

# 1 Growth folds above propagating normal faults

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## 9 **Keywords**

10 Fault-propagation fold, forced fold, normal fault, fault-related fold, rifting, extension, salt-  
11 influenced rift

12

## 13 **Abstract**

14 Growth folds developed above the upper tips of propagating normal faults are ubiquitous in  
15 extensional settings, especially during the early phases of extension and in salt-rich basins. As  
16 growth folds develop as slip accumulates on the underlying normal fault, the geometry and size  
17 of the fold changes, reflecting the dip, throw and displacement rate of the underlying normal  
18 fault and the thickness and rheology of the overlying cover. This has a marked impact on basin  
19 physiography and thus, the architecture and distribution of synkinematic strata but also the  
20 geometry and density of secondary deformation. This study analyses a large dataset of fault-  
21 propagation and forced folds in nature and models to: (i) characterise their diagnostic features;  
22 (ii) investigate the controls on their geometry, size and differences; and (iii) describe how they  
23 grow with increasing extensional strain. The examined dataset demonstrates that larger growth  
24 folds are associated with larger fault throws, thicker and weaker cover, whereas small throws,

25 thin and strong brittle cover generates smaller folds. We show that the geometry and size of  
26 growth folds vary through time; the width of the fold is established relatively early during fold  
27 growth, whereas the fold amplitude increases gradually and incrementally with fault throw. The  
28 fold width and amplitude become increasingly similar during fold evolution, until they are  
29 breached by the underlying normal fault. We also derive a number of parametric equations that  
30 are potentially powerful tools in estimating unknown fold geometry and size in profile by  
31 utilising other known structural and stratigraphic parameters for both salt-free and salt-rich  
32 settings. As forced folds are typically found in salt-rich basins, forced fold geometry is often  
33 affected by across- and along-strike salt flow, so that these folds have typically larger fold  
34 amplitudes and widths compared to fault-propagation folds for the same fault throw. In addition,  
35 we discuss how fault growth models (i.e. constant-length vs. isolated) may impact the three-  
36 dimensional evolution of growth folds. This work also highlights that growth folds are likely  
37 more common than they have previously been credited for. Although weak and ductile cover  
38 strata and low strain rates promote growth folding, the dataset illustrates that growth folds may  
39 occur in brittle, strong cover and in regions with high strain rates. However, the underlying  
40 controls on fold occurrence remain tentative. This review has implications for hydrocarbon  
41 trapping and reservoir distribution, structural restoration and estimating strain in salt-rich and  
42 salt-free extensional settings.

43

## 44 **1. Introduction**

45 Fault-related folds are ubiquitous in extensional settings (Fig. 1; Appendix A) and strongly  
46 control basin physiography through time. One of the most common fault-related folds,  
47 particularly during the early phases of extension are ‘growth folds’ (Fig. 2) (e.g. Gawthorpe and  
48 Leeder, 2000; Jackson and Lewis, 2016). Growth folds develop above the vertical tips of  
49 upward-propagating normal faults and may be classified as either: ‘fault-propagation folds’ or

50 ‘forced folds’. Where deformation is predominantly faulted at depth but gradually transitions  
51 upwards into a distributed zone of folding, we use the term ‘fault-propagation folding’ (Fig.  
52 2A; after Withjack et al., 2002; cf. Withjack et al., 1990; Gawthorpe et al., 1997) . Where the  
53 deformation at depth is faulted but transitions abruptly to folding at shallow levels, we use the  
54 term ‘forced folding’ (Fig. 2B; sensu Stearns, 1978; cf. Withjack and Callaway, 2000; Withjack  
55 et al., 2002).

56 Fault-propagation and forced folds grow as slip accumulates on the underlying fault at depth,  
57 with concomitant changes in the geometry and size of the folds. This has a marked impact on  
58 the architecture and distribution of synkinematic sediments (e.g. Gawthorpe et al., 1997; Lewis  
59 et al., 2015), as well as the styles of secondary deformation as strain is accommodated within  
60 the fold (e.g. Ameen, 1988; Ameen, 1990; Cosgrove and Ameen, 1999; Sharp et al., 2000a;  
61 Jackson et al., 2006; Tavani et al., 2018). Furthermore, the geometry and evolution of growth  
62 folds has implications for how and where hydrocarbons are trapped (e.g. Mitra, 1990), where  
63 synkinematic strata may be deposited during sea level changes (e.g. Lewis et al., 2015), for  
64 fluid flow in normal fault zones (e.g. Wibberley et al., 2008; Tavani et al., 2018), determining  
65 strain in sedimentary and volcanic basins (e.g. Morley, 1996; Coleman et al., 2017) (e.g.  
66 Morley, 1996; Coleman et al., 2017), and for interpreting fault length for earthquake hazard  
67 evaluation (e.g. Allmendinger and Shaw, 2000; Blakeslee and Kattenhorn, 2013).

68 Despite the importance of growth folds, the relationship between the geometry and size of a  
69 fold as it evolves remains poorly-understood. Whilst physical and numerical models have shed  
70 light on these relationships (e.g. Withjack et al., 1990; Hardy and McClay, 1999; Finch et al.,  
71 2004), documenting a parametric relationship between structural- (e.g. fault throw, fault dip,  
72 etc.) and stratigraphic (e.g. cover thickness, rheology, etc.) -related factors, they are rarely  
73 quantitatively compared to natural examples. Furthermore, several questions regarding growth  
74 folds remain unanswered: how does the geometry and size of growth folds change with ongoing

75 fault slip? Do fault-propagation and forced folds grow differently, and if so, why? And what  
76 controls the occurrence of growth folds?

77 To understand and answer these questions, this study firstly reviews the wealth of recent  
78 literature that has advanced our understanding of these folds, including two key aspects: how  
79 growth folds affect synkinematic strata, and how strain is accommodated within growth folds.  
80 We then quantitatively analyse a large dataset of c. 420 natural examples from > 150  
81 sedimentary and volcanic basins, and c. 250 physical and c. 180 numerical models to  
82 investigate: (i) the controls on the geometry and size of growth folds, (ii) the differences  
83 between fault-propagation and forced folds, and (iii) their occurrence in extensional settings.  
84 To the best of our knowledge, this is the largest known global compilation of growth fold  
85 parameter measurements. We then place these examples into a dynamic context to investigate  
86 how fault-propagation and forced folds grow with increasing slip in two- and three-dimensions.  
87 In addition, we construct a data-driven interpretation method to aid the identification of growth  
88 folds, so that they are not confused with other fault-related folds e.g. frictional drag, inversion  
89 and drape folds (Fig. 1). We also derive a number of parametric equations that are potentially  
90 powerful tools in estimating unknown fold parameters by utilising other known structural and  
91 stratigraphic parameters. Finally, we discuss the implications of our results for hydrocarbon  
92 systems and structural restorations in sedimentary and volcanic basins.

93

## 94 **2. How is the development of growth folds preserved in the stratigraphic record?**

95 Growth folds developed above the tips of upward-propagating normal faults have a marked  
96 impact on the geomorphic development of extensional basins, and thus, the architecture and  
97 distribution of synkinematic strata (e.g. Jackson and Leeder, 1994; Maurin and Niviere, 1999;  
98 Corfield and Sharp, 2000; Sharp et al., 2000b; Corfield et al., 2001; Ford et al., 2007; Lewis et

99 al., 2015). Synkinematic strata therefore provide important information on the geometry and  
100 growth of these folds, such as the amplitude and width through time (cf. Gawthorpe et al., 1997;  
101 Corfield et al., 2001; Patton, 2004; Lewis et al., 2015).

102 As fault-propagation and forced folds grow above the tips of blind normal faults, strata typically  
103 thin towards the fold crest and thicken basinwards (Gawthorpe et al., 1997; Gawthorpe and  
104 Hardy, 2002; Patton, 2004; Lewis et al., 2015; Fig. 3A). Pronounced unconformities develop  
105 towards the fold, whereas off-structure, these same unconformities pass basinward into  
106 conformable sections (Sharp et al., 2000b; Patton, 2004). The geometry and occurrence of these  
107 unconformities are principally controlled by the interplay of eustasy (sea level) and the  
108 structural relief related to growth folding. These in turn, affect the architecture and distribution  
109 of synkinematic sediments (Burbank et al., 1996; Gupta et al., 1999; Corfield et al., 2001; Lewis  
110 et al., 2015).

111 During sea level rise, if the rate of fold amplification is less than the rate of rising sea level, a  
112 synkinematic growth wedge will cover both limbs of the fold. When the rate of fold  
113 amplification is greater than the sea level rise rate, the upthrown fold limb may be sub-aerially  
114 exposed, and strata will onlap onto the dipping fold limb. This forms an off-structure wedge  
115 (Gawthorpe et al., 1997; Gupta et al., 1999; Lewis et al., 2015).

116 During sea level fall, if the subsidence related to growth folding is slower than the rate of falling  
117 sea level, no synkinematic deposition takes place. Where the growth fold is sub-aerially  
118 exposed, the folded prekinematic strata may be eroded (Gawthorpe et al., 1997; Patton, 2004;  
119 Lewis et al., 2015). If synkinematic strata do not cover the entirety of the fold and/or erosion  
120 takes place, information about the fold geometry (and its growth) are not preserved in the rock  
121 record. This partially explains why the growth folds and the structural style of early rifts,  
122 particularly in continental settings, is poorly constrained (cf. Gawthorpe and Leeder, 2000).

123 Sea level changes during growth folding not only affect the architecture of synkinematic units  
124 but also, control whether the synkinematic units are mud- or sand-dominated. Lewis et al.  
125 (2015) speculated two end-member scenarios: (i) growth folding during sea level rise (Fig. 4A),  
126 and (ii) growth folding during sea level fall (Fig. 4B). In the first scenario (Fig. 4A), fold growth  
127 is restricted to periods of sea level rise so that wedge-shaped mudstone-dominated strata onlap  
128 and thin onto the fold. Sand-dominated strata are deposited immediately after fold  
129 amplification, are tabular and have a sharp contact with underlying mudstone-dominated unit  
130 (Lewis et al., 2015). In the second scenario, (Fig. 4B), fold growth is restricted to periods of sea  
131 level fall, so that wedge-shaped sand-dominated synkinematic strata onlap and thin onto the  
132 fold. Mudstone-dominated strata are deposited immediately following fold growth, are  
133 isopachous and have a sharp contact with the underlying sandstone-dominated units (Lewis et  
134 al., 2015).

135 Growth folds developed in basins with rheological heterogeneities, such as thick salt, may have  
136 significantly different geometries and evolve differently from those that form in largely  
137 homogeneous and brittle strata. During early extension, salt may inhibit the propagation of sub-  
138 salt, basement-involved faults, mechanically decoupling them from, but being kinematically  
139 responsible for, forced folds in the supra-salt strata (e.g. Withjack and Callaway, 2000; Ford et  
140 al., 2007; Lewis et al., 2013; Ge et al., 2016; Jackson and Lewis, 2016; Coleman et al., 2017).

141 The size and geometry of these supra-salt forced folds is dependent, at least in part, on the throw  
142 of the sub-salt fault along-strike. Fold size is largest towards the fault centre where sub-salt  
143 throw is greatest and smallest at the fault tips (Fig. 1A in Corfield and Sharp, 2000; cf. Fig. 11  
144 in Sharp et al., 2000b).

145 As the forced fold grows with increasing sub-salt throw, salt flows along-strike below the supra-  
146 salt strata towards the location of maximum throw (Richardson et al., 2005). Supra-salt  
147 synkinematic depocentres are created in the hangingwall of the sub-salt faults, but because of

148 the forced folding and salt swell, they are offset from and thin towards the fault trace (Fig. 5A).  
149 As the sub-salt faults grow and their tips propagate laterally (cf. Jackson et al., 2017), not only  
150 does the along-strike extent of forced folding lengthen but the sub-salt faults may interact with  
151 neighbouring sub-salt faults (Fig. 5B). The linkage of the sub-salt faults may lead to changes in  
152 the position of the throw maxima along-strike stimulating further salt flow towards the new  
153 throw maximum. This draws more salt into the space beneath the supra-salt strata, forming a  
154 larger salt swell (Richardson et al., 2005). Synkinematic depocentres associated with each of  
155 the forced folds and their associated fault segments will subsequently merge to create a single,  
156 large depocentre (Fig. 5C). The newly formed, synkinematic sediments within the large  
157 depocentre will then thin over the crest of the forced fold and salt swell (Richardson et al., 2005;  
158 cf. Fig. 3A). Additional across-strike salt flow may further complicate stacking patterns within  
159 synkinematic strata (cf. Duffy et al., 2013; Warsitzka et al., 2015) and may even mask changes  
160 in sea level and accommodation, independent of regional extension (Duffy et al., 2013).

161 During the latter stages of regional extension, in either salt-rich or salt-free settings, growth  
162 folds may be breached as the upward propagating fault tip breaks-surface. At this point, a  
163 hangingwall depocentre may form next to the fault and strata may thicken into it (e.g.  
164 Gawthorpe et al., 1997; Corfield and Sharp, 2000; Sharp et al., 2000a; Kane et al., 2010; Duffy  
165 et al., 2013; Fig. 3B). Fold breaching may not occur along the full length of the fault  
166 contemporaneously, and instead, unbreached folds of different sizes and geometries may be  
167 located along-strike from breached folds (Fig. 3) (e.g. Gawthorpe et al., 1997; Gupta et al.,  
168 1999; Corfield and Sharp, 2000; Sharp et al., 2000b; Corfield et al., 2001; Khalil and McClay,  
169 2002; Willsey et al., 2002; White and Crider, 2006; Lewis et al., 2013; Lewis et al., 2015; Khalil  
170 and McClay, 2016). Furthermore, the architecture and distribution of synkinematic strata may  
171 vary significantly along-strike within the same extensional basin (Gawthorpe et al., 1997;  
172 Corfield and Sharp, 2000; Richardson et al., 2005; Lewis et al., 2015).

173

174 **3. How is strain accommodated within growth folds?**

175 The distribution of strain in extensional basins controls where faults and folds develop and thus,  
176 the location of synkinematic depocentres and secondary deformation. Growth folds,  
177 particularly during early extension, accommodate a significant proportion of extensional strain,  
178 and as these folds grow, there will be associated changes in the style and distribution of fracture  
179 and fault populations (Fig. 6) (e.g. Sharp et al., 2000a; Tavani et al., 2018).

180 Initially, as a growth fold forms above a propagating normal fault (herein termed ‘master fault’),  
181 secondary normal and reverse faults form in the cover (e.g. Fig. 7 in Koopman et al., 1987; Fig.  
182 13 in Harvey and Stewart, 1998; Fig. 7 in Withjack and Callaway, 2000; Fig. 13 in Jackson et  
183 al., 2006; Fig. 11A in Tavani et al., 2018). These secondary faults may nucleate at the uppermost  
184 tip of the master fault and propagate upwards (e.g. Withjack et al., 1990; Mitra, 1993; Paul and  
185 Mitra, 2015), or nucleate in the folded cover and propagate downwards (Parfitt and Peacock,  
186 2001; Peacock and Parfitt, 2002; Martel and Langley, 2006; White and Crider, 2006) forming  
187 sigmoidal geometries with normal offsets at their base, and reverse offsets at their top (Sharp et  
188 al., 2000a; Sharp et al., 2000b; Jackson et al., 2006; Paul and Mitra, 2015; Fig. 6D).

189 As the fold amplifies, secondary faults are rotated, translated and become inactive as the dipping  
190 fold limb steepens. To accommodate further strain within the fold, new secondary faults form  
191 (e.g. Horsfield, 1977; Mitra and Islam, 1994; Patton et al., 1998; Berg and Skar, 2005; Jackson  
192 et al., 2006; Tavani and Granado, 2014; Paul and Mitra, 2015; Tavani et al., 2018) which often  
193 offset earlier fault generations until they too become inactive and become offset, either by latter  
194 faults or the propagating master fault (e.g. Matthews III and Work, 1978; Palmquist, 1978;  
195 Patton et al., 1998; Sharp et al., 2000a; Berg and Skar, 2005; Fodor et al., 2005; Egholm et al.,  
196 2007).



197 The location of, density of and net slip on the secondary faults through time is directly related  
198 to the along-strike curvature of the growth fold and the underlying master fault. The greater the  
199 along-strike curvature, the denser the population of secondary faults in the immediate  
200 hangingwall (Sharp et al., 2000a). The width of this secondary fault zone, normal to the fold  
201 hinge, is dependent on the geometry of the growth fold and thus, the slip and dip of the  
202 underlying master fault; gently-dipping faults produce broader folds and wider zones of  
203 fracturing compared to steeply-dipping faults (Horsfield, 1977; Withjack et al., 1990; Willsey  
204 et al., 2002; Paul and Mitra, 2015). In addition to secondary faulting, boudinage, sigmoidal  
205 veins and foliation textures may develop to accommodate flexural slip along bedding planes  
206 (Fig. 11 in Gross et al., 1997; Fig. 10 in Lynch et al., 1998; Sharp et al., 2000b; Fig. 6A). Where  
207 flexural slip cannot take place, fracturing and faulting increases (cf. Couples and Lewis, 1999;  
208 Fig. 6B - C).

