described in analogue modelling (e.g. Horsfield, 1977; Vendeville, 1987; Withjack et al., 1990; Ge  
366 and Jackson, 1998; Dooley et al., 2003; Soto et al., 2007). In general, they are restricted to the upper  
367 sand layers, but they potentially develop inside the experiment between two layers of silicone (see  
368 sand 3 in Fig. 4e). They are related to the gliding and rotation of the sand layer in the direction of  
369 the graben resulting from the variation in subsidence velocity between the graben and its platform  
370 borders (Fig. 8). These reverse faults are systematically branched at depth on a décollement level,  
371 and are observed for the experiments with a variation in both the amount and rate of extension (Fig.  
372 4). This structure corresponds to local deformation and does not provide any information about the  
373 boundary conditions. Thus, it is very important to recognise that these reverse faults may be  
374 generated in a pure extensional system, and to not associate them systematically with compression,  
375 strike-slip movement or inversion.

376

377 **5. Conclusions**

378 The presence of a décollement level largely controls the geometry of normal faults characterised by  
379 distinctive associated structures such as ramp-flat-ramps, forced folds and reverse faults all  
380 developing in a pure extension context.

381 - The genesis of flats along normal faults depends on the strength ratio between the sand and  
382 silicone layers: the higher the strength ratio, the wider the flats. Thus, the lower the velocity of the  
383 extension, the thicker the décollement layer, or the deeper the location of the décollement layer, and  
384 the wider the flat.

385 - A forced fold, associated with the flats, develops in the hanging wall and is characteristic of the  
386 presence of a décollement level as well as a flat just under the fold. Therefore in seismic  
387 interpretations, the presence of forced folds may be a good proxy to locate the décollement levels in  
388 sedimentary series and potential associated permeability barriers.

389 - Gliding reverse faults develop in the hanging wall on the border of the normal faults of the graben.  
390 They result from a variation in the subsidence velocity and accommodate the differential subsidence  
391 in the sand layers near the border of the normal fault of the graben. They are not related to  
392 shortening but are typical structures created in extension and are facilitated by the presence of a  
393 décollement level.

394 - The structures associated with the flats are often interpreted as the result of shortening, but as  
395 mentioned in nature (e.g. Sharp et al., 2000; Jackson and Rotevatn, 2013) and shown by the  
396 experiment here (e.g. Horsfield, 1977), it is possible to create both a forced fold and reverse fault in  
397 pure extension when the stratigraphy is not homogeneous, but is instead comprised of an alternation  
398 between brittle and ductile layers. Therefore, it is very important to characterise these typical  
399 structures in order to avoid misinterpretation.

400

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406

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517

518

519

520 **Figure captions**



521 Figure 1: Multi-scale examples showing a normal fault geometry in a brittle-ductile system, the blue  
522 line show a fold associated to a flat of the fault (in red): a1) thin section and a2) corresponding line  
523 drawing from La Moutiere (Southern Alps, France) where the (-) symbol indicates a very fine-  
524 grained lithology and (+) symbols indicate a coarser-grained layer (modified from Du Bernard,  
525 2002); b) outcrop photograph with alternating layers of chalk and marl at Flamborough (Yorkshire,  
526 UK, modified from Childs et al., 2009); c) seismic section and line drawing from the Gulf of Suez  
527 (modified from Jackson and Rotevatn, 2013); d) seismic profile and line drawing from the  
528 Stavanger Fault System (North Sea, modified from Lewis et al., 2013); e) analogue modelling of an  
529 extensional forced-fold associated with a pre-cut flat-ramp fault (Expt. E59-2, modified from  
530 McClay, 1990).

531 Figure 2: Experimental apparatus and strength profile on left side.

532 Figure 3: Schematic cross-section showing the main structural features of the experiments (standard  
533 stratigraphy, experiment 3). Zoom with a forced fold related to the fault flat geometry at left.

534 Figure 4: Cross-sections showing the effect of displacement rate on the final deformation (amount  
535 of extension: 1 cm in all experiments).

