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Influence of synkinematic sedimentation in a thrust system with two decollement levels; analogue modelling

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Abstract:

Compressive systems in foreland domains are characterised by fold and thrust belts linked to the presence of one or several ductile layers in depth acting as a decollement level. The main parameters controlling the structural evolution are: the presence of a decollement level, the amount and rate of shortening, and the amount of synkinematic sedimentation. The effect of these parameters has only been studied on a thrust belt scale. Furthermore, only the effect of synkinematic sedimentation on a simple system with one decollement level has been studied at the scale of a single structure. The aim of this study was to use analogue modelling to test the effect of shortening rate, velocity and the localization of sedimentation on a single system characterised by the presence of two prekinematic decollement levels. The main results showed variations in the structural vergence, folding geometry (symmetric or asymmetric), the evolution of the deformation (horizontal propagation versus vertical uplift), and the decoupling of the lower and upper brittle structures in relation with the main parameters (shortening rate and mass transfer). The results of the experiments were then compared to natural examples from the sub-Andean thrust belt.

Keywords: Thrust; Decollement level; Synkinematic sedimentation; Analogue modeling

Introduction

30 In a compressive system, and especially in a thin-skinned thrust belt, a deformation induced by one or
31 several decollement levels is commonly observed (e.g. flat, ramp, fault-related folding). Decollement
32 levels present a low basal friction directly related to the lithology (marls, shales, coals and evaporites)
33 and/or to overpressure conditions. The Sub-Andean fold and thrust-belt shows a major west-to-east
34 propagation of the deformation (Fig. 1). This deformation is characterised by north-south folds-faults
35 (Fig. 1b) and is related, in depth, to two decollement levels (Fig. 1c). These structures, which developed
36 during sedimentation, present mostly a west-to-east vergence with a huge horizontal and vertical
37 displacement. Previous analogue studies have investigated the entire scale of the thrust-belt (Leturmy et
38 al., 2000; Couzens-Schulz et al., 2003; Smit et al., 2003). The main characteristics of this system are the
39 basal angle of the wedge and the shortening rate, which control the propagation of the thrust sequences
40 (Smit et al., 2003). The presence of two decollement levels favours either coupling or decoupling,
41 related to the shortening rate (Couzens-Schulz et al., 2003; Massoli et al., 2006). The presence of
42 synkinematic sedimentation modifies the thrust wavelength and the major propagation of the
43 deformation (Leturmy et al., 2000). On a structural scale, only a few studies have addressed the
44 relationship between deformation and sedimentation using analogue modelling (Nalpas et al., 1999;
45 Casas et al., 2001; Barrier et al., 2002; Nalpas et al., 2003; Gestain et al., 2004). All of these studies
46 were carried out with only one prekinematic ductile layer and showed an increase in the uplift
47 associated with the sedimentation rate. At the scale of a single structure with two prekinematic ductile
48 layers, the vergence of thrust, the localization of deformation, the relation between structuration in depth
49 and at the surface, and the effect of mass transfer are still in debate.

50 The aim of this paper is to study the deformation of a structure in a domain presenting two prekinematic
51 decollement levels in relation to the (i) shortening rate variation, (ii) synkinematic velocity of the
52 sedimentation and (iii) localization of the synkinematic sedimentation. Our approach was based on
53 analogue modelling and field examples (e.g. Sub-Andean thrust-belt).

54

55 **2. Experimental procedure**

56 The modelling techniques used here are similar to those usually used for experiments dealing with
57 brittle-ductile systems in the Laboratory of Experimental Tectonics of Géosciences Rennes (Rennes
58 University, FRANCE) and which have been described in numerous studies (e.g. Faugère and Brun
59 1984; Vendeville et al. 1987; Davy and Cobbold 1991). Brittle layers (pre and synkinematic) were
60 represented by sand, with an angle of internal friction close to 30° (Krantz, 1991) and a density (ρ)
61 around 1,400 kg/m³. Weak ductile layers such as shales, clay, marl or salt were represented by two

62 silicone putties (Rhône Poulenc, France) with a viscosity (μ) around 10^5 Pa.s at 20°C and a density (ρ)
63 close to $1,400\text{ kg/m}^3$ for the silicone putty 70 009, and a viscosity (μ) around 10^4 Pa.s at 20°C and a
64 density (ρ) close to $1,000\text{ kg/m}^3$ for the transparent silicone putty SGM 36.

65 The experimental apparatus consisted of a fixed rigid basal plate over which a thin mobile plate fixed on
66 a mobile wall was pushed at a constant rate (Fig. 2a). The shape of the mobile plate induces a velocity
67 discontinuity (VD) at the base of the model, which localises the deformation (cf. Malavielle 1984; Balé
68 1986; Allemand et al. 1989; Ballard 1989). The model was set in a $70 \times 60\text{ cm}$ sandbox, wide enough to
69 achieve a relatively large amount of shortening without border effects.

70 In order to make comparisons with natural examples, where the thickness of the ductile and brittle
71 layers are different from the base to the top of the sedimentary pile of the basin, we chose a four-layer
72 brittle-ductile model with ductile and brittle material that is thicker in the lowermost layers than in the
73 uppermost layers. The prekinematic pile of the models was made of a four-layer brittle-ductile system,
74 composed of, from bottom to top: 1 cm of either pink or purple silicone; 1.5 cm of black and white
75 sand; 0.5 cm of transparent silicone; and 1cm of black and white sand (see Fig. 2a). The basal and the
76 medium silicone layers represent potential decollement levels, while the sand layers represent brittle
77 prekinematic formations. Several shortening rates, ranging from 0.25 to 10 cm/h, were tested, and a rate
78 of 0.5 cm/h was kept for the experiment. The geometric and dynamic scaling of these models was
79 presented in Table 1. The scale ratio and stress ratio between model and nature has the same order (10^5),
80 and the velocity in the model corresponds to observed velocity in nature (see Table 1).

81 In order to simulate synkinematic sedimentation, fresh sand was continuously sprinkled manually onto
82 the model during the shortening (Barrier et al., 2002). The sedimentation modes (Fig. 2b) were chosen
83 to constrain the possible sedimentation modes within natural basins (see § 3.2, below). Photographs of
84 the model surface were taken at regular time intervals in order to observe structure development. After
85 deformation, the internal structure was observed on a series of cross-sections cut parallel to the
86 compression direction (perpendicular to the VD). Brittle sand layers were made of various colours of
87 sand in order to reveal the structures and to observe them on photographs. The colour of the sand does
88 not modify its behaviour.