209 During the latter stages of fold growth, the dipping fold limb may become very steep and  
210 gravity-induced thin-skinned faults may develop (cf. Stewart et al., 1997; Stewart, 1999;  
211 Stewart and Argent, 2000). Where detachments are present, such as salt or shale, these thin-  
212 skinned faults may either detach (e.g. Fig. 3 in Withjack et al., 1989; Morley and Guerin, 1996;  
213 Sharp et al., 2000b; Withjack and Callaway, 2000; Fig. 9B in Jackson et al., 2006) or become  
214 layer-bound (e.g. Fig. 4 in Gross et al., 1997; cf. Couples et al., 1998; Fig. 10 in Lynch et al.,  
215 1998; cf. Couples and Lewis, 1999; Fig. 9 in Keller and Lynch, 1999; cf. Soliva et al., 2005;  
216 Fig. 9C in Jackson et al., 2006; Fig. 9B in Tavani et al., 2018). As larger amounts of strain are  
217 localised onto the detachment surfaces, the ductile units may become stretched and thin (cf.  
218 'tectonic thinning' after Brown, 1988). If the detachment on the footwall thins sufficiently,  
219 secondary normal faults in the cover above the detachment may link with the master fault at  
220 depth (Fig. 6C – D). Furthermore, the growth fold may become breached (Koyi et al., 1993;

221 Koyi et al., 1995; Stewart et al., 1996; Pascoe et al., 1999; Withjack and Callaway, 2000; Dooley  
222 et al., 2003).

223

#### 224 **4. What are the controls on the geometry and size of growth folds?**

225 The geometry, size and occurrence of growth folds above propagating normal faults is widely  
226 understood to be controlled by the interplay of structural factors (related to fault character) and  
227 stratigraphic factors (related to the rheology and thickness of the cover) (Fig. 7). Critically  
228 however, the relative importance of each of these structural and stratigraphic factors upon the  
229 geometry and size of a growth fold is not well-constrained. This is largely because: (i) we only  
230 observe the *final* geometry of growth folds in nature; (ii) there are few natural examples of  
231 growth folds in nature with high-resolution growth strata that permit the geometric evolution  
232 of the fold to be constrained; (iii) a large number of different factors control fold geometry  
233 through time; and (iv) it is difficult to quantify some of these factors e.g. the strata may not be  
234 preserved, or the parameters themselves may change through time. Examples of changing  
235 parameters through time include but are not limited to, the detachment thickness and the  
236 proportion of rheologically strong vs. weak strata.

237 Structural factors are associated with the kinematic and geometric evolution of the underlying  
238 fault, including the dip, throw, and shape of the fault, and the fault tip propagation and  
239 displacement rate. Stratigraphic factors are associated with the mechanical behaviour, thickness  
240 and rheology of the strata, including the confining pressure (depth of burial), differential  
241 compaction, and rheological heterogeneity. The effect of each controlling factor on the fold size  
242 and fold-shape-factor (the ratio of fold amplitude-to-width; FSF) is summarised in Fig. 7. When  
243 the fold-shape-factor is greater than 1 ( $FSF > 1$ ), the fold width is larger than its amplitude.  
244 Where the fold-shape-factor is equal to 1 ( $FSF \sim 1$ ), the fold width and amplitude are the same.

245 Where the fold-shape-factor is less than 1 ( $FSF < 1$ ), the fold width is smaller than the fold  
246 amplitude.

247 In this section, we review how each structural and stratigraphic factor influences the two-  
248 dimensional (2D) fold geometry and size as the throw on the underlying fault increases.

249

#### 250 **4.1. Influence of structural factors on the geometry and size of growth folds**

251 Prior studies have shown that structural factors strongly control the 2D geometry and size of  
252 growing folds. Here, we summarise how the dip, throw and displacement rate of the fault,  
253 affects fold geometry and size (Fig. 7A – C).

254 As a fault propagates towards the surface, fault dip plays an increasingly important role in fold  
255 geometry (e.g. Horsfield, 1977; Tsuneishi, 1978; Vendeville, 1987; Richard, 1989; Withjack et  
256 al., 1990; Koyi et al., 1993; Howard and John, 1997). Gently-dipping faults form wide folds  
257 (high FSFs) with gently-dipping fold limbs, while steeply-dipping faults form narrow folds (low  
258 FSFs) with steeply-dipping fold limbs (Fig. 7A). As there is a larger amount of rock material in  
259 front of the propagating fault tip for gently-dipping faults compared to steeply-dipping faults,  
260 all else being equal, a steeply-dipping fault will be break-surface earlier than a gently-dipping  
261 fault (Fig. 8). Where the fault dip changes with depth, complex growth fold geometries may  
262 develop. For example, where there are ramp flats, forced folds may form at multiple  
263 stratigraphic levels (Stewart et al., 1997; Lewis et al., 2013; Gabrielsen et al., 2016; Vasquez et  
264 al., 2018).

265 Fault throw, in contrast to fault dip, controls not only the fold geometry but also its size. As  
266 throw increases, so does the fold amplitude and width and thus, the FSF changes (e.g. Fig. 4 in  
267 Horsfield, 1977; Fig. 5 in Ameen, 1988; Fig. 4 in Withjack et al., 1990). Large throws are  
268 associated with large folds with low FSFs, while small throws are associated with small folds

269 with high FSFs (e.g. Horsfield, 1977; Patton et al., 1998; Fig. 7B). If the throw becomes too  
270 large, eventually the fold will be unable to accommodate any further strain, and the fold will  
271 become breached as the fault breaks-surface (e.g. Fig. 7 in Withjack and Callaway, 2000; cf.  
272 Fig. 3B). Once breached, folding ceases.

273 Similar to fault throw, the displacement rate of the fault, which is intimately linked to the  
274 propagation rate of the upper fault tip not only has the potential to control the shape, size and  
275 even the occurrence potential for a fold (e.g. Allmendinger, 1998; Withjack and Callaway, 2000;  
276 Cardozo et al., 2003; Finch et al., 2004; Jin and Groshong, 2006; Ford et al., 2007; Hardy and  
277 Allmendinger, 2011; Carola et al., 2013; Tavani and Granado, 2014; Deckers, 2015; Wilson et  
278 al., 2015). Slowly-propagating faults form wide folds with high FSFs as they take a longer to  
279 breach the cover, hence more folding occurs (e.g. Fig. 11A in Withjack and Callaway, 2000;  
280 low propagation rates are required in the Rhine Graben to form forced folds - Ford et al., 2007).  
281 Rapidly-propagating faults in contrast, form narrow folds with low FSFs and in some cases,  
282 may propagate so quickly through their cover that folds do not develop (Fig. 7C) (e.g. Fig. 10  
283 vs. 11 in Withjack and Callaway, 2000).

284 Applying this logic, growth folds are more likely to occur in basins where the upper tip  
285 propagation rate of individual faults is slow and rare in basins with rapidly-propagating faults.  
286 For example, we may hypothesise that rapidly-extending basins (cf. Nicol et al., 1997; Meyer  
287 et al., 2002; Mueller, 2017) will express rapid fault-propagation rates, therefore restricting the  
288 development of growth folds. Meanwhile, slowly-extending basins may be prone to slower tip  
289 propagation rates and thus, more growth folding. Alternatively, mechanical barriers to fault  
290 propagation, such as shale or salt (e.g. Morley and Guerin, 1996; Maurin and Niviere, 1999;  
291 Duffy et al., 2013; Jackson and Lewis, 2016; Coleman et al., 2017), may produce slowly-  
292 propagating faults. However, this hypothesis remains untested.

293 We may also expect the prevalence of growth folds will vary temporally and spatially within  
294 an extensional fault array. For example, during rift initiation, where regional strain is distributed  
295 over a large number of isolated faults, each with relatively low fault-propagation rates, growth  
296 folds may be common across the rift. Whereas during rift climax, where regional strain is  
297 localised onto a few, well-connected large faults but also towards the rift axis (Cowie, 1998;  
298 Gupta et al., 1998; Cowie et al., 2000; Gawthorpe and Leeder, 2000; Cowie et al., 2005), growth  
299 folds may be expected to develop in the strain shadows of larger faults or abandoned faults  
300 away from the strain locus, perhaps towards the rift margins. Although this too, remains poorly  
301 constrained.

302

#### 303 **4.2. Influence of stratigraphic factors on the geometry and size of growth folds**

304 Stratigraphic factors also exert significant controls on the geometry and size of growth folds.  
305 Here, we summarise the influence of the rheology and thickness of the cover, the detachment  
306 thickness and the confining pressure (depth of burial) on fold growth with increasing slip on  
307 the underlying fault (Fig. 7D – G).

308 As a fault tip propagates upwards, it may encounter ductile as well as brittle lithologies in its  
309 cover. These rheological variations in the cover have a profound impact upon the growth folding  
310 at the upper tip. Cover comprising ductile rocks such as salt or overpressured shale typically  
311 produce wider folds (high FSFs) than those in brittle sequences (low FSFs) (Withjack et al.,  
312 1990; Withjack and Callaway, 2000; Finch et al., 2004; Fig. 7D). As rheologically-weak strata  
313 tend to inhibit the upward propagation of a fault (e.g. Nicol et al., 1996; Couples and Lewis,  
314 1999; Corfield and Sharp, 2000; Wilkins and Gross, 2002; Benedicto et al., 2003; Soliva and  
315 Benedicto, 2005; Soliva et al., 2005; Lăpădat et al., 2016), folding is likely to last longer in  
316 ductile strata and may not be breached as rapidly as in brittle-cover scenarios. Thus growth

317 folds in rheologically-weak cover may be large and well-developed, whereas growth folds  
318 developed in homogeneous, rheologically-strong cover sequences (e.g. in volcanic basins) are  
319 likely to be rare and poorly-developed. Given that rheological variations in the cover can control  
320 the geometry and size of growth folds, it follows that cover with rheological heterogeneities  
321 such as multiple salt or shale layers, may be expected to produce broader folds (high FSFs) as  
322 the fault tip becomes temporarily arrested by each of the mechanical barriers. However, these  
323 hypotheses remain untested.

324 In addition to the rheology, the thickness of the cover also has been shown to control fold  
325 geometry and shape (Fig. 7E). Where the cover is thin, lesser degrees of folding are expected  
326 as the propagating fault takes a shorter time to breach the fold compared to when the cover is  
327 thick (e.g. Allmendinger, 1998). Furthermore, physical (Withjack and Callaway, 2000) and  
328 numerical models show thin cover typically produces narrow, poorly-developed folds (i.e. low  
329 FSFs) whereas thick cover is associated with wide, well-developed folds (i.e. high FSFs).  
330 Although these findings are commonly shown in models, it is yet to be found if these concepts  
331 hold in natural systems.

332 Detachment thickness also affects fold geometry and size (Fig. 7F). Cover with very thin  
333 detachments do not significantly inhibit fault tip propagation, thus growth folds developed in  
334 such systems tend to be narrow, poorly-developed and with low FSFs. In contrast, thick  
335 detachments generate wide, well-developed folds with high FSFs, as detachments buffer against  
336 underlying fault displacement and tip propagation (Richard, 1991; Vendeville et al., 1995;  
337 Withjack and Callaway, 2000; Stewart, 2007; Deckers, 2015; Lăpădat et al., 2016; Hardy,  
338 2018). This prediction, largely derived from physical models (except Hardy, 2018), has never  
339 been tested in nature.

340 The final stratigraphic factor that influences fold geometry is confining pressure (Fig. 7G) (e.g.  
341 Friedman et al., 1976; Weinberg, 1979; Bartlett et al., 1981; Koyi et al., 1993; Patton et al.,  
342 1998; Schöpfer et al., 2007). As a growth fold is buried and the confining pressure increases,  
343 the rocks within the cover progressively compact and the rheology changes. Patton et al. (1998),  
344 in their Fig. 7, showed that the same cover lithology under different confining pressures can  
345 lead to significant changes in the fold width. Shallowly-buried folds at low confining pressures  
346 are typically narrower (low FSFs) than deeply buried folds at high confining pressures (high  
347 FSFs). This occurs as the bulk ductility of the cover and zone of microfracturing increases with  
348 higher confining pressures (Patton et al., 1998). Given that the hangingwall and footwall fault  
349 blocks lie at different depths with different confining pressures, the rheology of the cover may  
350 be different across the fault. For example, across-fault differential compaction may alter the  
351 bedding dips in the fold. In the shallowly-buried footwall where compaction is less, the dips are  
352 gentler, whereas in the deeply-buried hangingwall, compaction is greatest and the dips are  
353 steeper (Jin et al., 2009). Furthermore, differential compaction and burial depth will also  
354 influence fold shape (e.g. Skuce, 1996; Færseth and Lien, 2002).

355

### 356 **4.3. Unanswered questions**

357 Having reviewed how each of the structural and stratigraphic factors affects growth fold  
358 geometry, a number of unanswered questions remain: (i) how do growth folds evolve with  
359 increasing fault throw?; (ii) what are the differences, if any, between the growth of fault-  
360 propagation and forced folds?; (iii) what controls the occurrence of growth folds?; and (iv)  
361 which factors exert the greatest control on growth fold geometry and size? To answer these  
362 questions, we analysed published examples of growth folds in nature and models to quantify  
363 relationships between parameters of the fault, fold and cover to investigate and subsequently  
364 predict how, where and why growth folds evolve. These predictions allow us to infer the

365 geometric and kinematic characteristics of growth folds in areas lacking high-resolution growth  
366 strata or poor exposure/seismic imaging.

367

## 368 **5. Fold, fault and cover parameters**

369 Several geometrical parameters (as defined in Fig. 2), have been measured from published-  
370 cross-sections. In cross-section, the amplitude and width are determined by the vertical and  
371 horizontal distances between the ‘toe’ and ‘head’ of the fold, respectively. The toe is defined as  
372 the point at which a marker bed meets the regional datum on the hangingwall of a normal fault.  
373 The head is defined as the point where a marker bed drops below the regional datum on the  
374 footwall of a normal fault. As previously mentioned, the fold-shape-factor (FSF) is the ratio of  
375 the amplitude-to-width and is used to quantitatively compare fault-propagation and forced  
376 folds, irrespective of their scale. High values of FSF indicate the fold is far wider than it is tall,  
377 whereas low values of FSF indicate the fold has a larger amplitude than its width. The  
378 prekinematic thickness is the stratigraphic thickness of the largely tabular, isopachous strata  
379 deposited prior to extension. For forced folds, the detachment thickness is the vertical thickness  
380 of the detachment layer which separates folded strata above and faulted strata below. Where  
381 applicable, the cover-detachment (C:D) ratio is used to quantitatively compare forced folds,  
382 irrespective of their scale. High C:D ratios indicate the prekinematic cover is thicker than the  
383 detachment thickness, whereas low C:D ratios indicate that the detachment thickness is thicker  
384 than the prekinematic cover thickness. Fault dip is measured from the underlying master fault.  
385 Fault throw is the vertical change in elevation of a prekinematic marker bed across a fault; for  
386 forced folds, throw is measured immediately below the detachment.

387



388 **6. How are the geometries and sizes of growth folds affected by structural and**  
389 **stratigraphic parameters?**

390 Quantitative comparative analysis of parameters measured from published cross-sections  
391 oriented perpendicular to the underlying master fault was carried out for c. 600 fault-  
392 propagation folds (Fig. 9; Appendix B) and c. 300 forced folds (Fig. 10; Appendix C). The  
393 resulting global dataset characterises fault-propagation and forced folds from extensional  
394 settings (see Appendices D – E for all measured data). Without growth strata, the kinematic  
395 evolution of these growth folds is difficult to constrain. However, by compiling this database  
396 of fault-propagation and forced folds of different sizes and shapes, and at different stages of  
397 development (Table 1), we can assess the dynamics of these folds and predict the parameters  
398 and geometry for folds that are poorly-imaged in seismic reflection data or less well-preserved  
399 in the field.

400 For each fold, the geometrical parameters described in Fig. 2 were recorded. Measurements of  
401 the geometrical parameters in models and natural examples all have uncertainties, however,  
402 only high confidence examples have been used for the statistical analysis and the associated  
403 uncertainties have been noted (see Appendix F for the full details).

404

405 **6.1. Regression analysis**

406 To understand the genesis and development of growth folds, a quantitative study has been  
407 undertaken based on published literature. This extensive data compilation features >150  
408 different localities and >800 examples, each with its own unique tectonic parameters (e.g. strain  
409 rate, lithology, tectonic setting) allowing us to compare geometrical characteristics in volcanic  
410 and sedimentary extensional systems and isolate the primary controls on the geometric and  
411 kinematic evolution of growth folds in two-dimensions.

412 Relationships between these parameters are investigated in a series of cross plots (Figs. 11 –  
413 12), which show best-fit lines generated by least-square regression methods for moderate-  
414 strong correlations (coefficient of determination,  $R^2 = 0.5 - 0.8$ ,  $= 0.8 - 1.0$ , respectively).  
415 Equations describing best-fit lines between parameter pairs showing a moderate-strong  
416 correlation are shown in Table 2. Best-fit lines have been plotted using linear, power-law and  
417 2<sup>nd</sup> degree polynomial functions. The function that shows the best-fit to the data, characterised  
418 by the highest  $R^2$  value, has generally been selected for each parameter pair. The only  
419 exceptions are where polynomial functions that give best-fit lines with minima that are poorly  
420 constrained by data control and are geologically unreasonable. In these select cases, the second  
421 best-fit function has been chosen.

422 Two types of relationships between parameters are observed. The first type comprises positive  
423 and negative correlations between parameters from related domains (e.g. fold amplitude vs.  
424 fold-shape-factor). The second type comprises positive and negative correlations between  
425 parameters from different dimensional domains that were not derived from each other (e.g.  
426 amplitude vs. prekinematic thickness). The second type of relationship is more meaningful, as  
427 it highlights potential links between parameters that are not directly related. The presence of  
428 several moderate – strong correlations between these parameters is remarkable in its own right,  
429 as it indicates that growth folds at different scales, in different extensional settings and with  
430 varying lithological heterogeneity can be described quantitatively by our regression equations.  
431 These equations are potentially powerful tools that enable estimation of unknown parameters  
432 by utilising other known parameters extracted from folds.