536 Figure 5: a) Global view of the 3D numerical model (of experiment 3) with a top view photograph  
537 applied onto the topography; b) 3D fault network showing that the deformation is heterogeneous  
538 and varied. Orange surfaces are normal faults, green surfaces reverse faults and blue surfaces the  
539 flats.

540 Figure 6: Cross-sections showing the effect of the amount of extension on the final deformation  
541 (extension velocity: 1 cm/h in all experiments).

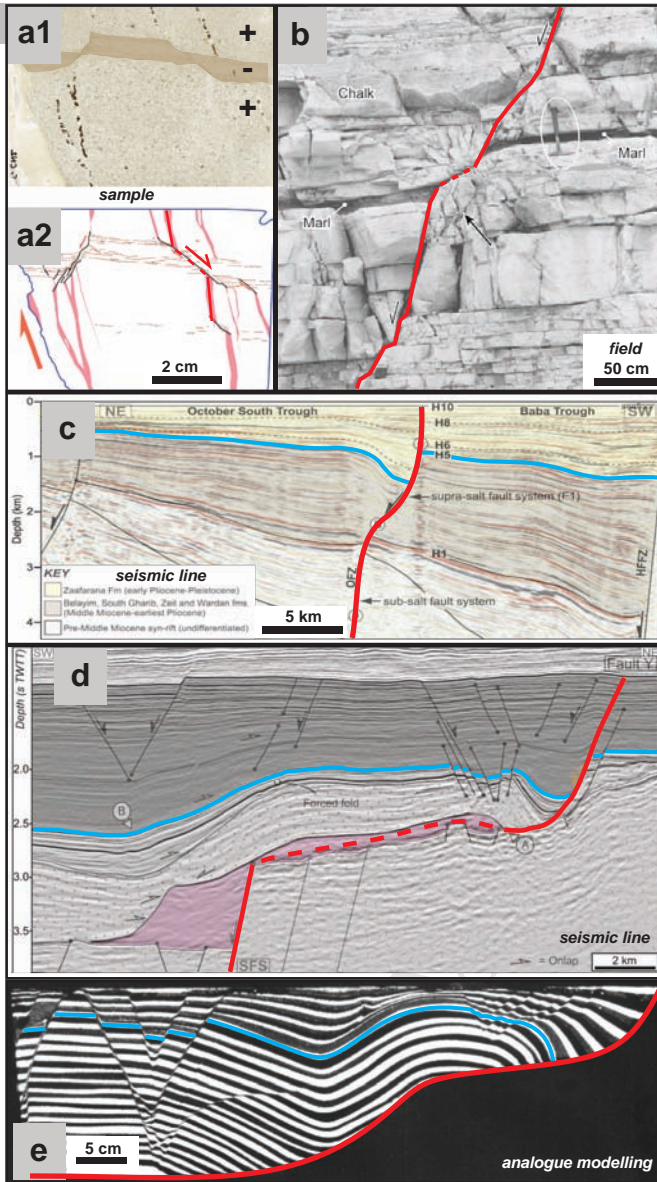
542 Figure 7: Cross-sections showing the influence of ductile thickness and the location of the ductile  
543 layers on the final deformation.

544 Figure 8: Diagram showing the different types of structures in relation to vertical movements in a  
545 extensional context.