89

90 **3. Analogue results**

91 *3.1. Shortening rate variation*

92 The first aim of our experiments was to test several shortening rates in order to define the best rate to
93 match thin-skinned tectonic features (e.g. flat, ramp, fault-related folding) unaffected by the influence of

94 the experimental apparatus. Six different shortening rates were applied to the model: 0.25, 0.5, 1, 2.5, 5
95 and 10 cm/h. We first tested 5 cm of shortening, followed by 10 cm of shortening. In this paper, we
96 present the results obtained with 3 shortening rates (0.5, 1 and 5 cm/h; Fig. 3).
97 It was possible to define the global geometries in all of the experiments. The deformation corresponded
98 to an uplift with an anticline shape, and which was always located above the linear velocity
99 discontinuity (VD). According to the definition of VD and the induced shear displacement (Ballard,
100 1989), a synthetic reverse fault occurs when the hanging wall moves toward the mobile plate. On the
101 contrary, an antithetic reverse fault is characterised by the hanging wall moving in an opposite direction
102 to the mobile plate. The lower brittle layer was always characterised by a major reverse fault with flat
103 and ramp geometry. This basal structure had an average ramp angle of 25° (Fig. 3). The major
104 deformation of the upper brittle layer was located above the major basal deformation in the lower brittle
105 layer. The major basal reverse faults in the lower brittle layer and the major reverse faults in the upper
106 brittle layer were associated with a sheet of silicone at the base of the hanging wall. In the upper brittle
107 layer, the vergence of the reverse fault was the same as seen for the reverse fault in the basal brittle
108 layer. In order to obtain a fault displacement with the same vergence in the lower and upper brittle
109 layers, it is necessary to have an opposite sense of shear in the upper ductile layer, as is observed in the
110 brittle layers. This opposite sense of shear is characteristic of fish tail structures described in nature
111 (Meneley, 2006). In all the experiments, the frontward or backward propagation was related to
112 development of the structures, with regard to the major lower brittle layer fault. Thus, a development of
113 structures above the footwall of the lower major fault corresponded to a frontward propagation, while a
114 development of structures above the hanging wall of the lower major fault corresponded to a backward
115 propagation.

116

117 *3.1.1. 5 cm/h of shortening rate*

118 In this experiment, the global geometry was strongly symmetrical throughout the entire model (Fig. 3a),
119 and the structure looked like a box-fold or pop-up structure. The lower brittle layer was characterised by
120 the presence of a major synthetic reverse fault (with regard to the mobile plate). This fault was
121 composed of two segments that defined a horizontal throw (flat) and a high dip vertical throw (ramp).
122 The major synthetic reverse fault was associated with a conjugate minor fault. Two faults formed in the
123 upper brittle layer which were directly linked to the lower brittle layer deformation and presented a flat
124 geometry.

125

126 *3.1.2. 1 cm/h of shortening rate*

127 The global geometry was asymmetrical (Fig. 3b), and the structure looked like a fault-bend fold. The
128 lower brittle layer was characterised by a well-developed major synthetic reverse fault (with regard to
129 the mobile plate), associated with a very weak conjugate minor reverse fault. The hanging wall of this
130 major fault generated a wedge which was underthrusting within the upper ductile layer. In the upper part
131 of the model, the deformation was accommodated by reverse fault systems related to this wedge. The
132 upper silicone layer acted as a passive roof thrust and as a decollement level for the uppermost structural
133 level (Bonini, 2001; 2003). The upper brittle layer deformation propagated forward: first, with a small
134 tilted asymmetric pop-up structure located above the basal major synthetic reverse fault, and then, with
135 a small pop-up structure.

136

137 *3.1.3. 0.5 cm/h of shortening rate*

138 The global geometry was strongly asymmetrical (Fig. 3c), and the structure looked like a fault-bend
139 fold. The deformation style evolved with a frontward propagation. The lower brittle level was
140 characterised by a well-developed major antithetic reverse fault (with regard to the mobile plate). At this
141 shortening rate, there were no conjugate fault systems in the lower brittle layer. The upper brittle layer
142 deformation propagated forward: first, with a planar reverse fault, and then, with a steep reverse fault
143 with the same vergence of the lower major brittle fault. In the upper brittle layer, a fault propagation
144 fold accommodated the shortening. The whole deformation was comparable to an active-roof duplex
145 (Couzens-Schultz et al., 2003).

146

147 *3.1.4. Influence of shortening rate*

148 Based on our experiments, we built strain profiles (in compression where $\sigma_v = \sigma_3$) based on the brittle
149 (Sb) and ductile (Sd) strength. Thus, we were able to use the brittle and ductile strength ratio ($SR = Sb/Sd$)
150 (Sd), which has either a high or low value (see Annex 1).

151 At 5 cm/h (i.e. a weak SR), the deformation style in the upper and lower brittle layers was linked by the
152 middle ductile layer (see § 3.1.1. above). At this shortening rate, the resistance of the middle ductile
153 layer did not allow for an efficient decollement level between the two brittle layers, and instead,
154 favoured a coupled deformation (see Annex 1). The global geometry was not dominated either by the
155 brittle or ductile layers, and the shortening was accommodated by diffused deformation (i.e. a
156 symmetrical global geometry with a pop-up shape).

157 At 1 cm/h, the deformation style in both the upper and lower brittle layers was not completely
158 decoupled. The middle ductile layer promoted a frontward propagation of the deformation in the
159 uppermost sand layer, as seen in the experiment with a shortening rate of 0.5 cm/h. As in the experiment
160 with a shortening rate of 5 cm/h, a very weak conjugate minor reverse fault in the lower brittle layer was
161 associated with a fault in the upper brittle layer. A transitional behaviour was observed at this shortening
162 rate.

163 At 0.5 cm/h (i.e. a strong SR), the deformation recorded in the upper brittle layer was decoupled from
164 the lower one (see § 3.1.3. above). Because of a weak Sd and therefore, a high stress ratio (SR) value,
165 the middle ductile layer became an efficient decollement level. The brittle sand layers were then
166 decoupled. A frontward propagation of the localised deformation occurred and consequently, an
167 asymmetrical geometry developed.

168 Six different shortening rates were tested (from 0.25 to 10 cm/h). We decided to retain a shortening rate
169 of 0.5 cm/h because: (i) the structure created in the lower brittle layer was either a synthetic or an
170 antithetic reverse fault (with regard to the mobile plate), meaning that the basal silicone putty acted as
171 an efficient decollement; (ii) a frontward propagation was developed in the upper brittle layer, meaning
172 that the silicone putty acted as an efficient decollement level between the two brittle layers; (iii)
173 shortening was accommodated by propagation folding and faulting, according to real thin-skinned fold-
174 and-thrust belts evolutions and (iv) according to the scaling of our experiments (see Table 1).

175

176 *3.2. Homogeneous synkinematic sedimentation*

177 In order to represent synkinematic sedimentation, sand was continuously sprinkled horizontally on the
178 top of the model during the deformation (alternating between a blue and white colour). The
179 sedimentation velocity was based on the most common rates observed in nature (Fig. 4). We used the
180 following ratio to define this rate: $R = V_s / V_u$, where R is the ratio between the velocity of the
181 sedimentation (V_s) and the velocity of the structure uplift (V_u) (see Barrier et al., 2002). In a natural
182 environment, it is possible to recognise four main situations related to the type of sedimentation in
183 relation with the base level and the variation of accommodation space situated below: 1) no creation of
184 accommodation space and then, no sedimentation (here, the ratio R is equal to 0); or 2) less creation of
185 accommodation space than creation of topography, and thus, less sedimentation than uplift ($0 < R < 1$);
186 3) the same amount of creation of accommodation space as creation of topography, and consequently,
187 the same amount of sedimentation as uplift ($R = 1$); or 4) more creation of accommodation space than
188 creation of topography, and thus more sedimentation than uplift ($R > 1$). In our experiments, we only

189 tested the influence of sedimentation without erosion, and our R ratio ranged from 0 to 2 (Fig. 4). In
190 order to estimate V_s and V_u , we manually measured the difference between the topography of the
191 experiment and a fixed point at a regular time interval. This evolution was checked on a cross-section at
192 the end of the experiment.