433

#### 434 **6.1.1. Fault-propagation folds**

435 Natural fault-propagation folds show moderate-to-strong correlations between: (1) fault throw  
436 and fold amplitude, (2) fault throw and fold width, (3) prekinematic thickness and fold  
437 amplitude, (4) prekinematic thickness and fold width, (5) fold amplitude and width (Table 1;  
438 Figs. 11A - E). These correlations suggest that the fault throw and thickness of the prekinematic  
439 strata cover control the size of the fold, and thus, large throws generate large fault-propagation  
440 fold amplitudes and widths.

441 Physical models show that fault throw and fold amplitude are moderately correlated for physical  
442 models of fault-propagation folds (Table 1; Fig. 11F), similar to natural examples. This suggests  
443 that fault throw is the principal control on fold amplitude.

444 Numerical models show strong correlations between: (1) fault throw and fold amplitude, (2)  
445 fault throw and fold width, (3) prekinematic thickness and fold amplitude, (4) prekinematic  
446 thickness and fold width, and (5) fold amplitude and fold width. In other words, these  
447 correlations suggest that large fault throws and thick prekinematic cover generate large folds  
448 with large amplitudes which are also wide (Table 1; Fig. 11H – L), similar to the natural  
449 examples but largely different from the physical models.

450

### 451 **6.1.2. Forced folds**

452 Natural examples of forced folds show moderate-to-strong correlations for: (1) fault throw and  
453 fold amplitude, (2) fault throw and fold width, (3) prekinematic thickness and fold amplitude,  
454 (4) prekinematic thickness and fold width and (5) fold amplitude and fold width, similar to  
455 fault-propagation folds (Table 1; Figs. 12A – B, E - G). In addition, forced folds also shown  
456 moderate-to-strong correlations for (6) detachment thickness and fold amplitude, and (7)  
457 detachment thickness and fold width (Figs. 12C - D). These correlations suggest that large fault  
458 throws, a thick prekinematic cover and a thicker detachment produce larger folds.

459 Physical models of forced folds lack moderate-to-strong correlations between fault, fold and  
460 stratigraphic geometrical parameters. This suggests that no single measured fault- or  
461 stratigraphic- related parameter controls the amplitude and width of the forced fold, at least for  
462 all examples in physical model. To the best of our knowledge, only Hardy (2018) has modelled  
463 forced folds numerically so quantitative analysis given the small sample size would not be  
464 appropriate. Trishear models, which have on occasion been used to investigate forced folds  
465 (Ford et al., 2007), have also not been included in our analysis.

466

## 467 **6.2. Principal Component Analysis (PCA)**

468 Physical models suggest that structural and stratigraphic factors control the geometry and size  
469 of evolving growth folds, but the lack of moderate-to-strong correlations for physical models  
470 in our regression analyses suggest this may not be the case (Table 2; Figs. 11 – 12). To  
471 investigate whether the quantitative relationships identified in the regression analyses are  
472 reasonable, not only for models but also in nature, and whether data scatter is obscuring trends  
473 between structural and stratigraphic factors, principal component analysis (PCA) has also been  
474 used. PCA simplifies the complexity of high-dimensional multi-variate data, such as our growth  
475 fold dataset (Appendices D – E), while retaining trends and patterns (e.g. Jolliffe, 1993; Jolliffe,  
476 2002; Ringnér, 2008; Abdi and Williams, 2010; Josse and Husson, 2016; Lever et al., 2017). In  
477 other words, PCA allows us to identify possible relationships between growth fold parameters  
478 which are non-linear, or at least, very complex. See Appendices G – H for further details.

479 To identify whether the measured growth fold parameters may be related, we apply PCA to  
480 examples of fault-propagation and forced folds in nature, physical models and numerical  
481 models in turn. We then interpret the results and suggest which parameters may control the two-  
482 dimensional fold size and shape.

483 **6.2.1. Fault-propagation folds**

484 In natural examples of fault-propagation folds, the first three PCs account for 85% of total data  
485 variation (Fig. 13A). The first PC comprises the amplitude and width of the fold, the thickness  
486 of the strata and the underlying fault throw, whereas the second and third PCs describe the dip  
487 of the fault and the fold-shape-factor. The percentage of total variation accounted for by each  
488 of the first PCs are 52%, 21% and 12%, respectively. In other words, our analysis indicates that  
489 the thickness of the prekinematic cover and fault throw likely control the fold amplitude and  
490 width, whereas fault dip controls the geometry of the fold.

491 In physical models, principal components 1 – 3 account for 78% of the data variance (Fig. 13B).  
492 PC1 comprises the prekinematic thickness and fold size parameters, PC2 comprises of fold  
493 shape and fault dip and throw, and PC3 comprises prekinematic thickness, fold shape and fault  
494 throw. The percentage of total variation accounted for by each of the first PCs are 38%, 24%  
495 and 16%, respectively. These results indicate that the thickness of the prekinematic cover  
496 controls fold amplitude and width, whereas the dip and throw of the fault controls the width  
497 and the overall geometry of the fold.

498 In numerical models, the first three principal components account for 93% of the data variance  
499 (Fig. 13C). The percentage of total variation accounted for by each of the first PCs are 63%,  
500 19% and 11%, respectively. PC1 describes fault throw and dip, prekinematic thickness, and fold  
501 size. PC2 describes fold shape, width and fault dip. PC3 is associated with fault dip only.  
502 Furthermore, the dip and throw of the underlying fault and thickness of the prekinematic cover  
503 control the fold size, whereas the fault dip controls the fold width and the overall shape of the  
504 fold.

505

506 **6.2.2. Forced folds**

507 Similar to the fault-propagation folds, PCA may also provide insights into related parameters  
508 in examples of forced folds in nature and from physical models. In natural examples, the first  
509 three principal components account for 74% of total data variation (Fig. 14A). The first PC  
510 comprises the fold amplitude, width, the thickness of the cover and the fault throw, whereas the  
511 second PC describes the fold shape and fold width, and the dip of the fault. The third PC  
512 comprises of the fold amplitude and width, and the cover thickness. The percentage of total  
513 variation accounted for by each of the first PCs are 36%, 23% and 15%, respectively. In other  
514 words, our analysis indicates that the fault throw and the cover thickness controls the fold size,  
515 whereas the dip of the fault controls the width of the fold and thus, the overall shape.

516 In physical models, principal components 1 – 3 account for 71% of the total data variance (Fig.  
517 14B). The percentage of total variation accounted for by each of the first PCs are 30%, 23%  
518 and 18%, respectively. The first PC comprises of the cover thickness, fold shape and fold width,  
519 whereas the second PC comprises of the fold amplitude and width, and fault throw. The third  
520 PC consists of the dip of the fault, the thickness of the cover and the proportion of ductile  
521 lithologies in the cover. In other words, the thickness of the cover and the fault throw control  
522 the shape and the size of the forced fold. The dip of the fault, in contrast to the natural examples,  
523 is not a major factor on fold shape or size. To the best of our knowledge, only Hardy (2018) has  
524 modelled forced folds numerically. In select cases (e.g. Ford et al., 2007), trishear models have  
525 also been used to reconstruct forced fold evolution, however, these have been excluded from  
526 the analysis.

527

528 **7. Do physical and numerical models accurately represent natural growth fold**  
529 **characteristics?**

530 By comparing the correlations between structural and stratigraphic parameters from our  
531 regression analysis (Figs. 11 – 12) and from our principal component analysis (Figs. 13 – 14)  
532 in nature and in models, we now investigate whether physical and numerical models accurately  
533 describe growth folds in nature.

534 In physical models, the strength and relative importance of structural and stratigraphic factors  
535 on fold geometry varies substantially and there is a high amount of scatter and weak correlations  
536 between fault-fold parameters (Table 2). For example, only fault throw and fold amplitude are  
537 moderately correlated for physical models of fault-propagation folds (Fig. 11F), while there are  
538 no moderate-to-strong correlations for physical models of forced folds. This could be due to the  
539 extensive range of material strengths for the cover (e.g. sand, wet clay, gypsum powder,  
540 limestone), detachment (e.g. silicon, asphalt, wax, oil, clay), and the temporal and spatial  
541 scaling used in the models (see Koyi, 1997; Panien et al., 2006; Schreurs et al., 2006; Schellart  
542 and Strak, 2016, for a discussion on the variability associated with physical modelling  
543 approaches).

544 When an individual model of a growth fold is taken in isolation, it show similar correlations  
545 between structural and stratigraphic factors and fold geometry as in nature. For example, fold  
546 amplitude increases with throw for individual models for fault-propagation (Fig. 15A) and  
547 forced folds (Fig. 15B). However, when all models are analysed together, the correlations are  
548 weaker or apparently, non-existent due to the large data variance (Fig. 15). Thus, for a physical  
549 model to be an appropriate analogue to a natural example, the rheologic, stratigraphic and  
550 structural parameters must be broadly equivalent; not all physical models will be appropriate

551 for comparing the geometry and size of natural examples, especially their evolution through  
552 time.

553 Kinematic models, that is those where rock properties are not incorporated in the model (e.g.  
554 Erslev, 1991; Hardy and Ford, 1997; Cardozo et al., 2011), and mechanical models where rock  
555 properties are incorporated (e.g. Finch et al., 2004; Hardy and Finch, 2006; Egholm et al., 2007;  
556 Hardy and Finch, 2007; Figs. 11F – L), produce very similar geometrical relationships to fault-  
557 propagation folds in nature (Figs. 11A – E). The similar correlations identified for both  
558 kinematic and mechanical models, and natural examples of fault-propagation folds suggest that  
559 cover rheology is not as important as fault throw and the cover thickness in determining fold  
560 shape and size. In addition, the correlations between structural and stratigraphic factors in  
561 numerical models and nature (e.g. fault throw vs. fold amplitude, prekinematic thickness vs  
562 fold amplitude, etc.) suggest that the final geometry of a growth fold may be accurately  
563 predicted by a model (cf. Cardozo et al., 2011). However, the two-dimensional geometric and  
564 kinematic evolution of growth folds in nature remains poorly-constrained, especially in areas  
565 lacking high-resolution growth strata.

566

## 567 **8. How are growth folds predicted to grow?**

568 Having established the two-dimensional geometrical relationships between the geometry of the  
569 growth fold and underlying propagating normal fault and the thickness of the cover, we now  
570 investigate how fault-propagation and forced folds grow with increasing displacement on the  
571 underlying fault. Given that we can only measure the final, present-day geometry of natural  
572 folds, we are unable to know how these folds grew with increasing extensional strain. Physical  
573 and numerical models therefore provide a snapshot of the growth fold geometry at different  
574 fault displacements with increasing extensional strain (cf. Hardy and McClay, 1999; Ford et al.,



575 2007; Cardozo et al., 2011). In this section, we use published models of growth folds above  
576 upward propagating normal faults to investigate how each of the controlling factors (Fig. 7)  
577 affects two-dimensional fold geometry and size through time, and with increasing fault throw  
578 in 2D (Figs. 16 – 19). In all cases, only a single controlling factor is changed i.e., throw is  
579 plotted against amplitude and the fold-shape-factor for each variable.

580 Weak or rheologically heterogeneous cover (Figs. 16A; 17A; 18A; 18E), higher confining  
581 pressures (i.e. greater burial depths; Fig. 16C), increased detachment content (Fig. 18E; 19A),  
582 thick cover thicknesses (Figs. 17D; 18D), with gently-dipping faults (Figs. 16B; 17C; 18C;  
583 19B), low fault propagation tip rates (Fig. 17B) and low regional strain rates and displacement  
584 rates (Fig. 18B) produce wide folds in physical (Ameen, 1988; Richard, 1989; Withjack et al.,  
585 1990; Withjack and Callaway, 2000; Miller and Mitra, 2011) and numerical models  
586 (Allmendinger, 1998; Hardy and McClay, 1999; Finch et al., 2004; Hardy, 2018). In all cases,  
587 folds initially have relatively high FSF values as final fold widths are established very early  
588 during fold growth and remain largely constant throughout. In contrast, fold amplitude increases  
589 gradually as throw accrues on the underlying normal fault. Therefore, the initial (and largest)  
590 FSF that can be developed is controlled by the structural and stratigraphic factors that control  
591 fold width. As the fold grows and amplitude slowly increases as throw accrues on the underlying  
592 fault, the FSF gradually decreases (Figs. 16 – 19).

593 In addition to the geometrical evolution of growth folds through time, models permit an insight  
594 into the structural and stratigraphic factors that affect the duration of folding and explicitly what  
595 factors control fold breaching. Folds with weak cover (Figs. 16A; 17A; 18A; cf. Fig. 19A), low  
596 strain rates (Fig. 18B), low fault propagation rates (Fig. 17B), higher confining pressures (i.e.  
597 greater burial depths; Fig. 16C), and gentle fault dips (Figs. 16B; 17C; 18C; 19B) inhibit the  
598 breaching of growth folds above the upper tips of propagating normal faults (Ameen, 1988;

599 Richard, 1989; Withjack et al., 1990; Allmendinger, 1998; Hardy and McClay, 1999; Withjack  
600 and Callaway, 2000; Finch et al., 2004; Miller and Mitra, 2011).

601

## 602 **9. Discussion**

### 603 **9.1. How do fault-propagation and forced folds grow?**

604 A growth fold pathway is the track that an evolving fault-propagation or forced fold takes as it  
605 amplifies and widens on Fig. 20. The growth fold pathways provide important insights into fold  
606 growth and allows us to predict the 2D geometry and size of growth folds through time. When  
607 the fold amplitude and width are plotted for all growth folds, we observe a relationship between  
608 the two, suggesting that fold amplitude and width grow together with increasing displacement  
609 on the underlying fault – Path 1 on Fig. 20A. However, it is striking that in the physical,  
610 mechanical and kinematic models (cf. Ameen, 1988; Richard, 1989; Withjack et al., 1990;  
611 Patton et al., 1998; Hardy and McClay, 1999; Withjack and Callaway, 2000; Finch et al., 2004;  
612 Miller and Mitra, 2011; Figs. 16 - 19), this is not the case. In these models we observe how the  
613 fold width and amplitude develop at different times and different rates during fold evolution,  
614 producing an initially high FSF that gradually declines with fold growth (see the dashed lines  
615 on Figs. 8, 16 – 19). In other words, the final fold width is established relatively early during  
616 fold growth, when the fold amplitude (and fault throw) is small. As the fold continues to grow  
617 with increasing fault throw, the fold amplitude then increases whereas the fold width remains  
618 largely constant – Path 2 on Fig. 20A. These growth fold pathways help explain how natural  
619 examples of fault-propagation and forced folds may geometrically and kinematically evolve in  
620 extensional settings. Furthermore, when seismic imaging or exposure is poor (cf. Botter et al.,  
621 2014), high-resolution growth strata are not available (such as during sub-aerial continental  
622 rifting - Gawthorpe and Leeder, 2000; Patton, 2004), or there is not an appropriate physical or

623 numerical model, these pathways may be used to make quantitative estimates for fold geometry  
624 and size through time in 2D.

625 So far, we have only discussed the 2D geometry and evolution of fault-propagation and forced  
626 folds, but in reality, growth folds change shape and size along- and across-strike and are  
627 dependent upon the growth of the underlying master fault, which varies in three-dimensions  
628 (Fig. 21). If the fault length and throw accumulate gradually and synchronously (Fig. 21A;  
629 ‘isolated fault model’ – e.g. Walsh and Watterson, 1988; Dawers and Anders, 1995; Fig. 4A in  
630 Jackson et al., 2017a), the along-strike width of the growth folds may be expected to increase  
631 progressively through time. Alternatively, if faults rapidly establish their along-strike length  
632 before accumulating displacement (‘constant-length fault model’ - cf. Childs et al., 1995; Meyer  
633 et al., 2002; Walsh et al., 2003; Jackson and Rotevatn, 2013; Tvedt et al., 2016; Fig. 4B in  
634 Jackson et al., 2017a), the along-strike width of the fold may be very large for a small amount  
635 of throw (Fig. 21B). Regardless of the fault growth model (i.e. isolated vs constant-length), the  
636 fold may be breached when the fault slip is large enough or the propagation rate of the upper  
637 fault tip increases sufficiently. This increase in displacement could be due regional extension  
638 rate (cf. Nicol et al., 1997; Hardy and McClay, 1999; Meyer et al., 2002; Mueller, 2017), or as  
639 strain becomes focused onto larger, well-connected faults during the latter stages of extension  
640 (e.g. Gawthorpe and Leeder, 2000; Cowie et al., 2005; Finch and Gawthorpe, 2017).

641

## 642 **9.2. Differences between fault-propagation and forced fold growth**

643 Given that fault-propagation and forced folds have different shapes and sizes for a given throw  
644 on the underlying fault, their growth pathways may be different. For example, forced folds have  
645 larger amplitudes (Fig. 22A) and widths (Fig. 22B) for a given fault throw than fault-  
646 propagation folds. This is likely due to the across- and along-strike salt flow. As a forced fold

647 grows, salt may move from the hangingwall into the footwall during extension (Koyi et al.,  
648 1993; Burliga et al., 2012) or sediment loading (e.g. the Cormorant structure, Jeanne d'Arc  
649 Basin - Withjack and Callaway, 2000; cf. Warsitzka et al., 2015; Warsitzka et al., 2017), causing  
650 the fold amplitude to increase ('salt inflation' in Fig. 20B) relative to a fault-propagation fold  
651 that has experienced the same fault throw. In addition, the fold amplitude may increase very  
652 rapidly compared to fold width, and more rapidly than a fault-propagation fold. Alternatively,  
653 salt may flow laterally away from a pre-existing sub-salt step in the basement ('detachment  
654 withdrawal' on Fig. 20B), creating a 'withdrawal drape fold' (Fig. 16 in Withjack and Callaway,  
655 2000; cf. Fig. 1). As salt is evacuated from beneath the supra-salt strata in the hangingwall, the  
656 amplitude of the fold may rapidly increase compared to width, appearing geometrically similar  
657 and growing very similarly to a forced fold (Path 2 on Fig. 20).