546 Table 1: Experimental parameters.

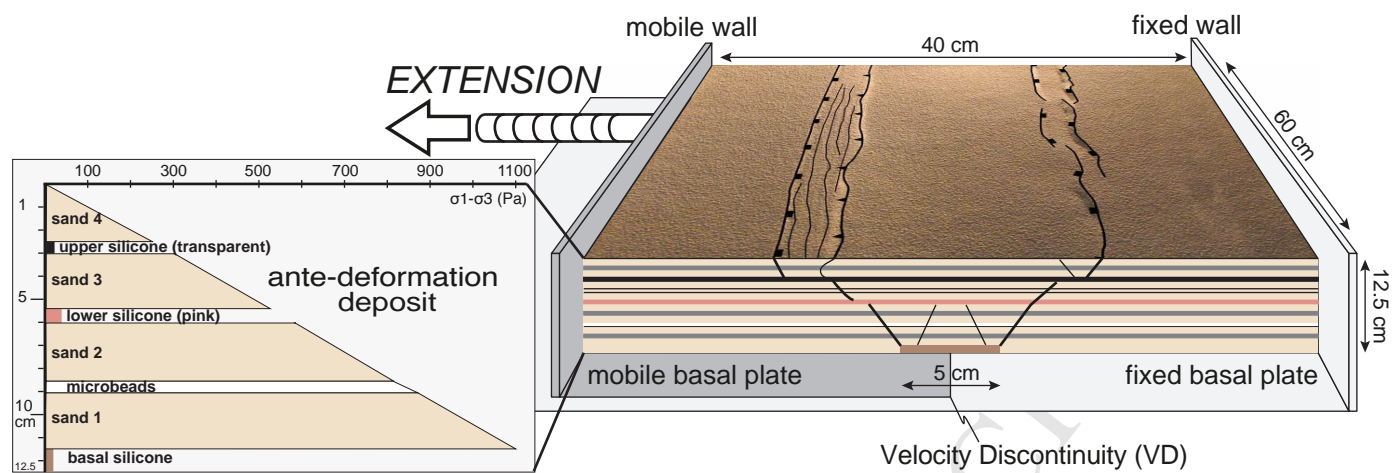
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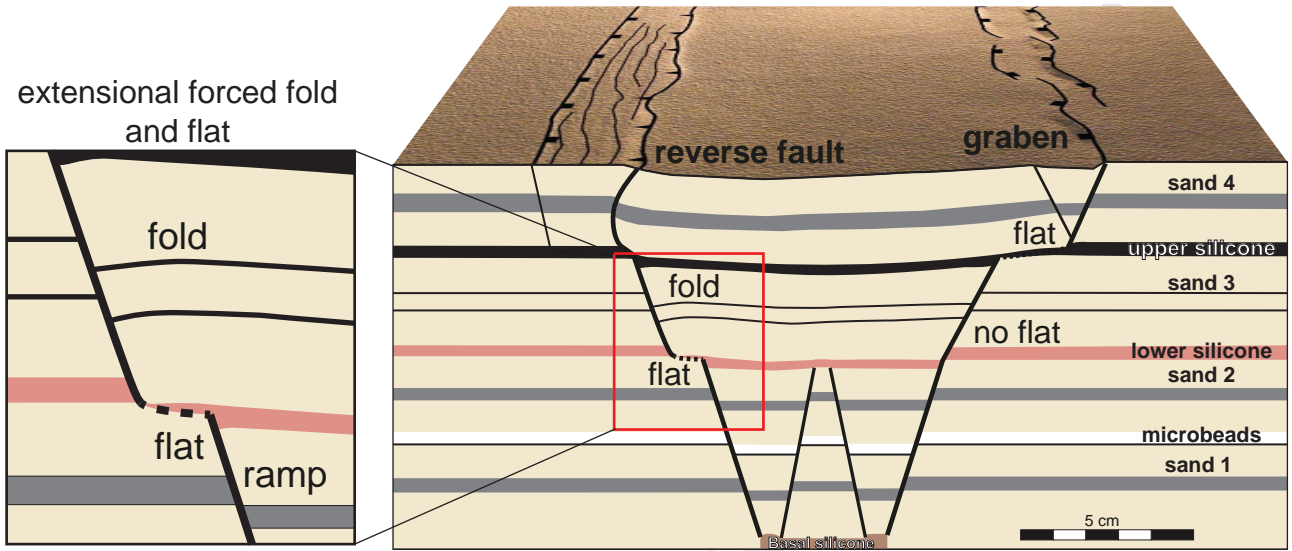
name	extension rate (cm/h)	extension (cm)	silicone thickness (cm)	layer order from base to top (where flat may be created)
1 (FANEX 3)	0.25	1	0.5	microbeads/pink silicone /transparent silicone
2 (FANEX 2)	0.5	1	0.5	microbeads/pink silicone /transparent silicone
3 (FANEX 4)	1	1	0.5	microbeads/pink silicone /transparent silicone
4 (FANEX 5)	2	1	0.5	microbeads/pink silicone /transparent silicone
5 (FANEX 16)	4	1	0.5	microbeads/pink silicone /transparent silicone
6 (FANEX 8)	1	0.5	0.5	microbeads/pink silicone /transparent silicone
7 (FANEX 1)	1	2	0.5	microbeads/pink silicone /transparent silicone
8 (FANEX 17)	1	4	0.5	microbeads/pink silicone /transparent silicone
9 (FANEX 7)	1	1	0.25	microbeads/pink silicone /transparent silicone
10 (FANEX 6)	1	1	0.5	transparent silicone /pink silicone / microbeads