193 In general, the upper and lower structures were superimposed (see Fig. 5) and had the same vergence
194 (except in Fig. 5a4). The lower brittle layer was characterised by a flat and ramp geometry with a very
195 weak vertical throw, in contrast with the uplifted upper structures. The synkinematic brittle layers
196 followed the deformation of the upper prekinematic brittle layer. From the bottom to the top, we
197 observed a progressive decrease of dip in the synkinematic layers. The homogeneous synkinematic
198 sedimentation located in the hanging wall was deformed and pinched out toward the thrust system while
199 in the footwall, the thickness of the sediments was more constant with a flatter geometry. The major
200 basal reverse faults in the lower brittle layer and the major reverse faults in the upper brittle layer were
201 associated with a sheet of silicone at the base of the hanging wall, as seen in the experiment without
202 sedimentation (Fig. 3). The silicone layers were thicker at the base of the ramp, in both the lower and
203 upper ductile layers, and also at the front of the hanging wall wedge in the upper ductile layer.

204

205 *3.2.1. 5 cm of shortening*

206 For $R = 3/4$ and $R = 1$, the major influence of the homogeneous synkinematic sedimentation was to
207 generate a single major thrust in the uppermost brittle layer (Figs. 5a2, 5a3). The throw and angle of this
208 major thrust increases with an increasing R (see Barrier et al., 2002). For $R = 2$, several faults were
209 created in the uppermost brittle layer (Fig. 5a4). This means that at a low sedimentation velocity ($R=3/4$,
210 and $R = 1$), a flexural deformation prevails, while at a high sedimentation velocity ($R=2$), brittle
211 deformation is predominant (Nalpas et al., 1999). In the present study, the lower brittle layer was
212 characterised by a well-developed fault-bend fold without a conjugate fault. At a high R, the major basal
213 thrust evolved into a well-developed flat hanging wall.

214

215 *3.2.1.1. $R = 0$.* Please refer to § 3.1.3. and Fig. 3c.

216

217 *3.2.1.2. $R = 3/4$.* The lower structure was characterised by a major antithetic thrust (with regard to the
218 mobile plate) with an angle of 15° (Fig. 5a2). In the upper prekinematic brittle layer, one reverse fault
219 (with the same vergence of the thrust in the lower brittle layer) was developed with an average angle of

220 18°, and with a ramp anticline in the hanging wall. This fault kept growing throughout the synkinematic
221 upper brittle layers without a significant change in the dip.

222

223 *3.2.1.3. R = 1.* The basal structure was characterised by a major antithetic thrust (with regard to the
224 mobile plate) with a ramp angle of 13° (Fig. 5a3). In the upper prekinematic brittle layer, one thrust was
225 developed with an average angle of 21° (with the same vergence of the thrust in the lower brittle layer).
226 This fault kept growing throughout the synkinematic brittle layer with an increasing dip up to 63° (see
227 Barrier et al., 2002). A large sheet of silicone was preserved between the footwall and the hanging wall
228 of this structure. The crest of this structure was very narrow, while the flanks were steeped. Note that in
229 the upper brittle layer, the deformation was associated with vertical displacement and uplift, while in the
230 lower brittle layer, the deformation was associated with horizontal displacement.

231

232 *3.2.1.4. R = 2.* The basal structure was characterised by a major antithetic thrust (with regard to the
233 mobile plate) with a ramp angle of 11° (Fig. 5a4). In the upper prekinematic brittle layer, one major
234 reverse fault (with an opposite vergence to the thrust in the lower brittle layer) was developed with an
235 average angle of 35° at the base, and was divided into two segments with a dip that progressively
236 increased its dip in the synkinematic brittle layers, up to 47° at the top. A conjugate reverse fault was
237 developed in its hanging wall during sedimentation of synkinematic brittle layers and stopped
238 progressively. A newly formed reverse fault was created in the synkinematic brittle layers during the
239 last stages of deformation. This fault was located in the footwall of the major reverse fault that
240 developed in the upper brittle layers, and was ramified to the base of this major reverse fault. In contrast
241 with the previous experiment, the deformation of synkinematic brittle layers did not show flexure with a
242 significant variation in layers dip.

243

244 *3.2.2. 10 cm of shortening*

245 *3.2.2.1. R = 0.* The vertical colours in the lower silicone layer were only used as passive markers in
246 order to analyse the deformation. The lower brittle layer was characterised by a major synthetic reverse
247 fault (with regard to the mobile plate, see § 3.1.4) with a significant horizontal throw creating a large
248 hanging wall flat (Fig. 5b1). The curvature of the hanging wall associated with the thrust was less
249 significant than seen in the previous experiment, and produced a large deformation. The upper sand
250 layer was affected by a large domain of a complex deformation characterised by synthetic and antithetic
251 reverse faults, fault-propagation fold and detachment fold, localised in both the hanging wall and the

252 footwall of the basal thrust. In the footwall domain, the deformation recorded a stronger shortening than
253 observed in the hanging wall domain, as illustrated by the pop-down structure. Just above the lower
254 thrust, extensional structures were developed and were associated with the uplift of silicone (diapiric
255 effect).

256 3.2.2.2. $R = 3/4$. The deformation was complex in the lower brittle level. One major antithetic thrust
257 (with regard to the mobile plate) was developed first, with a significant horizontal throw creating a large
258 hanging wall flat (Fig. 5b2). A conjugate high dipping minor reverse fault was developed during the last
259 stage of the deformation. The upper silicone layer was cut by the uplift of the lower brittle layer in the
260 direction of the base of the upper prekinematic brittle layer, related to the movement on the basal faults.
261 The base of the upper structure was gently symmetrical and evolved into a more complex deformation
262 toward the top. A first reverse fault was developed during the early stage of the deformation, with an
263 opposite vergence to the major thrust in the lower brittle layer. A second high dipping reverse fault, with
264 the same vergence to the major thrust in the lower brittle layer, cut the first one. The deformation of the
265 synkinematic brittle layers showed the same flexure in both the hanging wall and footwall.

266
267 3.2.2.3. $R = 1$. A major synthetic thrust (with regard to the mobile plate) developed at the base of the
268 model (Fig. 5b3). This thrust showed a horizontal hanging wall ramp, like a flat geometry, and a dip
269 hanging wall flat, like a ramp geometry. A conjugate high dipping minor reverse fault was developed
270 during the last stage of the deformation. The upper silicone layer was cut by the uplift of the lower
271 brittle layer in the direction of the base of the upper prekinematic brittle layer, related to the movement
272 on the basal faults. In the upper part of the model, the shortening was accommodated by a huge reverse
273 fault (with the same vergence to the major thrust in the lower brittle layer) with an angle of 31° at the
274 base, and which evolved upward to 59° in the synkinematic brittle layers.