658 Forced folds tend to have larger fold amplitudes and widths compared to fault-propagation folds  
659 (Figs. 22C - D) for the same total cover thickness (i.e. the thickness of the detachment and the  
660 prekinematic cover). Richard (1989) and Hardy (2018) showed that as the thickness of the  
661 detachment is increased relative to the prekinematic thickness i.e. the detachment content of the  
662 cover increases, growth folds are wider for a given fold amplitude and fault throw (Figs. 18E;  
663 19A). This behaviour might be because as the overall cover is weakened (by the introduction  
664 of ductile material), extensional strain may be distributed over a wider area (cf. Fig. 7D).

665

### 666 **9.3. What controls the occurrence of growth folds?**

667 Why do growth folds occur in some basins but not others? Prior studies (e.g. Corfield and Sharp,  
668 2000; Ford et al., 2007) have highlighted two key factors that may induce growth folding: (i)  
669 the presence of weak lithologies or mechanical heterogeneities in the cover, and (ii) low  
670 displacement (and low upper tip fault propagation) rates. Here, we discuss these factors in turn,

671 drawing upon key examples from our growth fold dataset, to critically assess whether these  
672 factors may control growth fold occurrence.

673 Folding is expected to be more common in relatively rheologically-weak cover, as the strain is  
674 not only distributed over a wide area but also these rheological heterogeneities inhibit upward  
675 fault propagation (cf. Couples and Lewis, 1998; Withjack and Callaway, 2000; Finch et al.,  
676 2004; Ford et al., 2007; Roche et al., 2012; Jackson and Lewis, 2016; Hardy, 2018). In contrast,  
677 folding may be expected to be absent in relatively rheologically-strong cover as strain is focused  
678 in the vicinity of the fault, permitting rapid propagation and leaving little time for folding (cf.  
679 Withjack and Callaway, 2000; Finch et al., 2004; Hardy and Finch, 2007; Hardy, 2011).  
680 Rheological strong and brittle volcanic sequences may therefore be expected to lack growth  
681 folds (e.g. Fig. 2 in Hardy, 2013), however, this is not always the case. For example, growth  
682 folds are documented in the flanks of Kilauea, Hawaii (Kattenhorn et al., 2000; Parfitt and  
683 Peacock, 2001; Peacock and Parfitt, 2002; Holland et al., 2006; Martel and Langley, 2006;  
684 Kaven and Martel, 2007; Podolsky and Roberts, 2008), the Modoc Plateau, USA (White and  
685 Crider, 2006; Blakeslee and Kattenhorn, 2013; Crider, 2015; Kattenhorn et al., 2016), and the  
686 Reykjanes Peninsula, Iceland (Bull et al., 2003; Grant and Kattenhorn, 2004; Bull et al., 2005;  
687 Tripanera et al., 2015) suggesting that cover rheology is *not* the principal control on growth  
688 fold occurrence, although it may affect their geometry and size (Fig. 7D). Although it is possible  
689 intra-basaltic heterogeneity e.g. paleosols, volcanoclastics, rubble horizons, mineralisation, pre-  
690 existing fractures may weaken the cover rheology (cf. Finch et al., 2004; e.g. Walker et al.,  
691 2012; Walker et al., 2013; Bubeck et al., 2018; Smart and Ferrill, 2018) and thus, permit folding.  
692 Although growth folds are seemingly more widespread in basins with rheological  
693 heterogeneity, such as salt or thick shale (cf. Jackson et al., 2006; Jackson and Lewis, 2016;  
694 Coleman et al., 2017), they clearly also occur in predominantly brittle successions (cf.

695 Gawthorpe et al., 1997; Willsey et al., 2002) in largely homogeneous crust (cf. Gawthorpe and  
696 Leeder, 2000).

697 Growth fold occurrence has also been linked to the interplay of the propagation rate and  
698 displacement rates of the upper tips of normal faults, that may in part, be related to the rheology  
699 of the cover (Hardy and McClay, 1999; Finch et al., 2004; Jackson et al., 2006). We can  
700 therefore speculate that relatively high propagation rates are less likely to cause growth folding  
701 as rapidly-propagating fault tips breach the surface early during fold growth. Rapidly-  
702 propagating faults may be expected in regions with high strain rates (cf. Nicol et al., 1997;  
703 Meyer et al., 2002; Mueller, 2017), during rift climax (cf. Cowie, 1998; Cowie et al., 2000;  
704 Gawthorpe and Leeder, 2000; Cowie et al., 2005), towards the rift axis (Cowie et al., 2005), or  
705 within fault arrays with relatively few faults (Walsh et al., 2003; Wilson et al., 2013; Nixon et  
706 al., 2014). However, do growth folds develop in these areas? Are they more widespread than  
707 perhaps, they are given credit for?

708 In the flanks of Kilauea, Hawaii (e.g. Macdonald, 1957; Duffield, 1975; Kattenhorn et al., 2000;  
709 Parfitt and Peacock, 2001; Martel and Langley, 2006; Kaven and Martel, 2007; Podolsky and  
710 Roberts, 2008; Bubeck et al., 2018) and in the eastern Gulf of Corinth (e.g. Vita-Finzi and  
711 King, 1985), fault-propagation folds are forming at the present-day despite very high regional  
712 extension rates (Kilauea Volcano - 9 – 12 cm/yr from Owen et al., 1995; Gulf of Corinth - 5 –  
713 15 mm/yr from Bell et al., 2011). Similarly, ancient growth folds have formed under different  
714 extension rates. In the Halten Terrace, km-scale growth folds formed over <60 Myr time period  
715 (Corfield and Sharp, 2000; Corfield et al., 2001; Marsh et al., 2010; Coleman et al., 2017),  
716 while in the Gulf of Suez, similarly-sized growth folds formed over 4 Myr (Sharp et al., 2000a;  
717 Sharp et al., 2000b). Even though salt is present in the Halten Terrace, which may have inhibited  
718 the upward propagation of fault tips to the surface, this variability highlights that regional  
719 extension rate does not seem to control the occurrence of growth folds. Instead, growth fold

720 occurrence is likely dependent on the propagation and displacement rates on individual faults  
721 which is likely to vary spatially and temporally within extensional fault arrays, as speculated  
722 by Withjack and Callaway (2000; in the Jeanne d'Arc Basin), Willsey et al. (2002), Ford et al.  
723 (2007) and Bubeck et al. (2018).

724 During rift initiation, strain is distributed over many small, isolated faults with low slip and  
725 propagation rates (Cowie, 1998; Gupta et al., 1998; Cowie et al., 2000; Cowie et al., 2005),  
726 promoting the development of growth folding (cf. Gawthorpe and Leeder, 2000). However, as  
727 these small faults interact and link during rift climax, slip is transferred onto increasingly large,  
728 well-connected faults (Cowie, 1998; Cowie et al., 2000; Gawthorpe and Leeder, 2000) that may  
729 rapidly propagate through the cover. Rapid fault propagation may not only breach pre-existing  
730 growth folds but may also inhibit the formation of new growth folds at their upper tips, so that  
731 they may not develop at all (cf. Bubeck et al., 2018). Furthermore, growth folds may develop  
732 in some locations with similar cover rheology and similar throws, but not others (e.g. Faroe  
733 Islands - Walker et al., 2012; Walker et al., 2013; e.g. presence of growth folds in the western,  
734 but not eastern Koa'e Fault System, Kilauea, Hawaii - Bubeck et al., 2018). In contrast, growth  
735 folds above isolated small faults in the stress shadows of these larger faults may be preserved.  
736 Examples may include the isolated faults in the vicinity of the Strathspey-Brent-Statfjord fault  
737 system of the Northern North Sea (McLeod et al., 2000), the Nopolo Structure of the Gulf of  
738 California (Willsey et al., 2002), or the El Qaa fault block of the Gulf of Suez (Lewis et al.,  
739 2015). In addition, as strain becomes focused onto larger faults, particularly towards the rift  
740 axis (Cowie et al., 2005), growth folds may preferentially develop at the rift margins (e.g.  
741 Laubscher, 1982). In the Gulf of Corinth, strain has become increasingly focused towards the  
742 rift margins (Nixon et al., 2016), opposed to the rift axis, but fault-propagation folds may still  
743 be found at the margin (Hemelsdaël and Ford, 2014).

744 Finally, individual faults as part of a large network (i.e. distributed deformation) may propagate  
745 at a slower rate compared to faults within a small fault network, where the strain is localised  
746 onto fewer faults (Walsh et al., 2003; Putz-Perrier and Sanderson, 2009; Wilson et al., 2013;  
747 Nixon et al., 2014). Although this is likely the case, as shown in physical models with one  
748 basement fault and high strain rates (e.g. Withjack and Callaway, 2000; Miller and Mitra, 2011;  
749 Paul and Mitra, 2015), few attempts (e.g. Ford et al., 2007) have been made to measure the  
750 displacement rates of individual faults. In addition, the displacement rates (and possibly, the  
751 propagation rates) may be greatest towards the centre of fault arrays but lower towards the tips  
752 (Cowie and Roberts, 2001; Papanikolaou and Roberts, 2007). Furthermore, growth folds may  
753 be expected to be rarer or at least breached (cf. Parfitt and Peacock, 2001; Grant and Kattenhorn,  
754 2004; Martel and Langley, 2006; White and Crider, 2006; Tavani et al., 2013; Tavani and  
755 Granado, 2014) towards fault array centres.

756 We do not claim here to know why growth folds occur in particular locations more readily than  
757 others, but this data compilation suggests that growth folds are far more prevalent than they  
758 have been credited for. Perhaps, growth folds occur in every basin worldwide, but instead, their  
759 small size (especially where folds are poorly-developed under high fault tip propagation rates;  
760 cf. Bubeck et al., 2018) and the lack of high-resolution synkinematic strata, particularly during  
761 early extension, make it difficult to identify them.

762

#### 763 **9.4. What controls the geometry and size of growth folds?**

764 Natural examples of fault-propagation and forced folds show similar relationships between fold  
765 size and geometry, and the properties of the underlying fault and cover. This suggests that the  
766 structural and stratigraphic factors controlling fault-propagation and forced folds are largely  
767 similar. The only exception is the thickness of the detachment in forced folds, which by



768 definition, require an abrupt transition from faulting to folding (cf. Withjack et al., 2002). We  
769 find that fault throw, and the thickness of the cover are the major controls on fault-propagation  
770 and forced fold geometry and size (Figs. 11 – 12), and although cover rheology and fault dip  
771 undoubtedly control fold geometry and size, as shown in physical (Figs. 7; 16; 18) and  
772 numerical models (Fig. 17; 19), their role is masked by the dataset scatter (as in Fig. 15). Here,  
773 we discuss in mechanical terms why the identified correlations may exist between growth fold  
774 parameters, and which parameters exert the greatest influence of fold size and shape.

775 Our analysis suggests that large fault throws and thicker prekinematic cover for fault-  
776 propagation and forced folds generates large fold amplitudes and widths, as suggested by  
777 Horsfield (1977), Withjack et al. (1990), Withjack and Callaway (2000), and Miller and Mitra  
778 (2011). As the fault throw increases, intuitively the amplitude of the folded cover increases too  
779 as the hangingwall block is displaced downwards relative to the footwall, and the cover is  
780 increasingly folded (Fig. 22A). Furthermore, the fault throw is the principal control on fold  
781 amplitude and explains why the values are very similar for the majority of growth folds. These  
782 results are corroborated by Lăpădat et al. (2016), in their Fig. 13C and D. Once the fold is  
783 breached, fold amplitude is independent of the fault throw (Appendix D – E), also documented  
784 by Lăpădat et al. (2016).

785 As the fault throw (and the fold amplitude) increases, the width also increases (Fig. 22B),  
786 similar to Conneally et al. (2017) in their Fig. 6C, 13C and 16. However, as discussed earlier,  
787 we suspect that the width is largely set during the initial stages of growth folding (cf. Path 2 on  
788 Fig. 20) and although it may increase slightly as throw is accrued on the underlying fault, the  
789 width may be instead dependent on the rheology (or flexural rigidity) of the cover, or the dip of  
790 the underlying fault (Figs. 7A; 7C).

791 The thickness of the prekinematic cover strongly affects fold growth. Thicker cover generates  
792 larger amplitude and width folds (Figs. 7E; 17D; 19D; 22C - D). We interpret that as the cover  
793 thickness increases, there is a larger amount of rock in front of the propagating fault tip. By  
794 increasing the thickness of the cover, the duration of folding will increase, permitting the growth  
795 of large folds with large throws.

796 We showed that as the cover rheology strength weakens, the fold becomes much wider for a  
797 given throw (Figs. 7D; 16A; 17A). This likely reflects that strain is accommodated in narrow  
798 zones near the fault tip in strong cover, but this same strain is far more distributed in weak  
799 cover. Similarly, gently-dipping faults distribute strain over a wider area compared to steeply-  
800 dipping faults, and thus, the dip of the fault will also control the fold width (Figs. 7A; 8). Given  
801 that both the rheology of the cover and dip of the fault strongly control fold width, they also  
802 strongly control the fold shape, corroborating results from Patton (2004). This is especially the  
803 case during the initial stages of folding, since the fold amplitude will be initially low (as fault  
804 throw is small), but the final width is established very early (cf. Path 2 on Fig. 20).

805 In addition to the aforementioned structural and stratigraphic factors, forced fold geometry and  
806 size is also affected by the thickness of the detachment (Figs. 7F; 12C - D). We suggest that  
807 detachments significantly weaken the overall strength of the cover and therefore, thicker  
808 detachments may distribute extensional strain over a broader area and increase the fold width.  
809 Given that the fold width is larger for a forced fold compared to a fault-propagation fold (Fig.  
810 22B), thicker detachments also increase the fold-shape-factor for a given amount of fault throw.  
811 This is similar to increasing the ductile portion of the cover, where folds have similar amplitudes  
812 for a given fault throw, but the width of the fold increases as the detachment content increases  
813 (Figs. 18E; 19A; Richard, 1989; Hardy, 2018).

814 As the detachment thickness also increases the total cover thickness, and thus, the amount of  
815 rock in front of the propagating fault tip, the folding duration also increases. A forced fold  
816 therefore has longer to grow before becoming breached by the underlying fault. This allows  
817 forced folds to reach larger amplitudes and widths compared to fault-propagation folds, and not  
818 become breached despite large fault throws. Ductile flow of the detachment, due to salt  
819 expulsion (cf. Fig. 5 in Koyi et al., 1993; Figs. 5 - 6 in Burliga et al., 2012; Figs. 5 - 6 in  
820 Warsitzka et al., 2015; Fig. 10 in Warsitzka et al., 2017), may also increase the amplitude of the  
821 forced fold. In some cases, the amplitude of the forced fold may be larger than the throw on the  
822 underlying fault (Fig. 22A).

823 Changes in structural and stratigraphic parameters are commonplace in extensional settings and  
824 thus, growth fold evolution may differ significantly between fault segments in different intra-  
825 rift settings (e.g. the rift margin vs. rift axis, transfer zones vs fault segment centres etc.) and in  
826 particular, between salt-free and salt-rich basins. We present conceptual models for how growth  
827 folds may vary between salt-free and salt-rich basins (Fig. 23), with particular emphasis on their  
828 3D geometry and size in relation to the dip, throw and displacement rate of master faults, the  
829 rheology, thickness, and rheological heterogeneity of the cover. These concepts are testable  
830 using natural examples, physical and numerical models, which may fill in gaps in our  
831 understanding in how growth folds develop through time and their occurrence.

832

### 833 **9.5. Implications for hydrocarbons and structural restoration**

834 We have shown that positive correlations exist between fault, fold and stratigraphic parameters.  
835 This means it is now possible to quantify: the fold amplitude (and structural relief) for growth  
836 folds for a given amount of throw on the underlying fault, the fold width during fold growth,  
837 and the fold shape during fold evolution once one or more growth fold- and/or fault-related

838 parameters (cf. Fig. 2) have been constrained. These have potentially important implications  
839 (Fig. 24), as understanding the likely shape and size of a growth fold through time is critical for  
840 determining palaeo- and present-day spill points for hydrocarbons in fold hinges (Mitra, 1990;  
841 Withjack et al., 1990; Withjack and Callaway, 2000; Tavani et al., 2018), as well as  
842 understanding the architecture and width over which synkinematic hydrocarbon reservoirs and  
843 seals may thin (Corfield et al., 2001; Patton, 2004; Lewis et al., 2015). This is especially useful  
844 in areas where synkinematic growth strata are below seismic resolution.

845 Fault-propagation and forced folds provide a rare opportunity to target vertically-stacked  
846 hydrocarbon plays (Fig. 24). Beneath the growth fold, hydrocarbons may become trapped in  
847 the underlying fault blocks (e.g. Uphoff, 2005). Within the growth fold, hydrocarbons may  
848 become trapped within the fold crest (e.g. Hibernia-Nautilus and Cormorant fields – Tankard  
849 and Welsink, 1987; Withjack and Callaway, 2000; Smørbukk Sør Field - Corfield and Sharp,  
850 2000; Corfield et al., 2001), within the heavily-fractured prekinematic cover or  
851 compartmentalised by secondary normal and reverse faults (Fig. 24). These secondary faults  
852 may either detach onto a detachment or link with the underlying master fault (Fig. 24B). The  
853 former creates fault-related traps, whereas the latter may allow hydrocarbons to leak from  
854 deeper to shallower levels (cf. Heggland, 1998; Ostanin et al., 2013; Mohammedyasin et al.,  
855 2016; Fig. 10D in Tavani et al., 2018) and may create fault-bound compartments in the cover  
856 (e.g. Mikkell, Midgard, Heidrun and Smørbukk fields of the Halten Terrace - Koch and Heum,  
857 1995; Corfield and Sharp, 2000). Above the growth fold, synkinematic reservoirs may thin over  
858 the fold (Fig. 24A – B; e.g. the Garn and Melke Fm of the Halten Terrace; Koch and Heum,  
859 1995; Corfield and Sharp, 2000; Corfield et al., 2001; cf. Lewis et al., 2013; Lewis et al., 2015).  
860 Fold-related relief may also affect transverse drainage patterns and control the distribution of  
861 fluvial (e.g. the Åre and Tofte formations of the Halten Terrace; Koch and Heum, 1995; cf.  
862 Burbank et al., 1996; Bernal et al., 2018) or turbidite reservoirs (cf. Grecula et al., 2003).