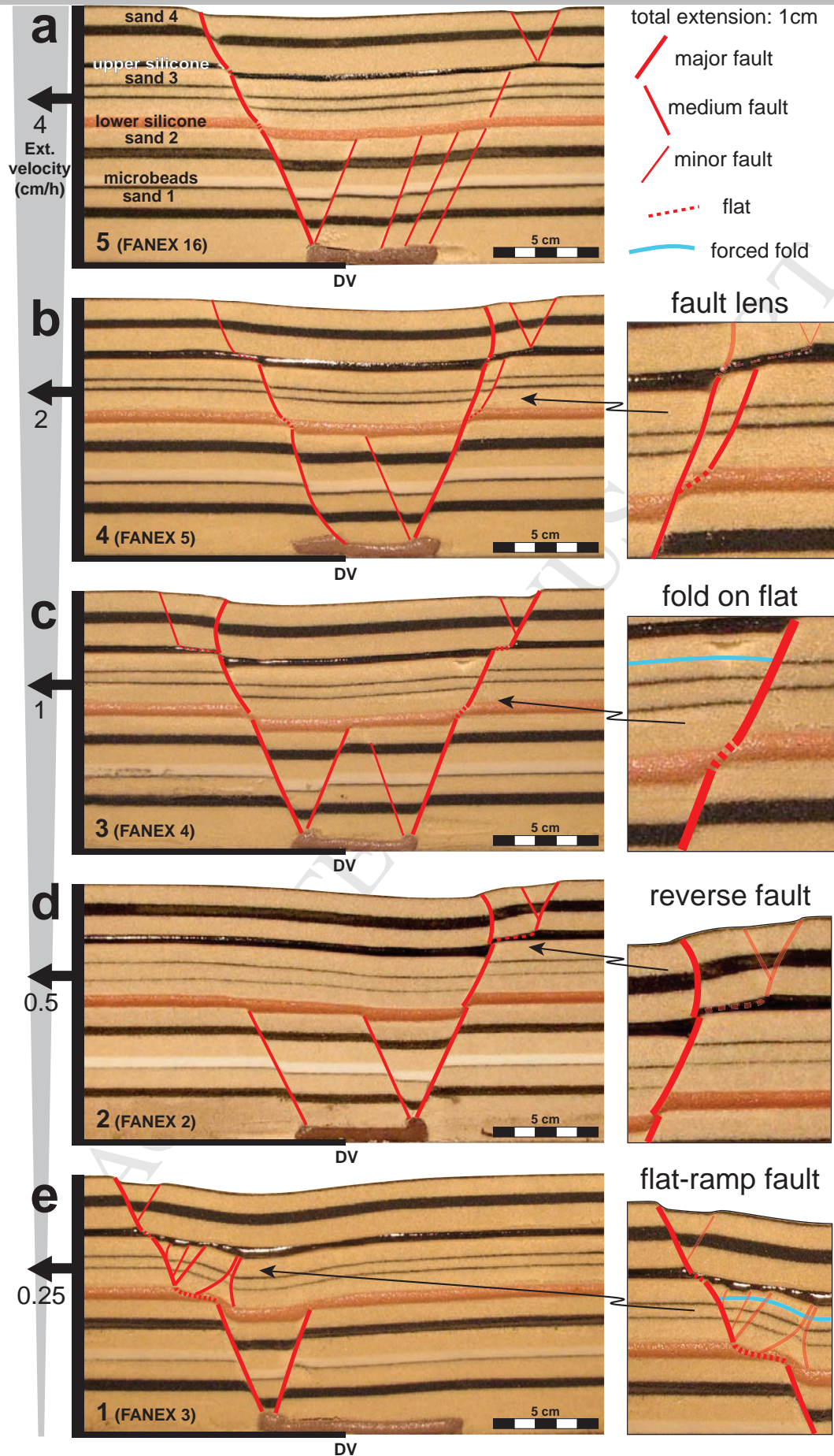