275
276 3.3. *Local synkinematic sedimentation*

277 For the sedimentation in these experiments, we used the same method as in the homogeneous
278 synkinematic sedimentation. However, synkinematic sedimentation ($R = 1$) was deposited only on the
279 footwall or only on the hanging wall, respectively, with the lower brittle thrust geometry (Fig. 6). In
280 Figure 6, all the experiments were presented with the same basal brittle thrust vergence so that in all
281 cross-sections, the hanging wall of the lower brittle thrust was in the left side, and the footwall in the right
282 side. This disposition of the experiments was presented in order to better compare the effect of the
283 localised synkinematic sedimentation on the evolution of upper brittle layer deformation. Because we

284 had chosen a velocity that allows the development of a synthetic or antithetic reverse fault in the lower
285 brittle layer, with regard to the mobile plate (see § 3.1.4), it was not a problem to change the position of
286 the mobile plate.

287 The main characteristics observed were a well-developed major thrust in the lower brittle layer and
288 several thrust propagations in the upper brittle layer, where synkinematic sedimentation was not applied.

289

290 *3.3.1. Synkinematic sedimentation in the hanging wall domain*

291 *3.3.1.1. 5 cm of shortening.* One thrust was developed in the lower brittle layer (Fig. 6a2). In the upper
292 brittle level, the shortening was only accommodated in the domain with no sedimentation (footwall).

293 The deformation propagated frontward (in the direction of the footwall, see § 3.1.) with the development
294 of two reverse faults (with the same vergence as the basal thrust), the second fault with a major throw.

295 The central part of the model, above the ramp anticline of the basal thrust, was characterised by an
296 extensional zone, which was localised on the main anticline of the upper brittle layer.

297

298 *3.3.1.2. 10 cm of shortening.* With an increase in shortening, the deformation was accommodated by a
299 greater number of more complex structures (Fig. 6b2). As already observed for a shortening of 5 cm, a
300 major thrust is developed first in the lower brittle layer with a flat hanging wall, and then, a small
301 reverse fault is developed frontward. In the upper brittle level, the shortening was only accommodated
302 in the domain with no sedimentation (footwall). The deformation first propagated frontward with the
303 development of two reverse faults with the same vergence as the basal thrust (the second one had the
304 major throw). Then, the third structure was a small asymmetrical pop-up with an opposite vergence to
305 the other structures. An extensional domain developed in the upper brittle layer, above the ramp
306 anticline of the basal thrust, was affected the upper brittle layer.

307

308 *3.3.2. Synkinematic sedimentation in the footwall domain*

309 *3.3.2.1. 5 cm of shortening.* One thrust was developed in the lower brittle layer (Fig. 6a3). The hanging
310 wall ramp of this thrust was uplifted, in contrast with the experiment with 5 cm of shortening, and
311 sedimentation in the hanging wall domain (Fig. 6a2). Associated with this thrust, an anticline grew
312 backward. The middle silicone was cut off by the contact between the uplifted basal thrust and the
313 prekinematic upper brittle layer. In the upper brittle layer, the shortening was first accommodated by a
314 step reverse fault located above the crest of the basal anticline, with the same vergence of this basal
315 thrust, and then by two reverse faults which propagated backward, with an opposite vergence to the

316 basal thrust. The main basal structure defined an underthrusting wedge within the upper silicone layer,
317 which acted as an active roof duplex and as a decollement level for the uppermost structural sequence.

318

319 *3.3.2.2. 10 cm of shortening.* Several thrusts developed in the lower brittle layer (Fig. 6b3). One major
320 thrust associated with a huge anticline was developed, which was faulted at its crest with the same
321 vergence. A second thrust developed backward with the same vergence. In the upper brittle layer, a
322 complex deformation was localised in the hanging wall, and propagated backward with an oscillating
323 vergence, with regard to the thrusts in the lower brittle level. The first reverse fault was created above
324 the lower brittle ramp anticline, with the same vergence of the basal thrust, and then the over-structures
325 (fault-propagation fold) were developed with an opposite vergence. The main basal structure was like a
326 wedge inserted into the upper silicone layer, which acted as a passive roof thrust and as a decollement
327 level for the uppermost structural sequence.

328

329 **4. Discussion**

330 *4.1. Influence of homogeneous synkinematic sedimentation*

331 The main observation of these experiments with homogeneous sedimentation, either with 5 cm or 10 cm
332 of shortening, is the absence of frontward or backward propagation of the deformation in the upper
333 brittle layer, contrary to the experiments performed without sedimentation, or with local sedimentation.
334 This is directly related to the evolution of the strength profile in the upper brittle layer, and thus, is
335 related to sedimentation (see Annex 1). When there is no sedimentation, the upper layer strength is the
336 same everywhere in the model (Fig. 7a), and when there is sedimentation around the structure, the
337 strength increases proportionally to the amount of sedimentation in the footwall and hanging wall (Fig.
338 7b).

339 The deformation in the upper brittle layer is concentrated in one major fault above the basal structure:
340 the fault dip of this major fault increases progressively during sedimentation. This is also related to the
341 effect of sedimentation and is in good agreement with Barrier et al. (2002).

342 In our experiments, we observed a large variation in the upward thrust dip linked to the ratio R and the
343 amount of shortening in the upper brittle layer. In the experiment where $R = 2$, (e.g. with a high rate of
344 sedimentation), the upper brittle layer strength increases very rapidly during the first stage of the
345 deformation and favours a brittle behaviour. Consequently, we observed several reverse faults cutting
346 the synkinematic brittle layer, with very low flexures between the faults.

347 In the lower brittle layer (for experiments with 5 cm of shortening), when the rate of sedimentation (R)
348 is increasing, the thrust dip decreases from 15° ($R = 3/4$) to 11° ($R = 2$). The same trend is seen in the
349 experiments with 10 cm of shortening. Related to the increase of R , the shortening in the lower brittle
350 layer is accommodated by a horizontal evolution of the structure, while in the upper brittle layer, it is
351 accommodated by a vertical evolution of the structure and uplift. This is directly related to the stress
352 induced by sediment load. The horizontal movement of the basal structure produces a penetration of a
353 wedge in the upper silicone layer (underthrusting), which induces a variation in thickness, with an
354 increase at the basal fault front and a decrease over the frontal limb of the anticline.

355

356 *4.2. Influence of local synkinematic sedimentation*

357 The main observation of these experiments, either for 5 cm or 10 cm of shortening, is the absence of a
358 propagation of the deformation in the upper brittle layer where sedimentation is applied, in contrary to
359 the domain without sedimentation. This is in good agreement with the evolution of the strength profile
360 in the upper brittle layer, related to sedimentation and brittle strength increases of the upper brittle layer
361 (see Annex 1, Fig. 7c). Where there is no sedimentation, the upper brittle layer is not as strong than
362 where there is sedimentation (Fig. 7c), and therefore, the deformation in the upper brittle layer is
363 concentrated in the weakest zone, without sedimentation, or frontward or backward (with regard to the
364 major basal structure).

365 The deformation of the lower brittle layer shows the same evolution as the upper brittle layer, with
366 propagation of the deformation and creation of a new fault in the zone where there is no synkinematic
367 sedimentation. This synkinematic sedimentation applied above the footwall, or above the hanging wall,
368 promotes a forced decoupling between the upper and lower brittle layers where there is no
369 sedimentation. The reason for this is the same as before: it is due to an increase in the lower brittle layer
370 strength (Fig. 7c).