863 Additional plays may also be found in the detachment, such stringers (cf. van Gent et al., 2011;  
864 Fig. 24B).

865 Our results also have implications for the structural restoration of growth folds. For structural  
866 restoration to be valid, the kinematics and mode of deformation need to be identified (Lingrey  
867 and Vidal-Royo, 2015). In growth folds, the method for structural restoration method in section  
868 depends on the rheology of the cover, the mechanical heterogeneity, and the amount of strain.  
869 In salt-free basins (Fig. 23 – top), deformation associated with fault-propagation folds is  
870 focused in a broadly triangular zone emanating from the propagating fault tip upwards into the  
871 cover. Here, the lengths and thicknesses of individual beds are not maintained, but by assuming  
872 the area of the strata are the same, trishear methodologies (cf. Erslev, 1991; Hardy and Ford,  
873 1997; Allmendinger, 1998) may be used for restoration (e.g. Khalil and McClay, 2002; Jackson  
874 et al., 2006; Ford et al., 2007; Jin et al., 2009). However, caution is often applied as the  
875 geological significance of the parameters associated with trishear are poorly understood (Hardy  
876 and Ford, 1997; Cardozo et al., 2011; Hardy and Allmendinger, 2011). In salt-rich basins (Fig.  
877 23 – bottom), salt may permit layer-parallel slip so that strain is not accommodated at the fault  
878 tip but instead outboard from the structure. Furthermore, the cover may not be stretched (cf.  
879 ‘tectonic thinning’ after Brown, 1988) and instead be faulted (cf. ‘detachment slide’ after  
880 Brown, 1988). Salt may also facilitate slip between the cover and the basement (cf. Johnson  
881 and Johnson, 2002) or out-of-plane flow (e.g. Rowan and Kligfield, 1989; Rowan and Ratliff,  
882 2012), which is not permitted in trishear and may produce a different fold geometry (cf. Johnson  
883 and Johnson, 2002). Fault block restoration and flexural slip may therefore be most appropriate  
884 for salt-rich settings as bed lengths and orthogonal thicknesses may be preserved, at least at  
885 moderate strains (cf. Lingrey and Vidal-Royo, 2015). If the salt becomes immobile or welded  
886 during growth folding, layer-parallel slip and out-of-plane salt flow may cease and thus, trishear  
887 methods may be more appropriate. This has implications for extension estimates, particularly

888 in settings where growth folds are common, as the amount of extensional strain and mechanism  
889 responsible may be difficult to discern (Coleman et al., 2017). This also means that the most  
890 appropriate technique for restoring growth folds may change with fold growth, so how may we  
891 select the most appropriate? And how can the geometry and size of a growth fold be inferred?  
892 High-resolution growth strata or inferences from scaled models may be used to constrain fold  
893 geometry through time and thus aid restoration, however, synkinematic strata may not always  
894 be preserved (cf. Gawthorpe and Leeder, 2000; Patton, 2004) and model analogues may not be  
895 appropriate (cf. Fig. 15). Our results provide an additional independent constraint on growth  
896 fold geometry and size for structural and stratigraphic parameters that may be easily measured.  
897 Inevitably an iterative approach is required to isolate the most appropriate structural restoration  
898 solutions for growth folds in in salt-free and salt-rich settings. However, by constraining these  
899 solutions with growth strata, inferences from models and our parametric equations (Table 2),  
900 our understanding of the geometry, size and development of growth folds in nature may  
901 improve significantly.

902

## 903 **10. Conclusions**

- 904 • Growth folds are very common in sedimentary and volcanic basins, and perhaps more  
905 prevalent than they have been historically given credit for. Not only do they form as  
906 transient features during the early stages of salt-free rifting and persist throughout most  
907 of salt-rich rifting, but they also occur in a wide range of settings, including those with  
908 high regional strain rates that were previously interpreted to be unlikely to host these  
909 folds. They also occur in relatively brittle (e.g. volcanic sequences in Iceland and  
910 Hawaii) and ductile cover sequences (e.g. salt or shale-rich sequences). Furthermore,  
911 rheology alone is unlikely to be the principal control on growth fold occurrence. Instead,

912 we speculate that the propagation rate of individual faults may vary within an area and  
913 may control the distribution of growth folds.

914 • Fault-propagation and forced folds rapidly attain their near-final width relatively early  
915 during fold growth before they amplify. The rate of fold amplification is likely a function  
916 of the throw on the underlying normal fault. Their shape therefore changes throughout  
917 fold growth, evolving from a relatively broad, low amplitude fold to a fold where the  
918 amplitude and width are largely similar. Furthermore, the fold-shape-factor of a growth  
919 typically decreases with time.

920 • During extension or sediment loading, salt expulsion in the hangingwall and/or the  
921 development of salt pillows in the footwall for example, may lead to increased fold  
922 amplitudes and widths for forced folds. Forced folds may therefore grow very  
923 differently to and be geometrically distinct from fault-propagation folds.

924 • Growth folds are also dependent on the character of the underlying normal fault. As the  
925 fault grows in three-dimensions, so does the overlying growth fold. If the fault length  
926 and throw accumulate gradually and synchronously, growth folds may be expected to  
927 widen along-strike gradually. If faults rapidly establish their along-strike length before  
928 accumulating displacement, the along-strike width of the fold may be very large for a  
929 small amount of throw.

930 • By comparing correlations of measured fold parameters between fault-propagation and  
931 forced folds, we show that:

932 ○ For a given throw, the amplitude and width of a forced fold is larger than that of  
933 a fault-propagation fold.

934 ○ For a given fold width, the amplitude of a forced fold is generally larger than  
935 that of a fault-propagation fold.

936           ○ For a given prekinematic thickness, the width of a forced fold is greater than that  
937           of a fault-propagation fold.

938       • We also derive a number of parametric equations that are potentially powerful tools in  
939       estimating unknown fold geometry and size in profile by utilising other known  
940       structural and stratigraphic parameters. However, their robustness will need to be tested  
941       with further examples.

942       • Physical models effectively capture the geometrical features of natural examples of  
943       fault-propagation and forced folds, although their structural and stratigraphic  
944       parameters are not well correlated, in contrast to natural examples where moderate to  
945       strong correlations are present. However, an individual physical model, when analysed  
946       independently of other models shows similar parameter correlations to natural examples  
947       (e.g. fault throw vs. fold amplitude). Overall, comparisons between physical models and  
948       natural examples should be used with care, especially if used to infer the geometrical  
949       evolution of growth folds.

950       • Numerical models show similar correlations between stratigraphic and structural  
951       parameters to natural examples. However, numerical models, especially those where  
952       mechanical properties of rock units are not incorporated (i.e. kinematic models), cannot  
953       accurately describe the small-scale deformation observed in nature or physical models.  
954       Kinematic models however, do match the final geometry of growth folds in physical  
955       models and in nature, allowing the evolving fold geometry to be inferred. This is  
956       particularly useful in areas lacking synkinematic sediments.

957

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965

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Fold type	3D Geometry	Section (with synkinematic strata)	Map	Refs
Forced fold		<p>Thinning towards fold</p>		[1 - 4]
Fault-prop. fold		<p>Thinning towards fold</p>		[5 - 8]
Fault-prop. fold (breached)		<p>Thickening towards fault</p>		[5 - 8]
Compactional drape		<p>Sub-vertical fold axis</p>		[9 - 11]
Withdrawal drape		<p>Nearby 'leak' point</p>		[2]
Frictional drag		<p>Folding immediately next to fault plane</p>		[13 - 14]
Inversion		<p>Onlap onto inversion fold Early growth strata folded</p>		[16 - 20]
Fault-line deflection (recess)		<p>Fold next to fault curvature</p>		[21 - 23]
Fault-line deflection (salient)		<p>Fold next to fault curvature</p>		[21 - 24]

Synkinematic
  Prekinematic
  Detachment
  Basement

Figure 1 - Fault-related folds in extensional settings. See Appendix A for brief description of how each fold is developed. References are as follows: 1 – Laubscher, 1982; 2 – Withjack and Callaway, 2000; 3 - Ford et al., 2007; 4 – Lewis et al., 2013; 5 – Withjack et al., 1990; 6 – Gawthorpe et al., 1997; 7 – Sharp et al., 2000; 8 – Jackson et al., 2006; 9 – Thomson and Underhill, 1993; 10 - Skuce, 1996; 11- Faerseth and Lien, 2002; 12 – Billings, 1972; 13 – Resor, 2008; 14- Davis et al., 2011; 15 – Spahic et al., 2013; 16 – Badley et al., 1989; 17 – Mitra, 1993; 18 – Mitra and Islam, 1994; 19 – Turner and Williams, 2004; 20 – Jackson et al., 2013; 21 – Wheeler, 1939; 22 – Stewart and Hancock, 1991; 23 - Ehrlich and Gabrielsen, 2004; 24 – Machette et al., 1991. Synkinematic and prekinematic strata are also shown. Example detachments could include but are not limited to, salt (or evaporitic sequences) and overpressured shale.

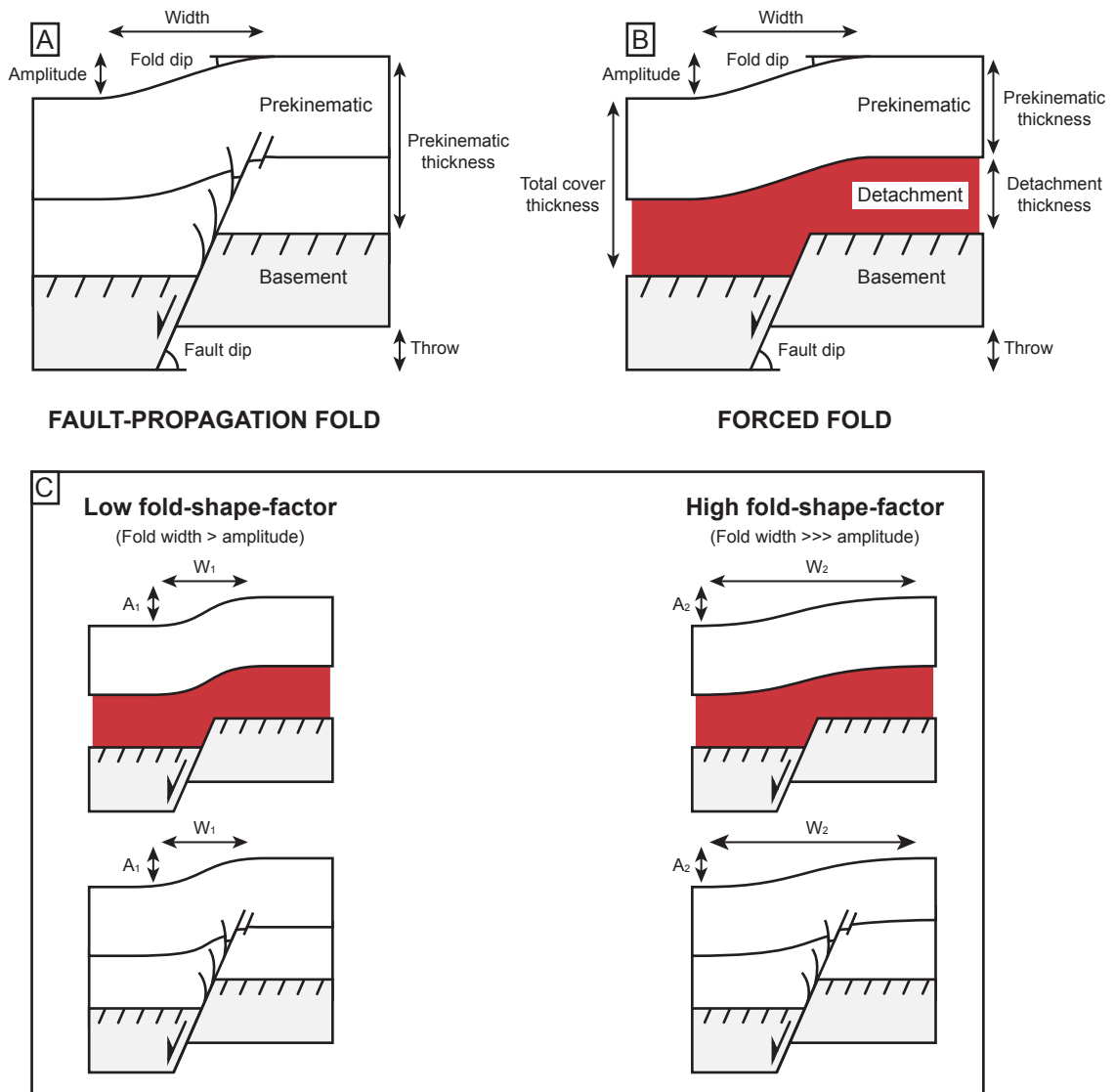
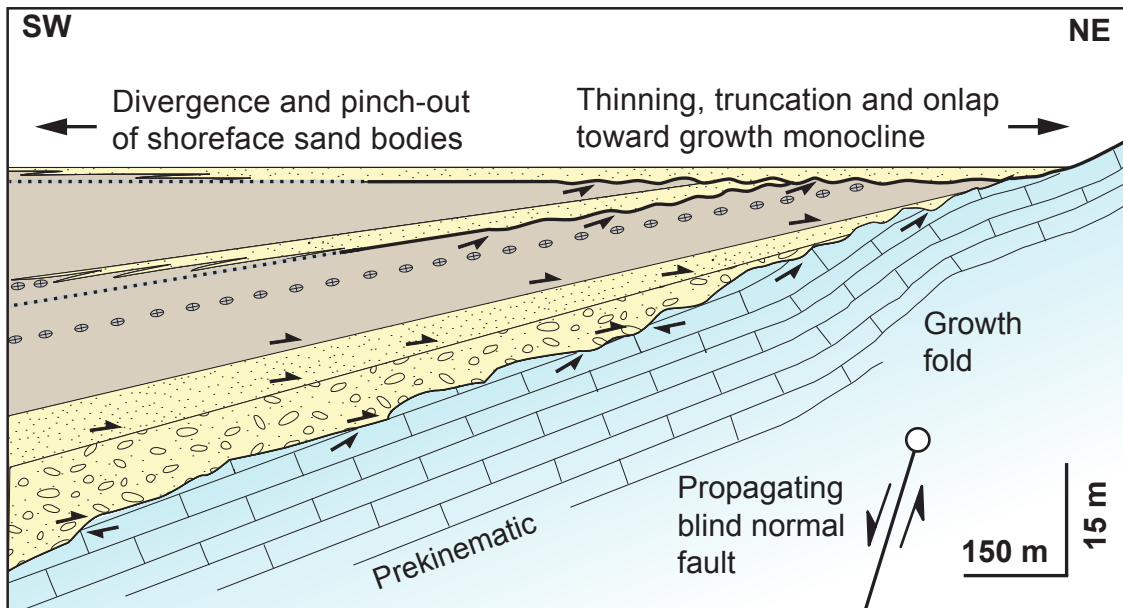


Figure 2 - Schematic, nomenclature and measured parameters for forced folds (A) and fault-propagation folds (B), showing the transition between faulting and folding. Modified after Withjack et al. (1990) and Stewart et al. (1996). Fold-shape-factor (FSF) = fold width/fold amplitude. Wide folds with small amplitudes have large FSF values, narrow folds with large amplitudes have low FSF values. Cover-detachment ratio (C:D) = prekinematic thickness/detachment thickness. Sequences with thick prekinematic strata and thin detachments have high C:D ratios. Sequences with very thin prekinematic strata and thick detachments have low C:D ratios. (C) Examples of high and low fold-shape-factor growth folds are also shown.  $A_1 - A_2$  and  $W_1 - W_2$  are widths and amplitudes for the different folds. Note that  $A_1 = A_2$ , but  $W_1 < W_2$ .