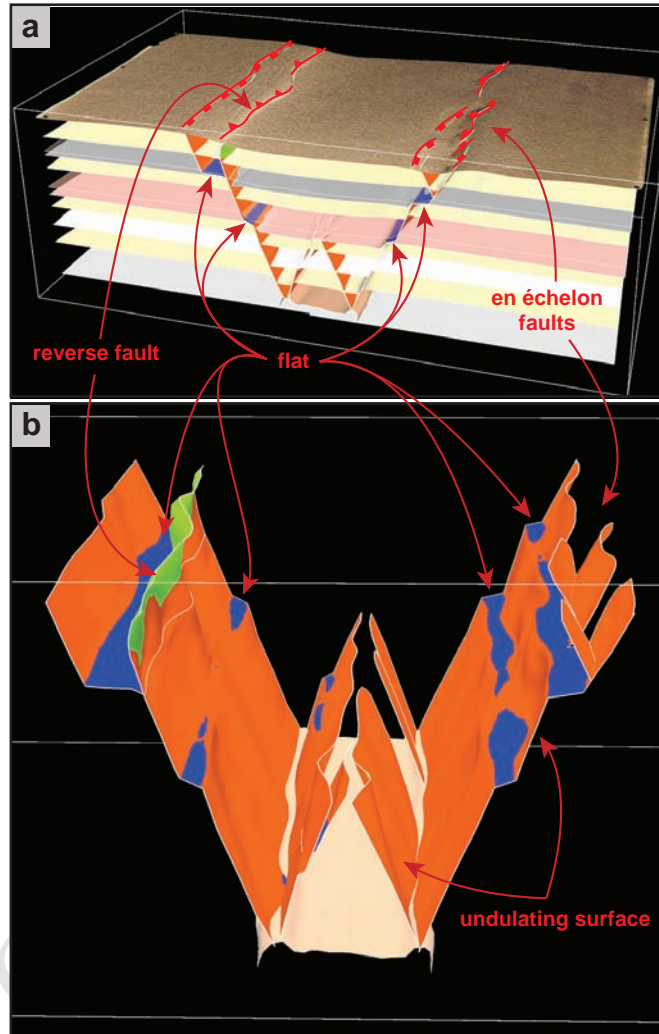
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