371 This means that sedimentation influences not only the evolution of the shape of one structure, but also
372 the localisation of the deformation.

373

374 *4.3. Comparison between field examples and analogue modelling*

375 In the Tarija basin example, numerous compressive structures are developed in association with two
376 superimposed decollement levels and sykinematic sedimentation. The vergence of these structures is
377 mostly eastward. They are composed of a lower decollement level in the Silurian Kirusillas shales and a
378 second decollement level in the Los Monos Devonian shales (Fig. 8). The deformation started at about

379 8.5-9 Ma with the formation of the El Pescado range and propagated eastward until 2.7 Ma, when the
380 Arguarague range lift started (Echavarria et al., 2003). During this period, synkinematic sedimentation
381 was accumulated, with a progressive decrease in thickness from west-to-east.
382 In the San Antonio Range example, a fault-bend fold was initiated in the Silurian shales and propagated
383 upward throughout the upper competent units, with an eastward vergence, until reaching the upper
384 incompetent layer (Devonian shales). The ramp anticline of this structure is cut by a second reverse
385 fault, which is steeper than the major basal structure. The upper part of the San Antonio Range (from the
386 Lower Permian to the Quaternary) is a more symmetric structure with a big vertical amplification (Fig.
387 8).
388 In the Arguarague Range example, the lower thrust was initiated in the Silurian shales and had a classic
389 fault-bend fold geometry. The upper part of the Arguarague Range shows the development of a reverse
390 fault, with the same vergence as the basal one. The main system is asymmetric with an eastward
391 vergence.
392 From our modelling results, we suggest that synkinematic sedimentation was the major parameter to
393 explain this variation in structure growth: (i) when synkinematic sedimentation velocity is low, the
394 development of the structure is mainly asymmetric with an easy thrusting, like in Figure 5a2, and (ii)
395 when synkinematic sedimentation velocity is high, the development of the structure is mainly
396 symmetric with a more vertical growth, like in Figure 5a2.
397 The implication of these interpretations is that from west-to-east, in the case of the Tarija basin, the
398 eastward decrease of the synkinematic sedimentation produces a large variation in compressive
399 structures. This is directly applicable at the foreland basin scale to explain the evolution of the structure
400 in the direction of the foreland (see Fig. 1c).

401

402 **5. Conclusions**

403 The main results are related to the rate of deformation, the velocity of synkinematic sedimentation, the
404 localization of synkinematic sedimentation and the comparison with nature.
405 - The deformation rate strongly influences a change in deformation style in analogue modelling. At a
406 high shortening rate, the strong resistance of the ductile layer does not allow for an efficient decollement
407 level and favours a coupled and symmetric deformation. At a low shortening rate, the weak resistance of
408 the ductile layer allows the decoupling between the brittle layers, and favours an asymmetrical
409 deformation, with the creation of an active roof duplex.

410 This decoupling favours the flow of the silicone layers, generating variations in thickness which allows
411 the system to accommodate the shortening, and then, produces an underthrust of the wedge within the
412 upper silicone layer, and therefore, compensates for the brittle deformation.

413 - The main observations from the experiments with homogeneous sedimentation suggest: (i) with
414 sedimentation, the deformation in the upper brittle layer cannot propagate either frontward or backward,
415 in relation to strength increases, (ii) with the increase of sedimentation velocity, the fault dip of the
416 major upper brittle fault increases progressively.

417 - With local sedimentation, the domain without sedimentation promotes the frontward or backward
418 propagation of the deformation in both the upper and lower brittle layers. Within the sedimentation
419 domain, synkinematic sedimentation inhibits the creation of such a structural evolution. The strength
420 ratio between these two domains is not equal, and the deformation is localised where the resistance is
421 weakest.

422 - As suggested by the Subandean natural examples, the variation of synkinematic sedimentation
423 produces a large variation in compressive structures; asymmetric thrusting with low velocity
424 synkinematic sedimentation, and mainly symmetric structure and vertical growth, with high velocity
425 synkinematic sedimentation.

426

427 **Annex 1:**

428 Strength profiles

429 Previous works have analyzed the effects of brittle-ductile coupling in terms of relative strength
430 between the brittle and ductile layers in compressive settings (Bonini, 2001; Smit et al., 2003). We have
431 chosen to apply the same approach.

432 The vertical normal stress (σ_v) at the base of the brittle layers is given by

$$433 \sigma_v = \rho \cdot g \cdot T_b \quad (1)$$

434 where ρ is the brittle layer density, g is the acceleration due to gravity and T_b is the thickness of the
435 brittle layer. Because $\sigma_v = \sigma_3$ in compression, the maximum differential stress is

$$436 \sigma_1 - \sigma_3 = 2 \cdot \rho \cdot g \cdot T_b \quad (2)$$

437 Thus, the maximum differential stress in the brittle layer is only controlled by the layer thickness (T_b)
438 and its density (ρ).

439

440 The shear stress (τ) in the ductile layer is given by

$$441 \tau = \mu \cdot V / T_d \quad (3)$$

442 where μ is the viscosity of the ductile layer, V is the shortening rate and T_d the thickness of the ductile
443 layer.

444 A strength profile is built according to these equations in order to define the strength ratio (SR) between
445 the brittle (S_b) and ductile (S_d) strength, e.g. $SR = S_b/S_d$ (Fig. 9).

446 The ductile layer is often a potential decollement layer. In the case of a weak shortening velocity, S_d is
447 very low and promotes an effective decollement level. Whereas with a high shortening velocity (strong
448 S_d), the ductile layer can not produce a decollement layer (Fig. 10).

449

450

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455

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525 **Fig.1.** (a) Geological map of the central Andean compressive system (after Horton, 1999), and (b) focus
526 geological map of the Bolivian sub-Andean thrust-belt (modified from Dunn et al., 1995). (c) Cross-
527 section of this system (see red line in Fig. 1b for location) showing the main structural organisation
528 (modified from Labaume and Moretti, 2001).

529

530 **Fig.2.** (a) Experimental apparatus and (b) sketch of homogeneous and local synkinematic sedimentation
531 depositions. R is the ratio between the velocity of the sedimentation: V_s , and the velocity of the
532 structure uplift: V_u ($R = V_s / V_u$, see Barrier et al., 2002).

533

534 **Fig.3.** Cross-sections of experiments for (a) 5 cm of shortening, (b) 1 cm of shortening and (c) 0.5 cm of
535 shortening. S = total shortening and VD corresponds to the Velocity Discontinuity. A thick black line
536 symbolizes the mobile wall and the mobile plate.

537

538 **Fig.4.** Simple cross-sections showing the relationship of the ratio R between sedimentation velocity
539 (V_s) and uplift velocity (V_u) and the base level.

540

541 **Fig.5.** Cross-section of experiments with homogeneous synkinematic sedimentation for (a) column with
542 5 cm of shortening and (b) column with 10 cm of shortening. The ratio R , between sedimentation
543 velocity (V_s) and uplift velocity (V_u), is related to each experiment presented in the same line. VD
544 corresponds to linear Velocity Discontinuity.