**A** Growth fold above blind fault (lower wedge)



**B** Surface-breaking fault (upper wedge)

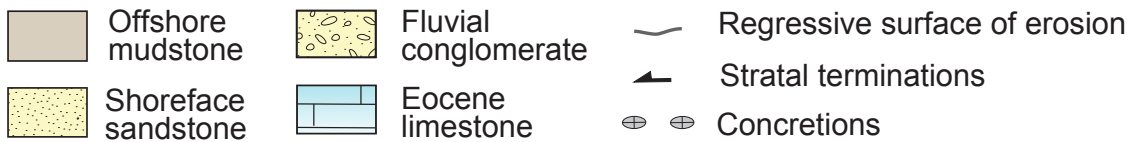
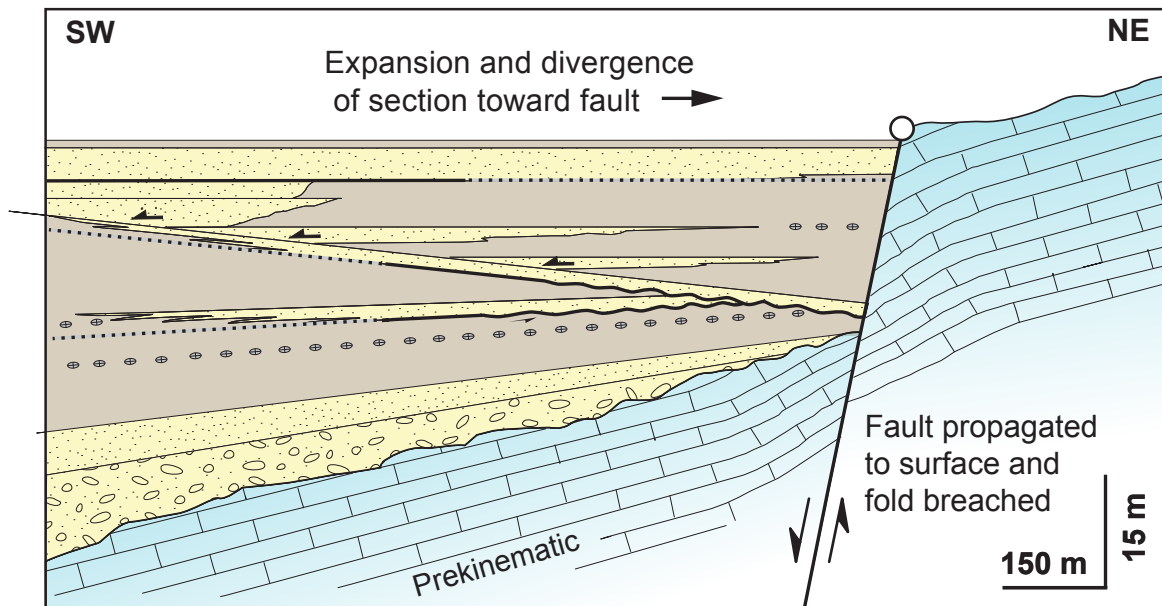


Figure 3 - Tectonostratigraphic evolution of the Baba-Sidri fault zone, Gulf of Suez. (A) Synkinematic sediments onlap onto the fault-propagation fold above a blind fault tip and thickening basinwards. (B) The fold is breached by the propagating normal fault and sediments thicken towards the fault. Modified from Gawthorpe et al. 1997.

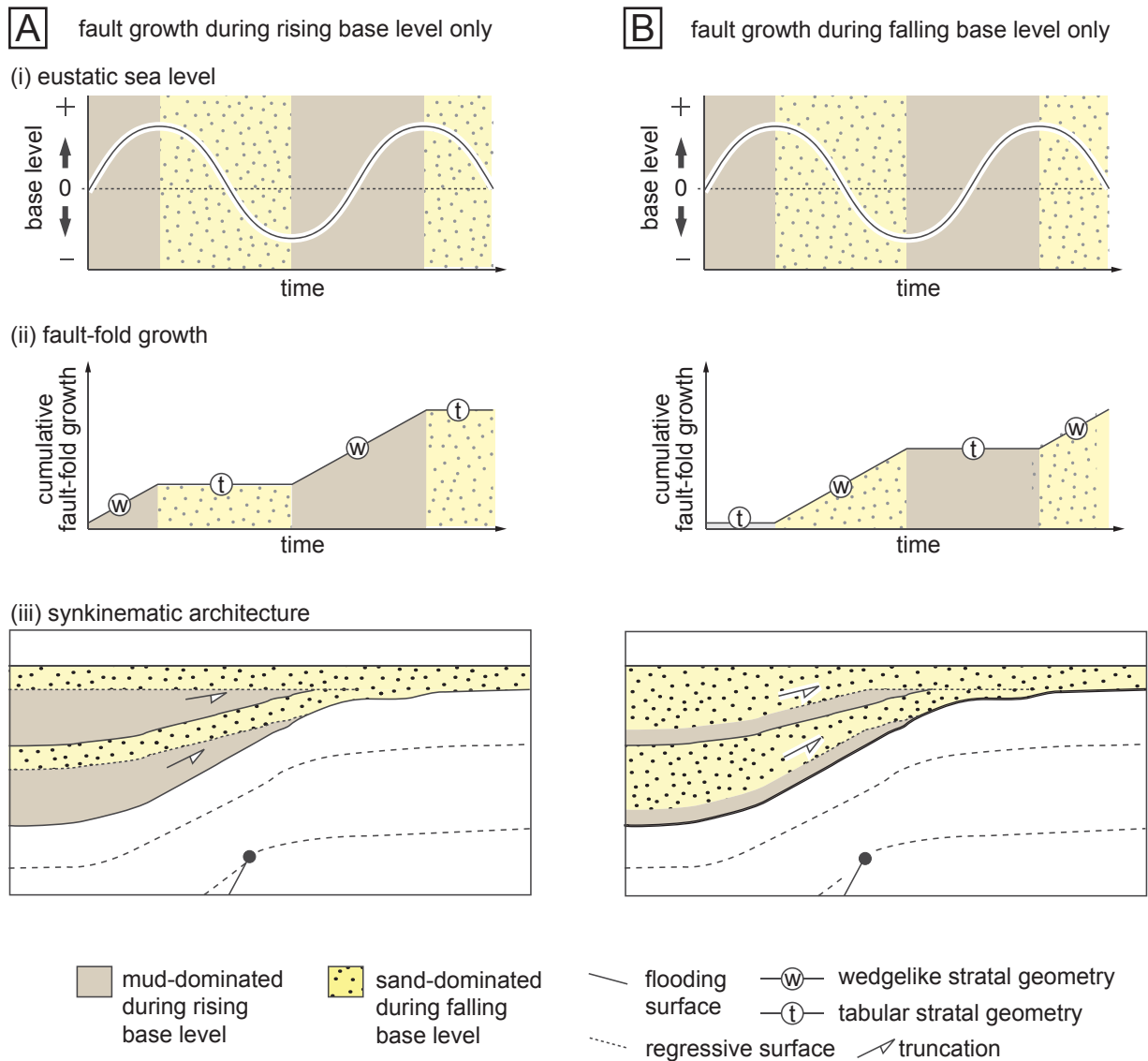


Figure 4 - How growth folds and eustasy interact to control synkinematic stratal architecture. Two end-members scenarios, depicting shallow marine shoreface sandstone deposition during falling base level (forced regression) are illustrated. (A) Surfaceward fault propagation and fold amplification during rising base level only results in basinward thickening of mudstone-dominated sediments. Shore face sands are deposited during times of tectonic quiescence, hence are tabular and truncate underlying mudstones. (B) Surfaceward fault propagation and fold amplification during falling base level results in basinward thickening of the sandstone units. Mudstones are deposited during times of tectonic quiescence, hence are tabular and are truncated near the fold crest. Unconformities near the fold may pass basinward into correlative conformities. Modified from Lewis et al. (2015).

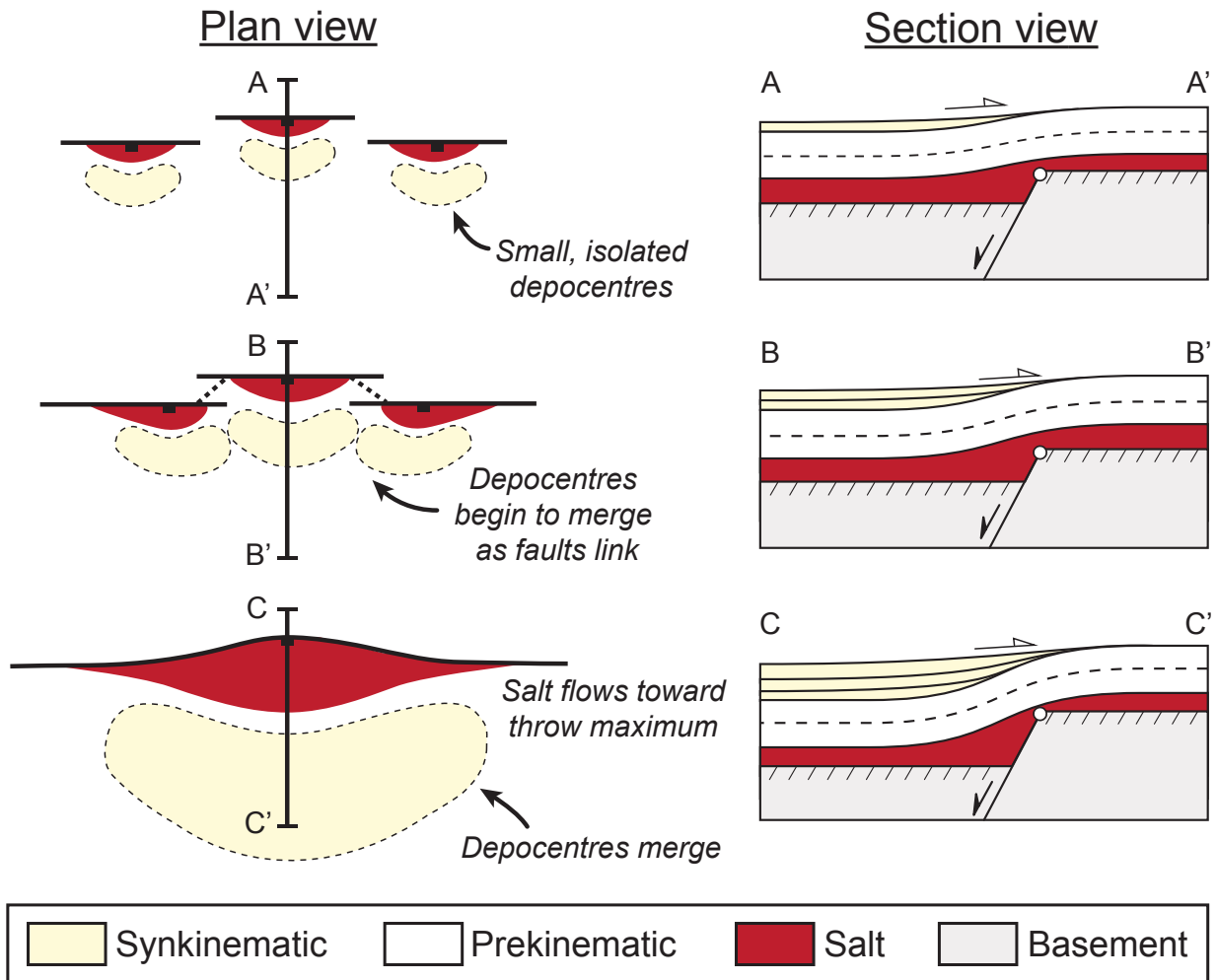


Figure 5 - Schematic diagram illustrating the evolution of salt-influenced fault-fold systems and their associated sedimentary depocentres. Modified from Richardson et al., 2005.

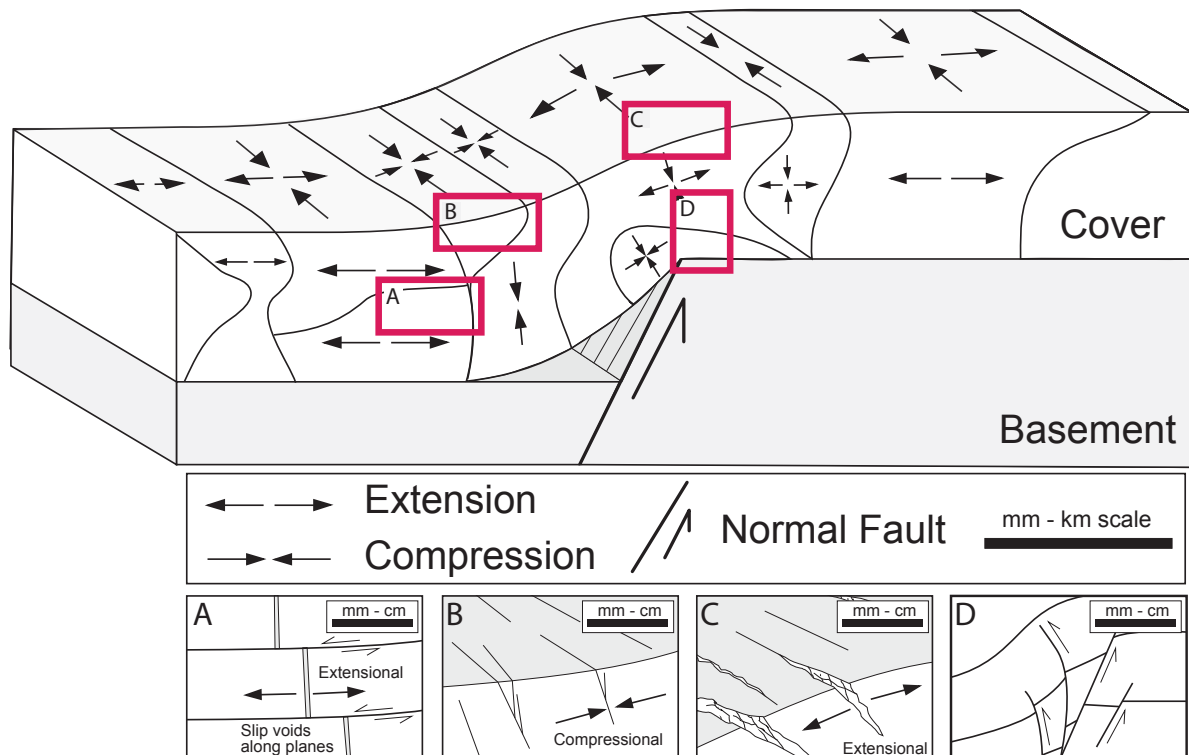
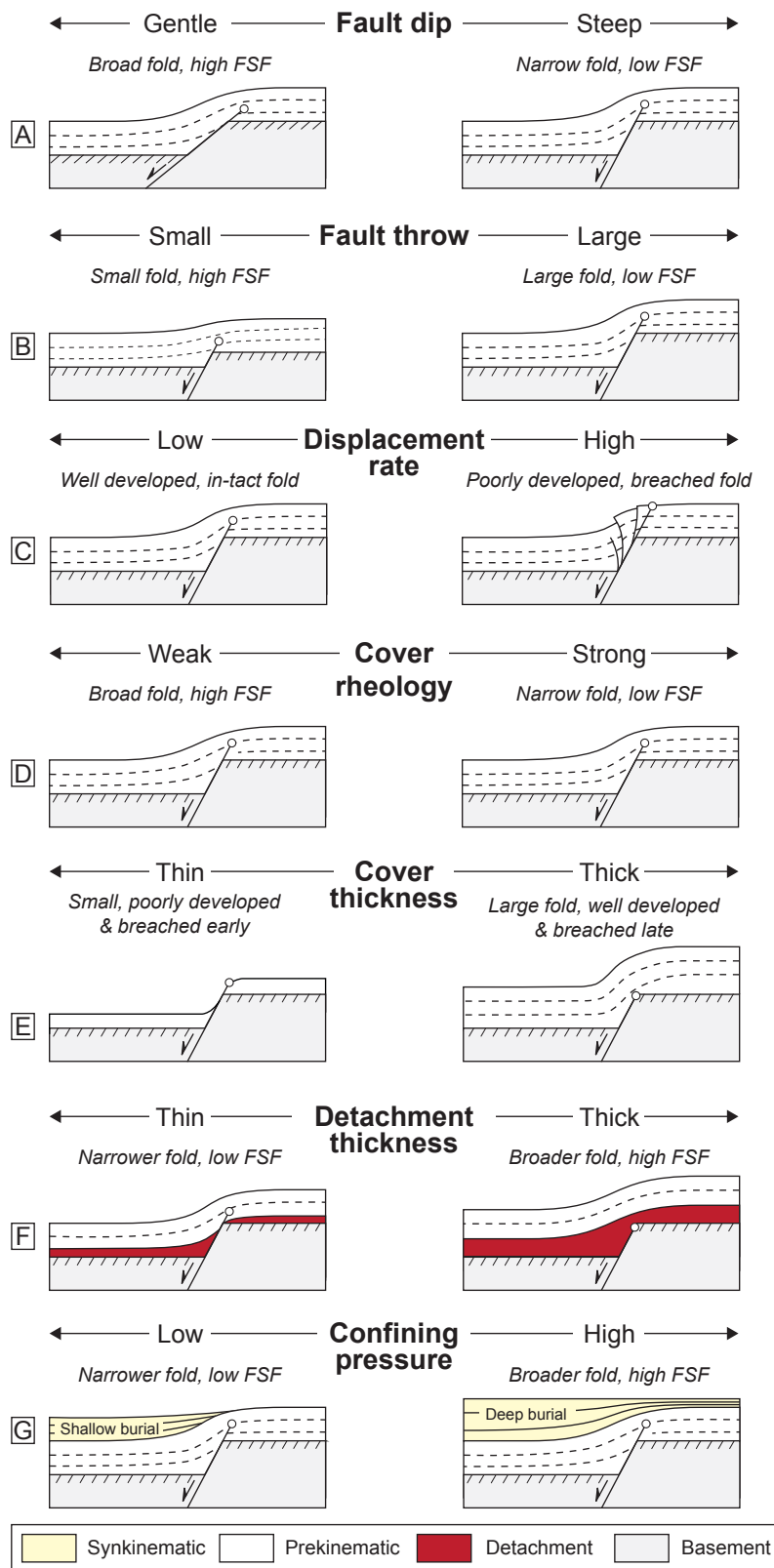


Figure 6 - Block diagram of a growth fold developed above a propagating basement normal fault. The fold has been divided into zones according to extensional or contractional strain, modified from Ameen, 1988 and Ameen, 1990. Idealised secondary deformation features are superimposed: (A) layer-parallel slip surfaces and slip voids, (B) compaction bands and closed fractures, (C) dilational fractures, and (D) secondary reverse faults. Secondary deformation inspired by observations from field studies, including the Gulf of Suez (e.g. Sharp et al., 2000a; b; Jackson et al., 2006), Brushy Canyon (e.g. Ferrill et al., 2007; Smart et al., 2010), and the Pyrenees (e.g. Tavani et al., 2018), and physical models (e.g. Withjack et al., 1990; Withjack and Callaway, 2000; Jin and Groshong, 2006; Paul and Mitra, 2015). This is not an exhaustive list of possible features, just of those traditionally reported from field studies – see text for details.