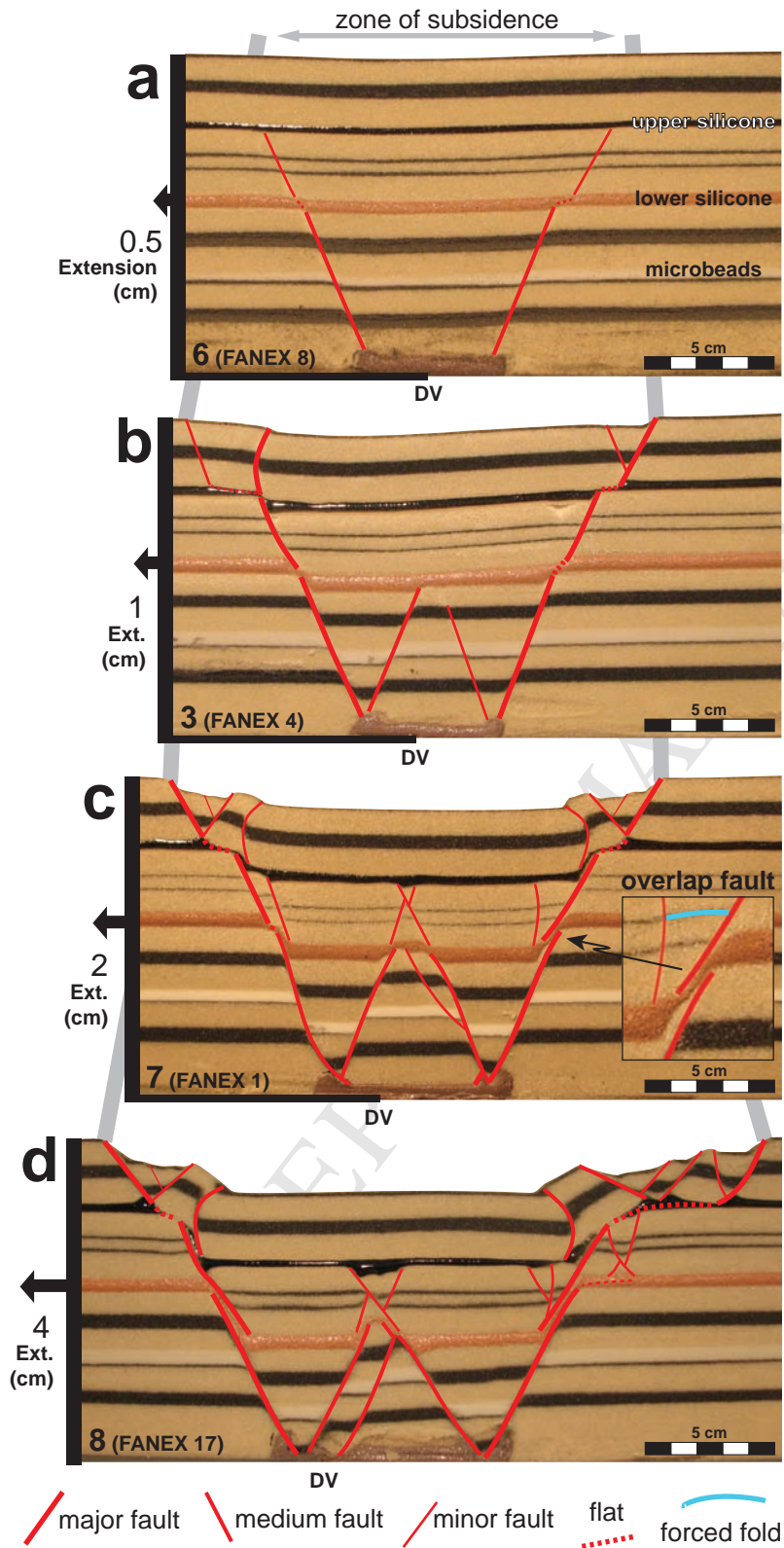