545

546 **Fig.6.** Cross-section of experiments with local synkinematic sedimentation for (a) column with 5 cm of
547 shortening and (b) column with 10 cm of shortening. The ratio R , between sedimentation velocity (V_s)
548 and uplift velocity (V_u), is related to each line of experiment. VD corresponds to linear Velocity
549 Discontinuity.

550

551 **Fig.7.** 3D sketch and strength profiles of the experiments with (a) 5 cm of shortening and without
552 synkinematic sedimentation, (b) 5 cm of shortening and with homogeneous synkinematic sedimentation,
553 and (c) 5 cm of shortening and with local synkinematic sedimentation. The number and letter show the
554 evolution of the deformation.

555

556 **Fig. 8.** Field examples of thrust structures related to two decollement levels, from the Tarija basin
557 (Argentina; modified from Echavarría et al. 2003).

558

559 **Fig. 9.** Strength profiles of our analogue model for a shortening rate ranging from 0.25 to 10 cm/h.

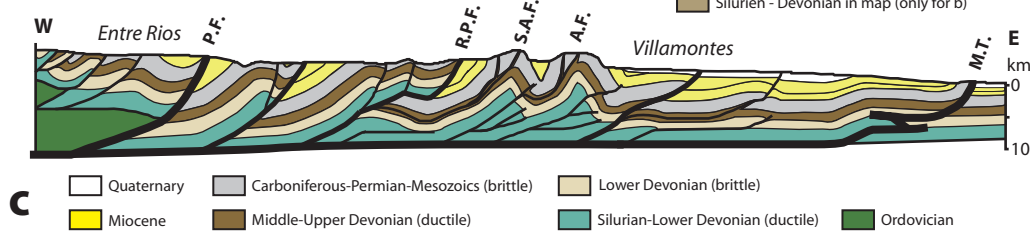
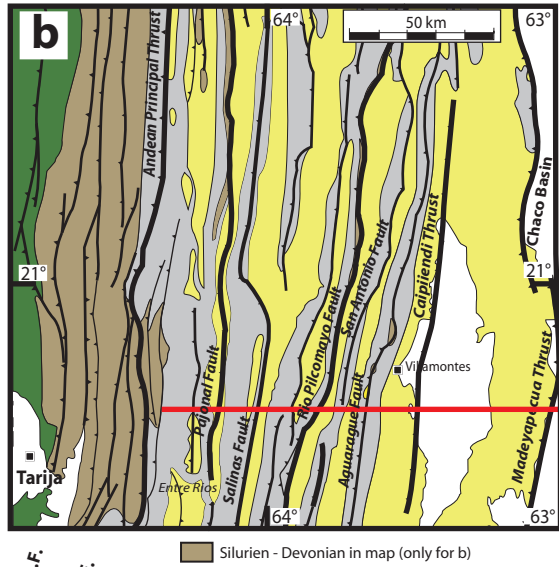
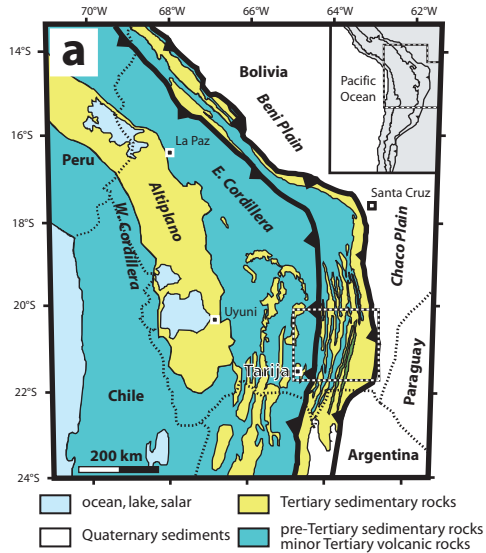
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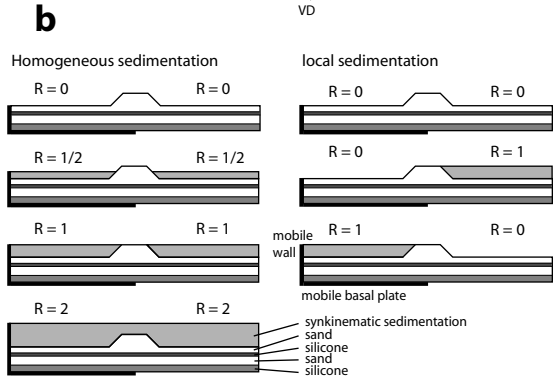
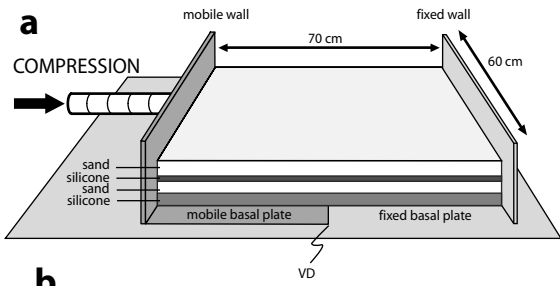
561 **Fig. 10.** Plots of relative strength between the lower brittle and lower ductile layers (black line) and
562 between the upper brittle and upper ductile layers (dashed line) for six different shortening rates
563 (ranging from 0.25 to 10 cm/h). SR is the ratio between the brittle (S_b) and ductile (S_d) strength. The
564 background colour domains correspond to whether or not the ductile layer was able to create an
565 effective decollement level.

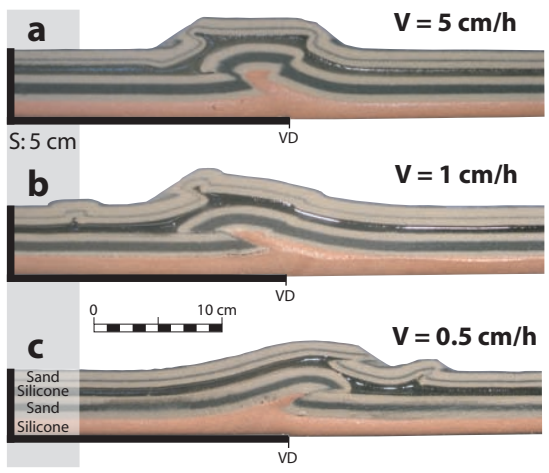
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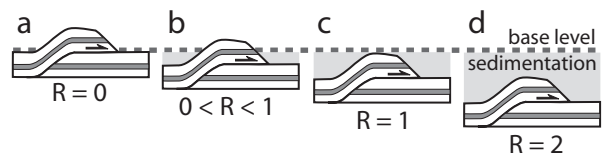
567 **Table 1.** Scaling Parameters.