## Key references

Mitra, 1993 - Fig. 4 & 9  
Withjack & Callaway, 2000 - Fig. 3  
Finch et al., 2004 - Fig. 7 & 8  
Hardy, 2018 - Fig. 6

Mitra, 1993 - Fig. 4  
Withjack & Callaway, 2000 - Fig. 7  
Miller & Mitra, 2011 - Fig. 9 - 11

Hardy & McClay, 1999 - Fig. 5  
Withjack & Callaway, 2000 - Fig. 14

Withjack & Callaway, 2000 - Fig. 5a  
& Fig. 11a  
Finch et al., 2004 - Fig. 9 - 11

Withjack & Callaway, 2000 - Fig. 14

Richard, 1989 - Fig. 4.8  
Withjack & Callaway, 2000 - Fig. 5  
Finch et al., 2004 - Fig. 13  
Hardy, 2018 - Fig. 7

Patton et al., 1998 - Fig. 7

Figure 7 - Controls on growth fold shape and size as identified by physical and numerical models. Displacement rate (C), is also linked to the strain rate and propagation rate of the upper fault tip in Withjack and Callaway (2000).

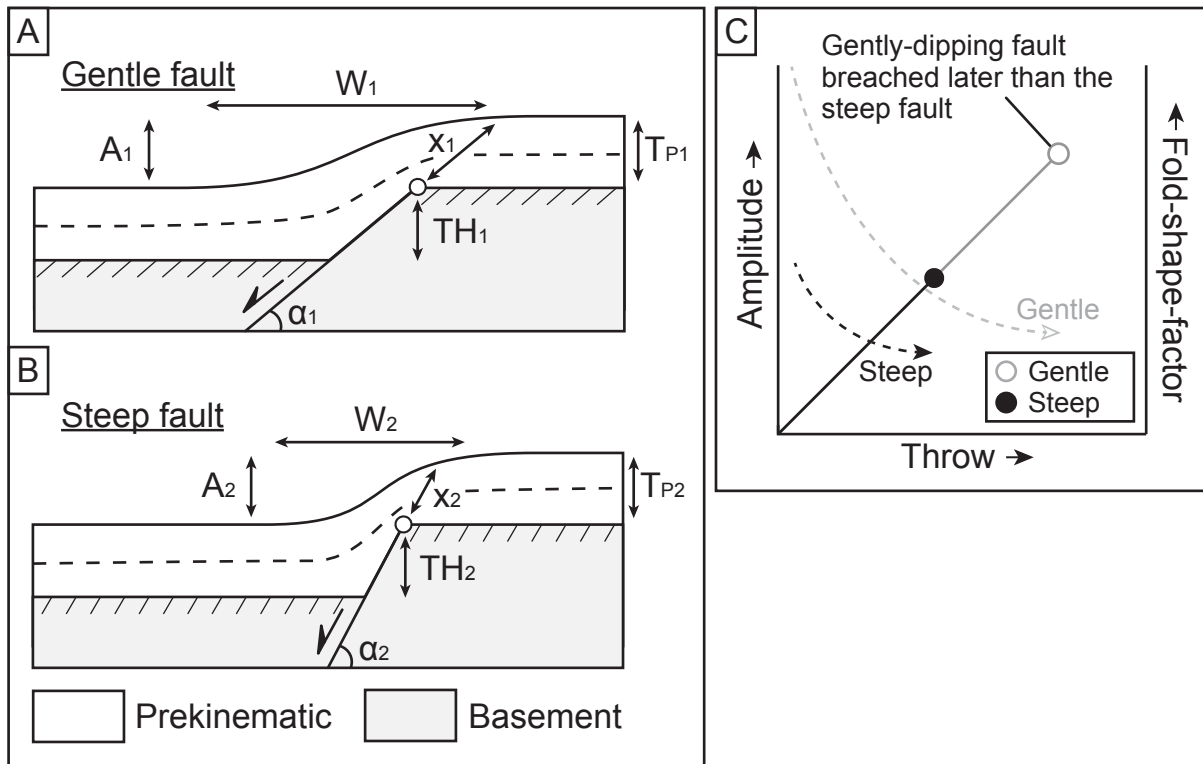


Figure 8. - Schematic showing the rapid breach of growth folds above a steeply-dipping fault (A) compared to a shallowly-dipping fault (B). The idealized geometry of the developing fold is also shown. (C) The amplitude (solid lines) for a gentle and steep fault increase with throw. Where faults breach the fold, a circle is plotted. The steeply-dipping fault breaches its associated fold more quickly than for a gently-dipping fault as there is a larger rock volume in front of the propagating upper normal fault tip i.e.  $x_1 \gg x_2$ . The fold-shape-factor is shown by the dashed lines, and both decrease with increasing throw on the basement fault. Symbology for the parameters are also shown. Note how the fold associated with the steeply-dipping fault is breached earlier than the gently-dipping fault, and how the FSF decreases as the fold grows.



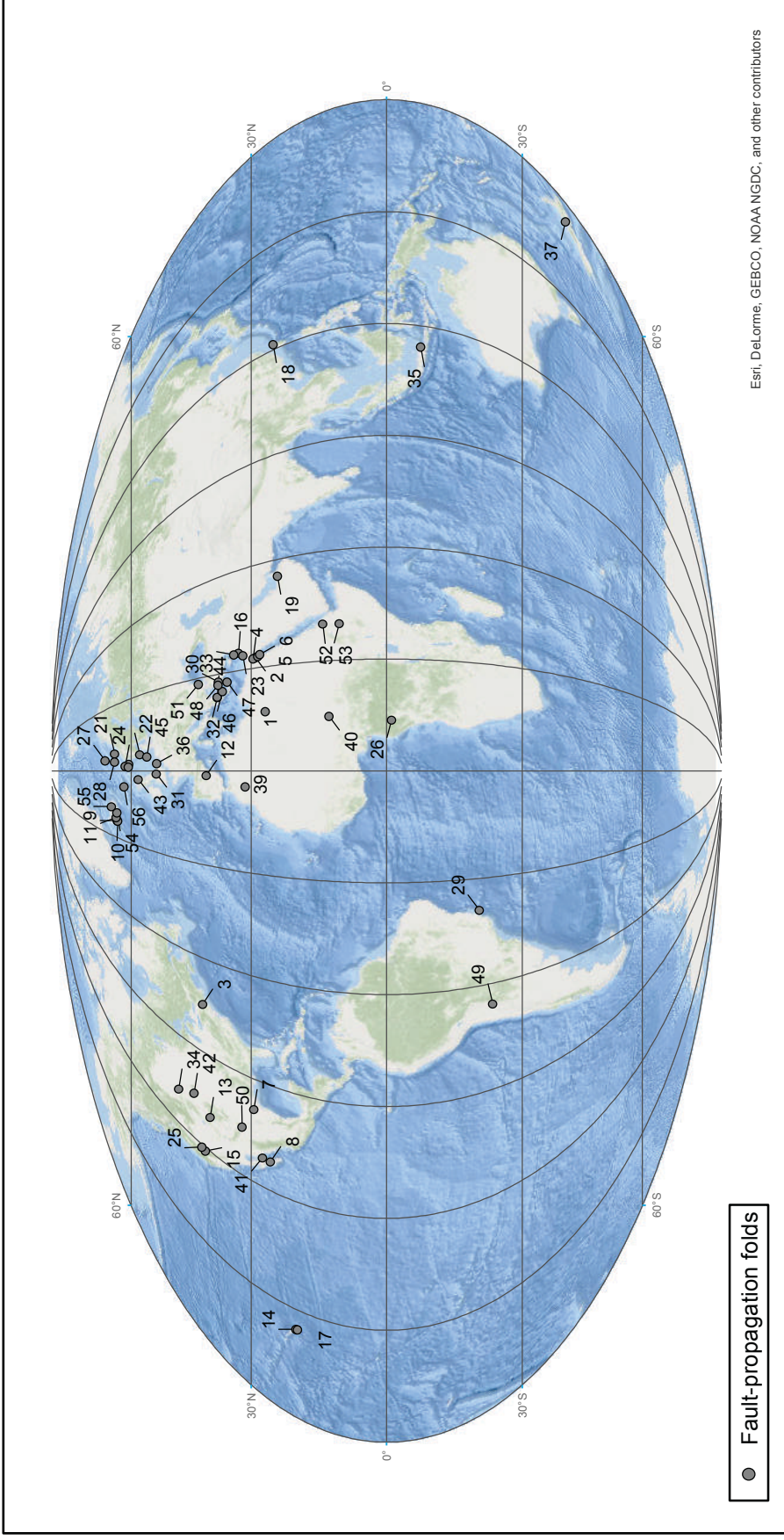


Figure 9 - Distribution of fault-propagation folds. See Appendix B for locations.



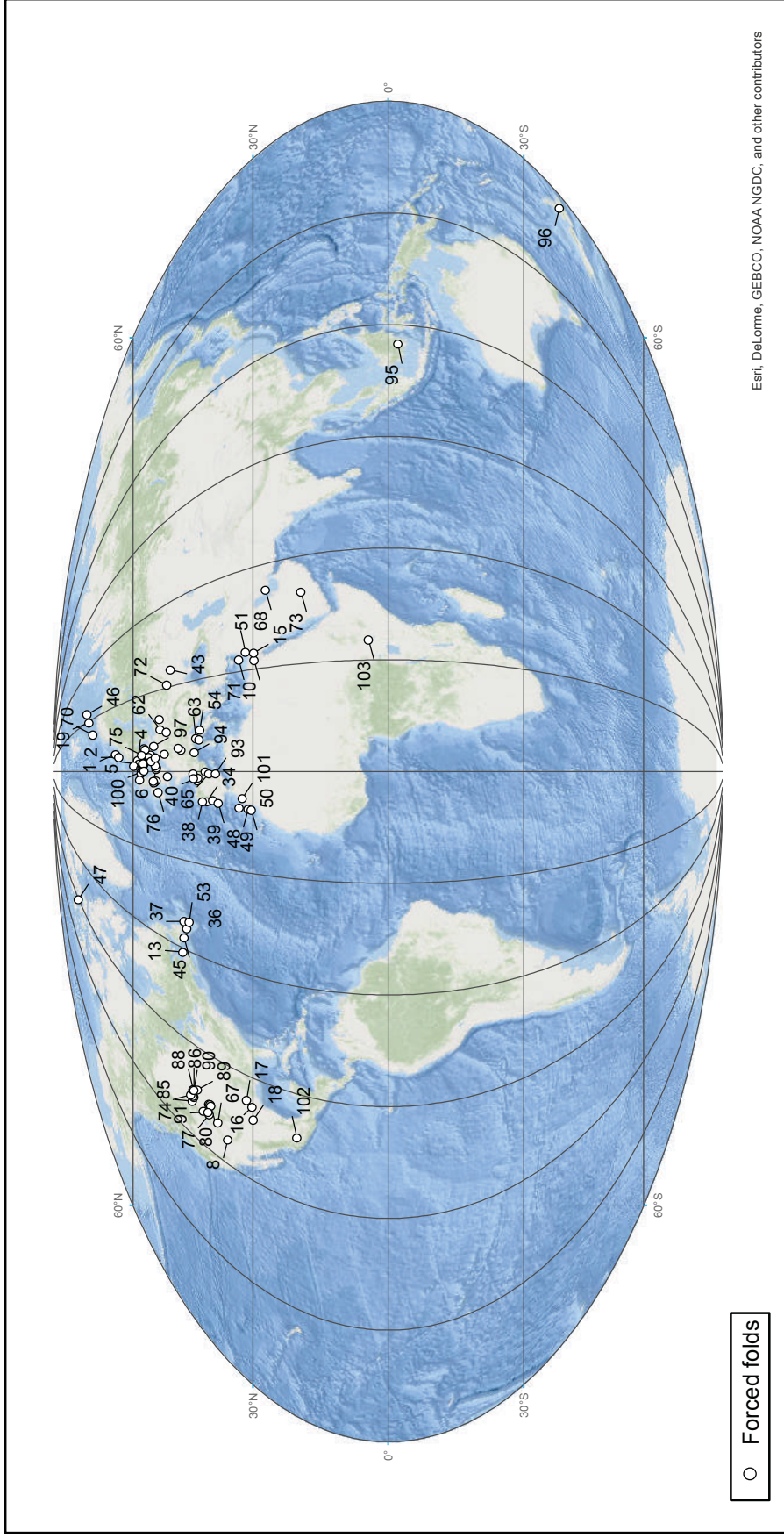
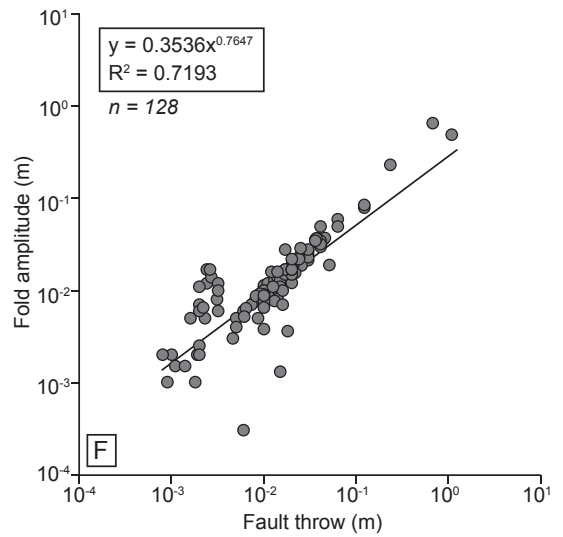
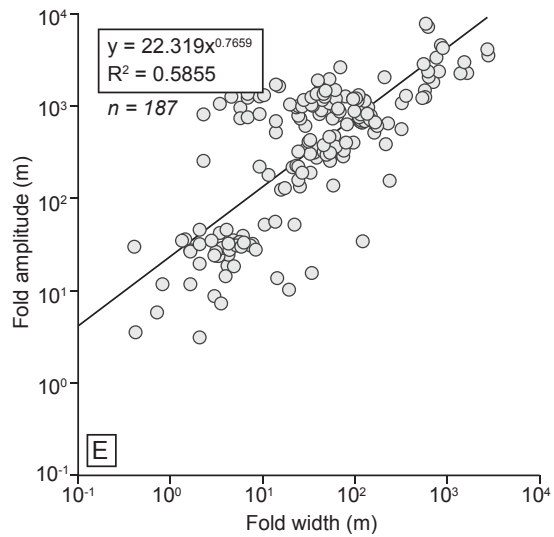
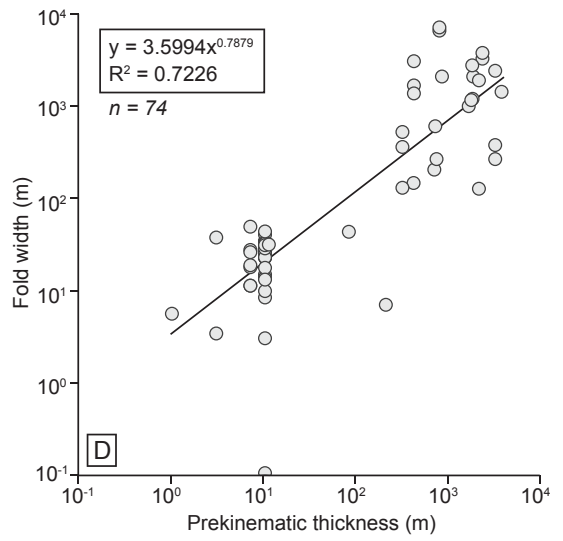
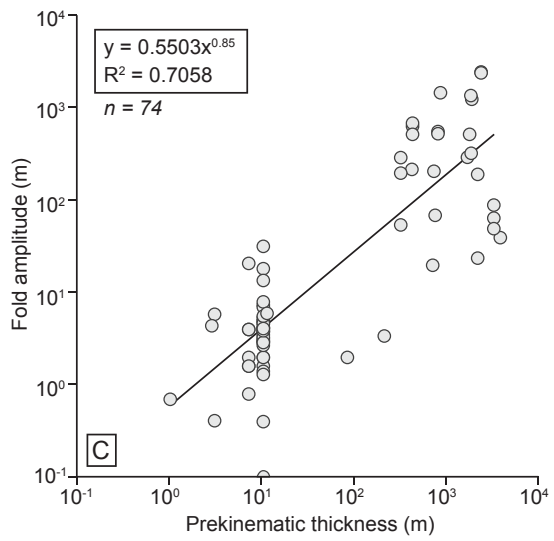
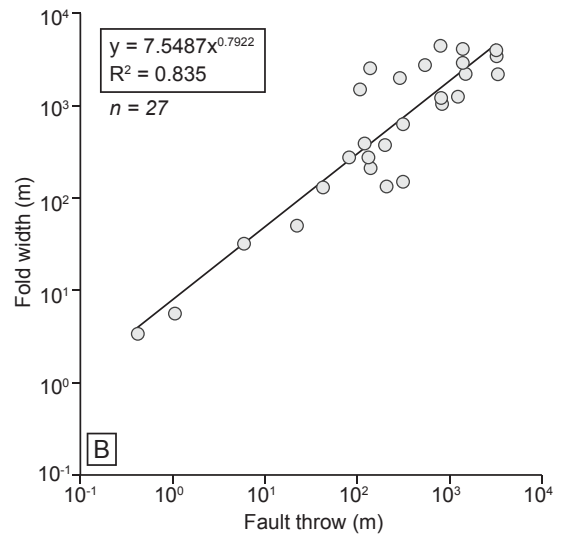
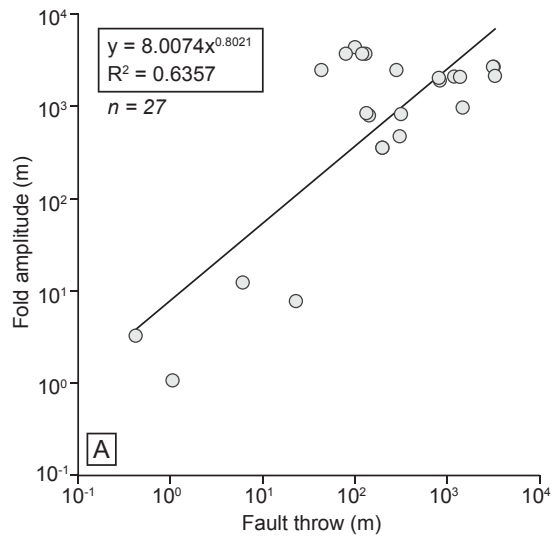


Figure 10. - Distribution of forced folds. See Appendix C for locations.