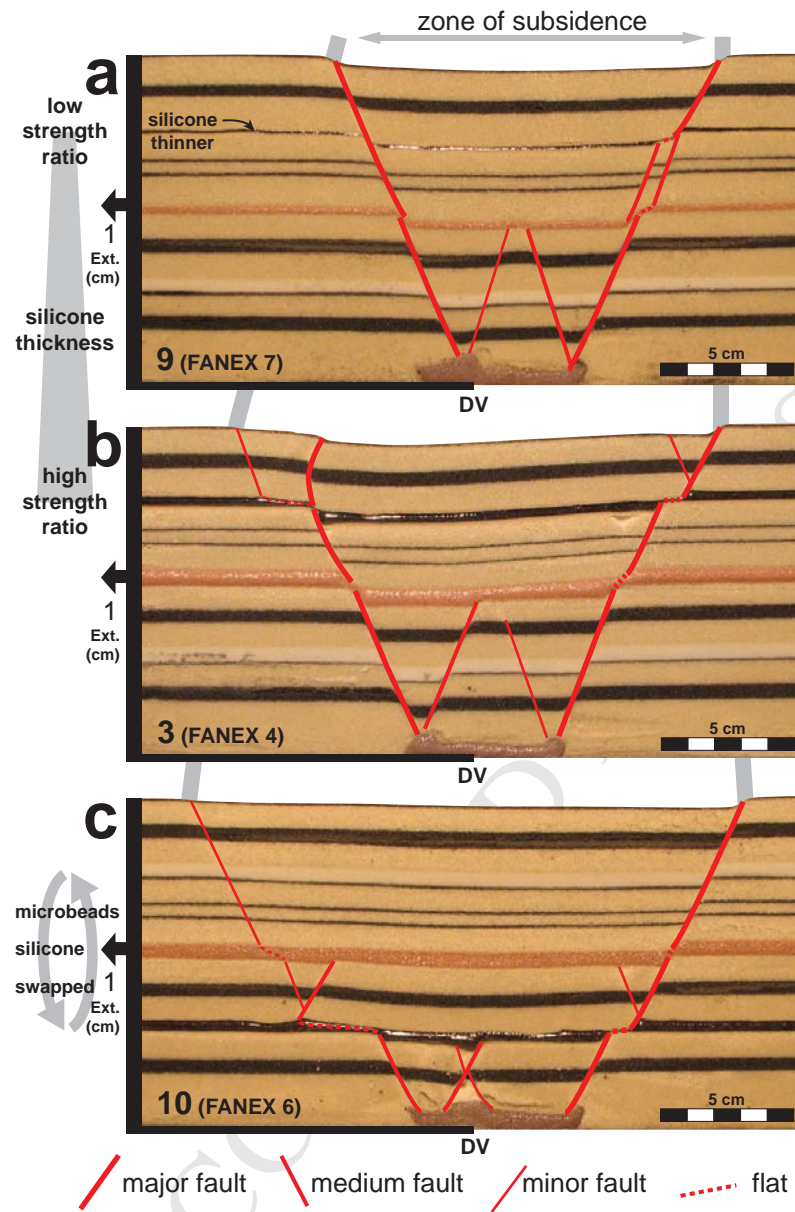


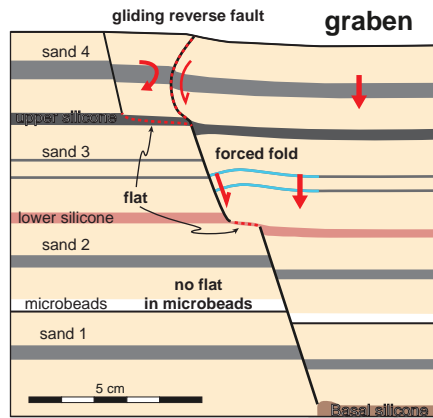








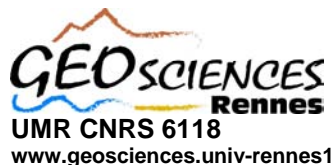






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Rennes 26/06/2017

Thierry NALPAS  
Maître de conférences

Reference: Vasquez et al, Highlights

The main point of the presented manuscript are:

- The control of the geometry of normal faults related to the presence of décollement levels;
- The geneses of flats along normal faults;
- The geneses of forced fold in the hanging wall of a normal fault;
- The geneses of gliding reverse faults in the hanging wall of a normal fault.

It is very important to recognize that these structures may be generated in a pure extensional system, and to not associate them systematically with compression, strike-slip movement or inversion.