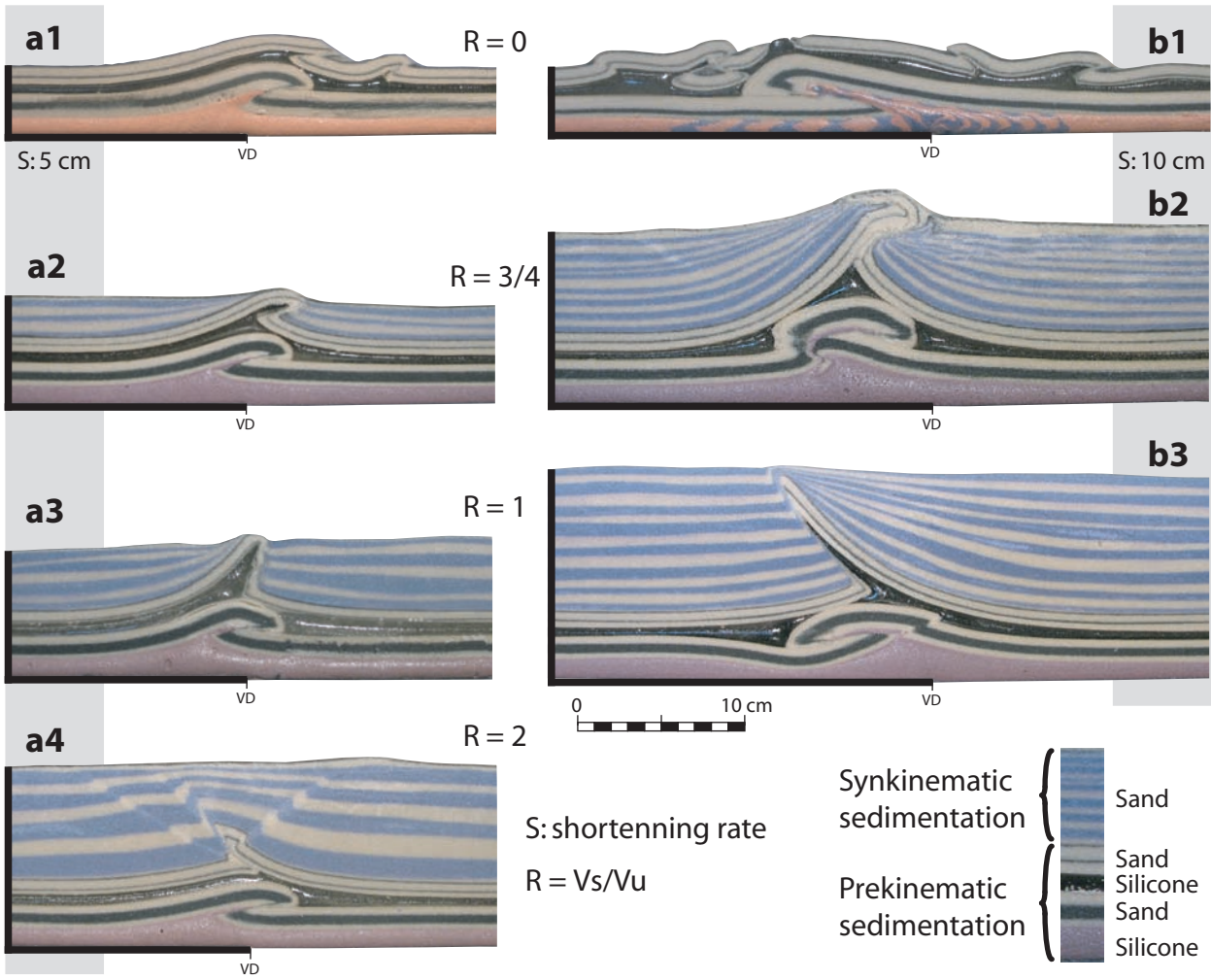
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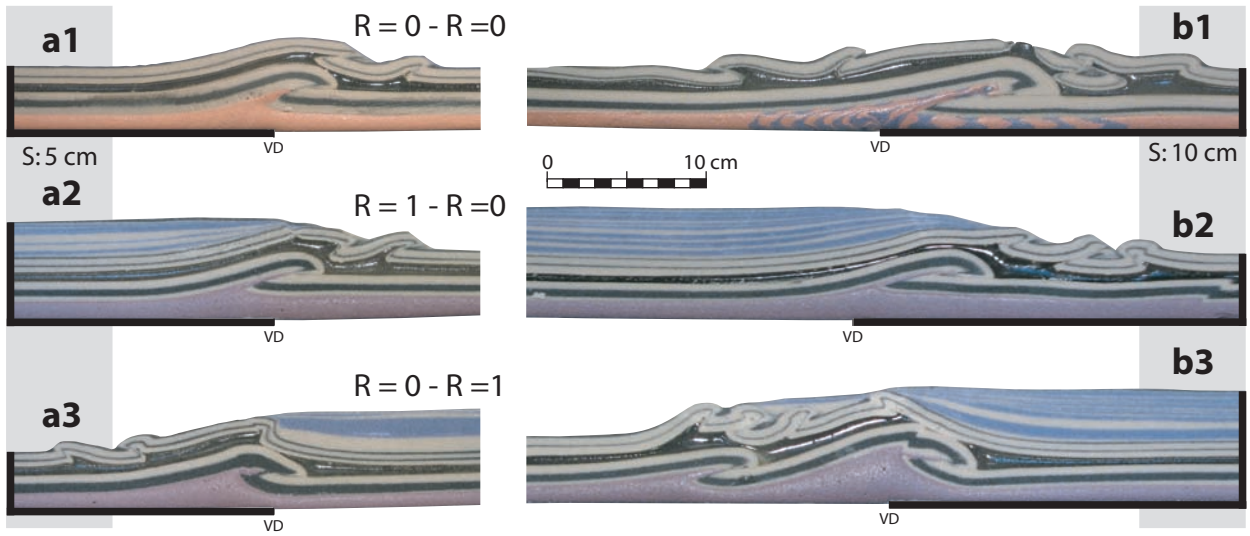


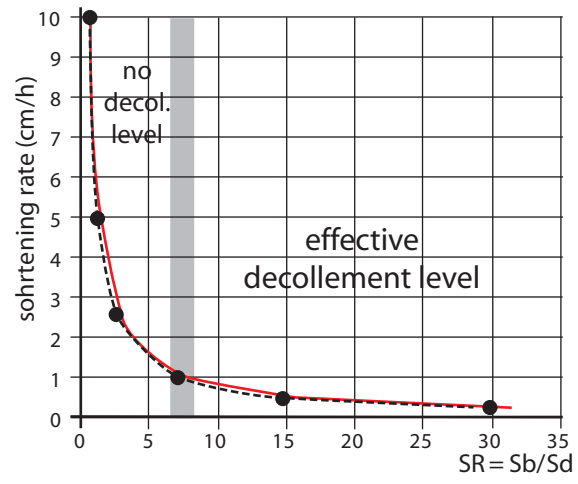


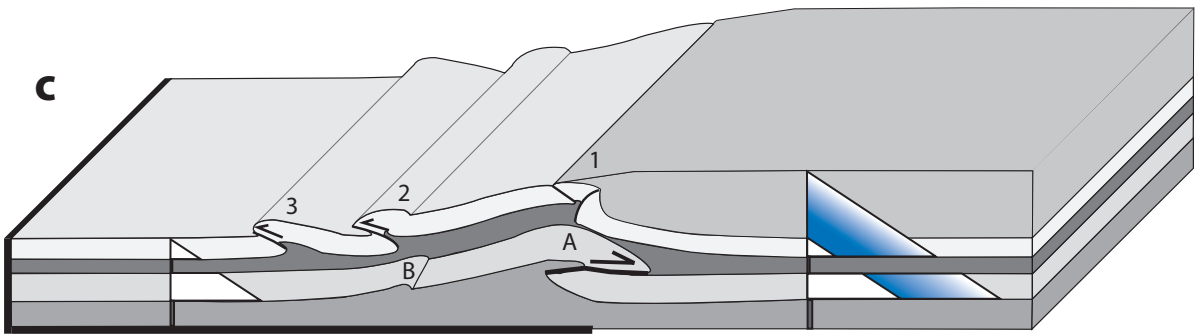
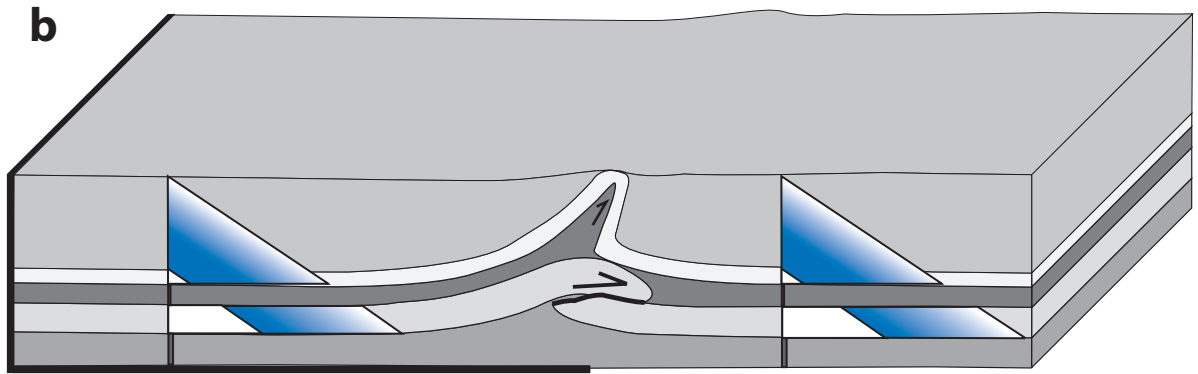
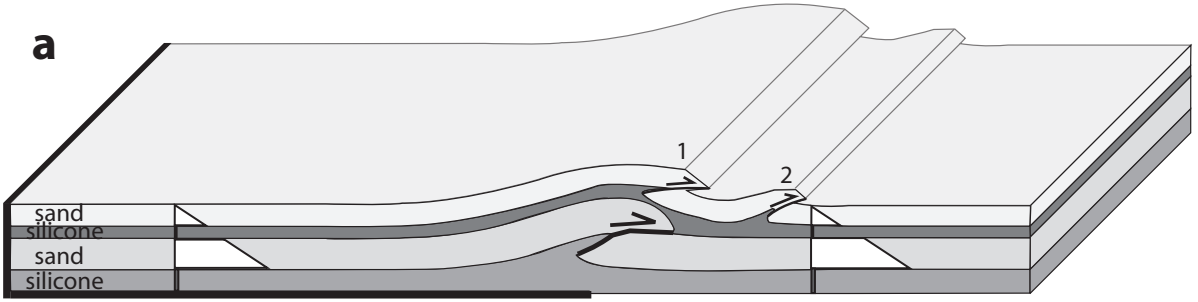


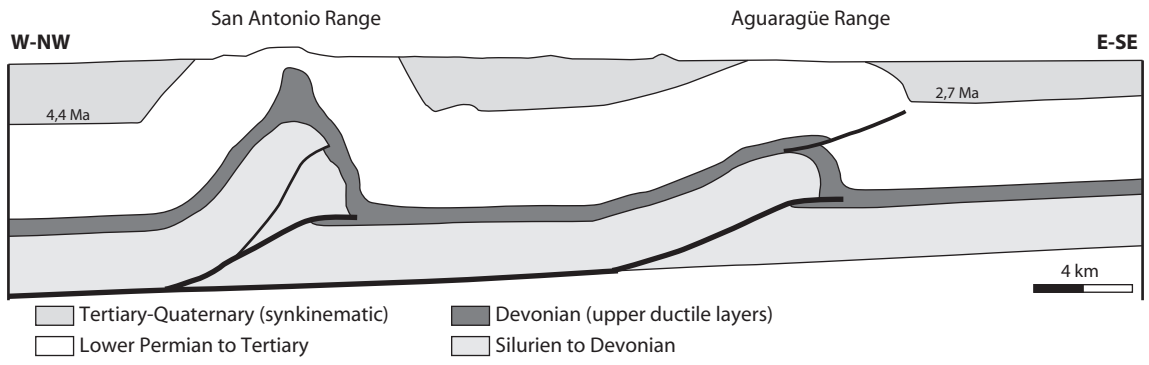


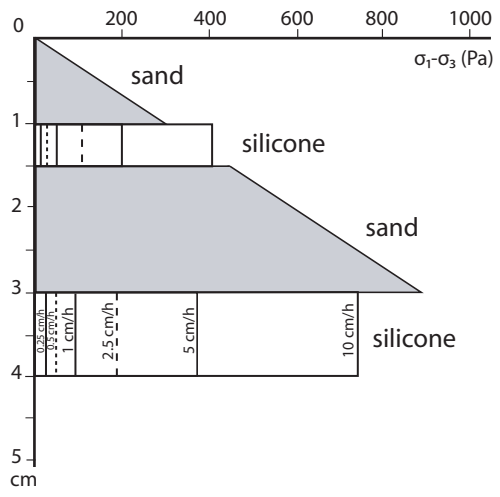


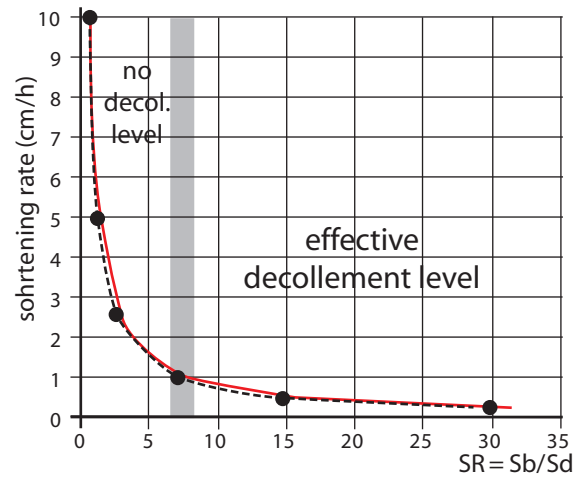












	L (m)	g (m/s²)	ρ (kg/m³)	μ (Pa.s)	V (m/s)	t (s)	σ (Pa)
Nature	1000 (1km)	9.81	2300	10 ¹⁷ - 10 ¹⁹	3.2x10 ⁻¹⁰ (1 cm/y)	1.6x10 ¹³ (0.5 Ma)	2.2x10 ⁷
model	0,01 (1cm)	9.81	1400	10 ⁴	1.4x10 ⁻⁶ (0.5 cm/h)	3.7x10 ⁴ (10 h)	1.5x10 ²
model / nature ratio	10 ⁻⁵	1	0.6	10 ⁻¹⁴	4x10 ³	2.6x10 ⁻⁹	6x10 ⁻⁵