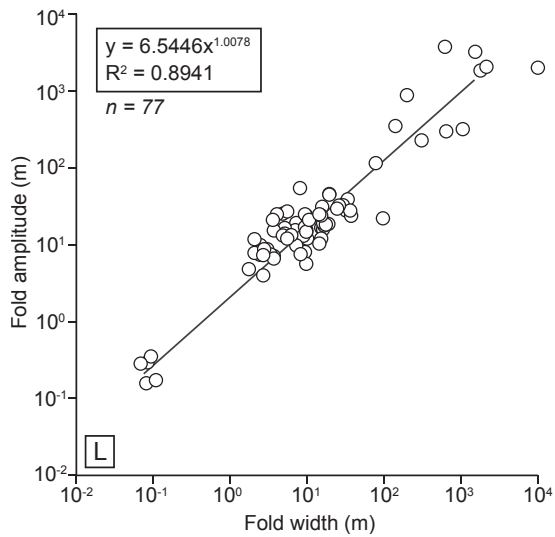
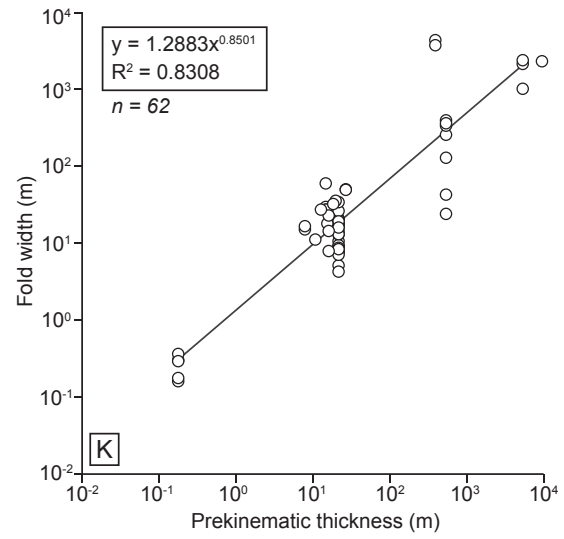
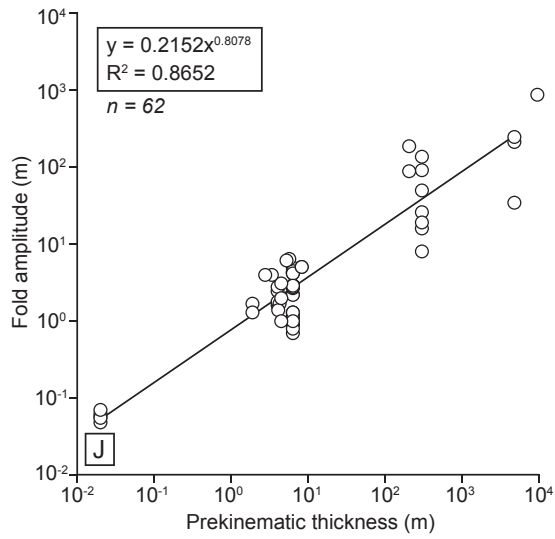
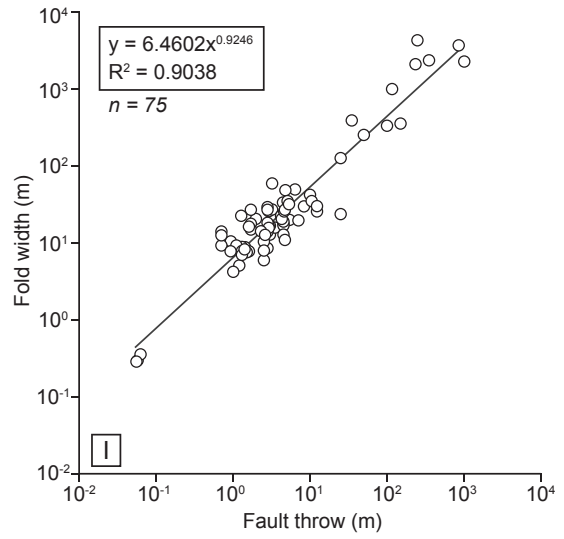
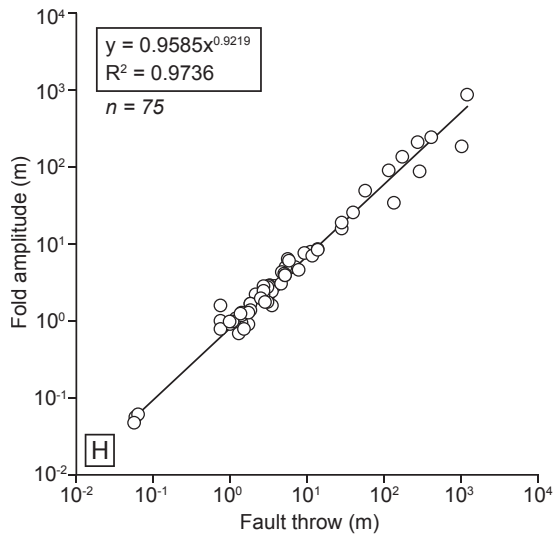
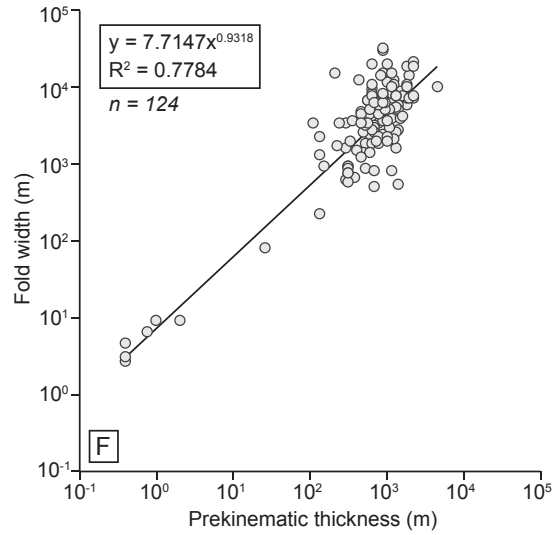
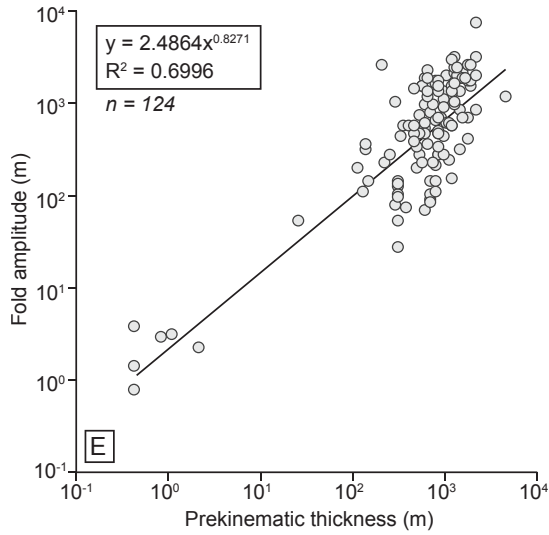
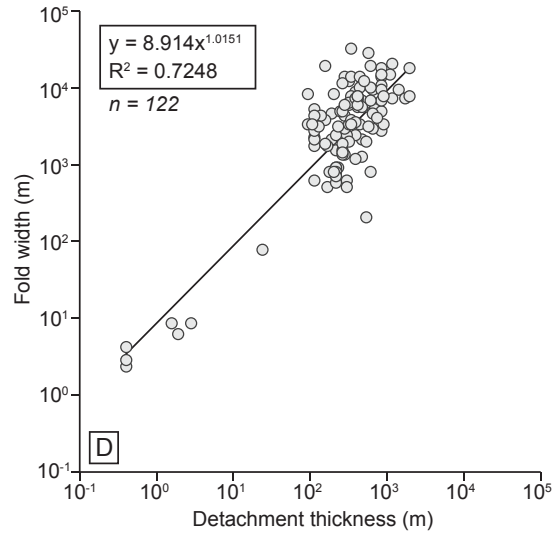
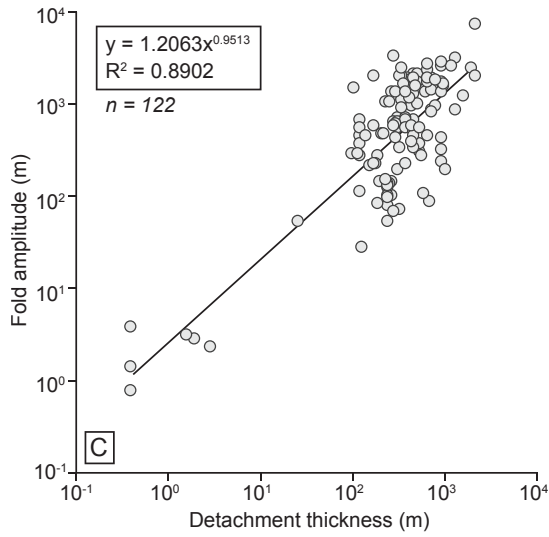
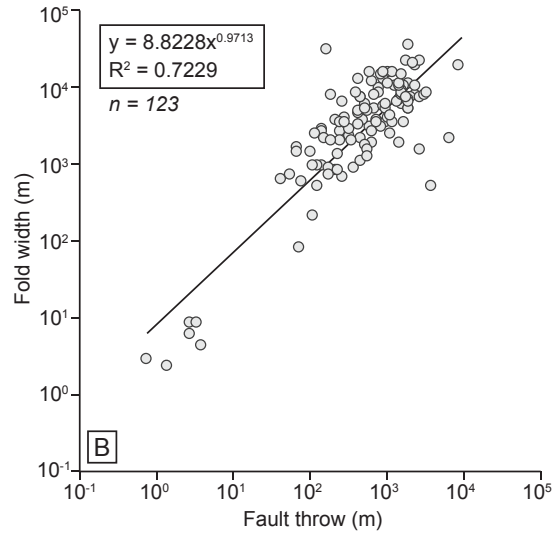
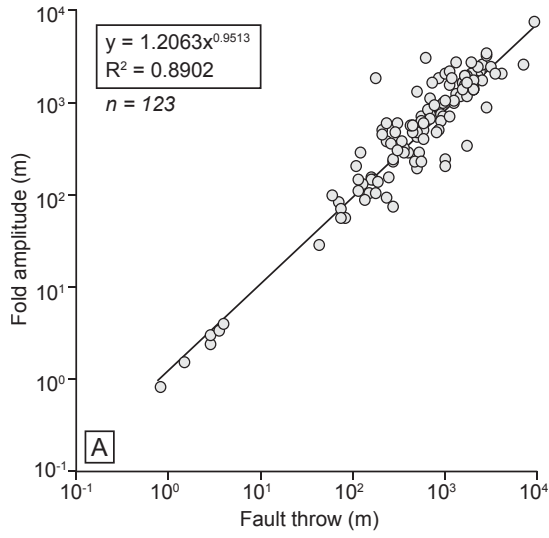


Figure 11 - Moderate-to-strong correlations for fault-propagation folds in nature (A – E; light grey circles), physical models (F; dark grey circles) and numerical models (H-L; white circles). The best-fit regression, correlation coefficient ( $R_2$ ) and number of observations (n) are also shown. See Table 2 for further details. See Fig. 2 for parameter descriptions.



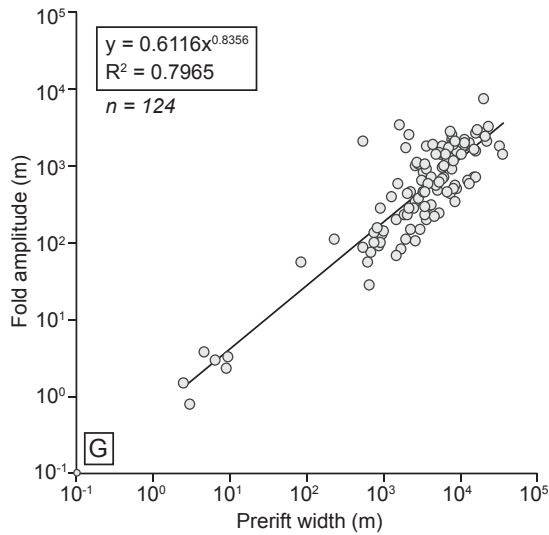


Figure 12 - Moderate-to-strong correlations for forced folds in nature (A – G; light grey circles). The best-fit regression, correlation coefficient ( $R^2$ ) and number of observations ( $n$ ) are also shown. Physical models lacked any moderate-to-strong correlations. See Table 2 for further details. See Fig. 2 for parameter descriptions. Analysis was not undertaken for numerical models of forced folds.

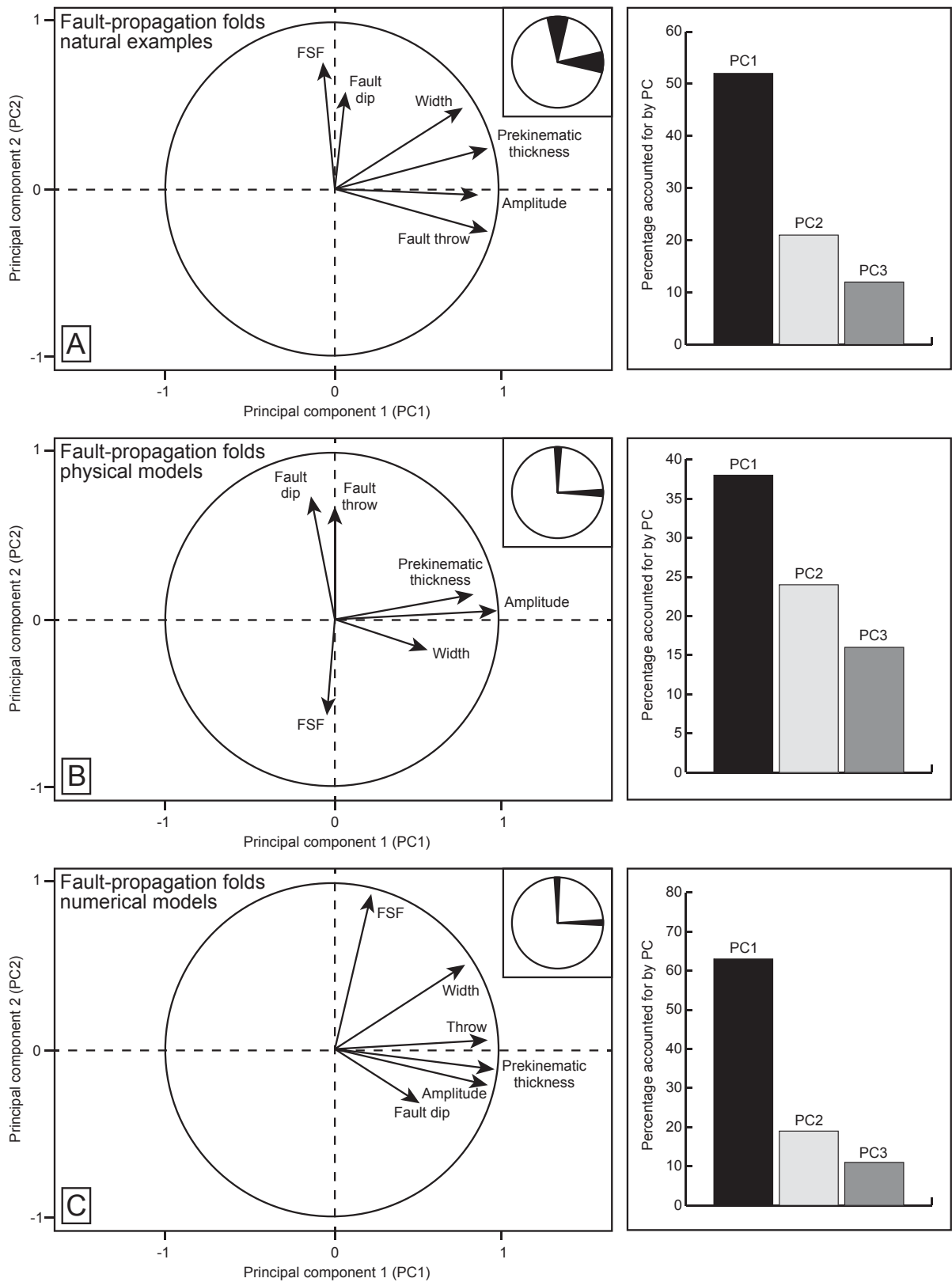


Figure 13 - Principal component analysis (PCA) for fault-propagation folds in nature (A), physical models (B) and numerical models (C). The percentage of the data variation accounted for by each principal component (PC) and uncertainty associated with missing values is shown in each case. See Fig. 2 for parameters.

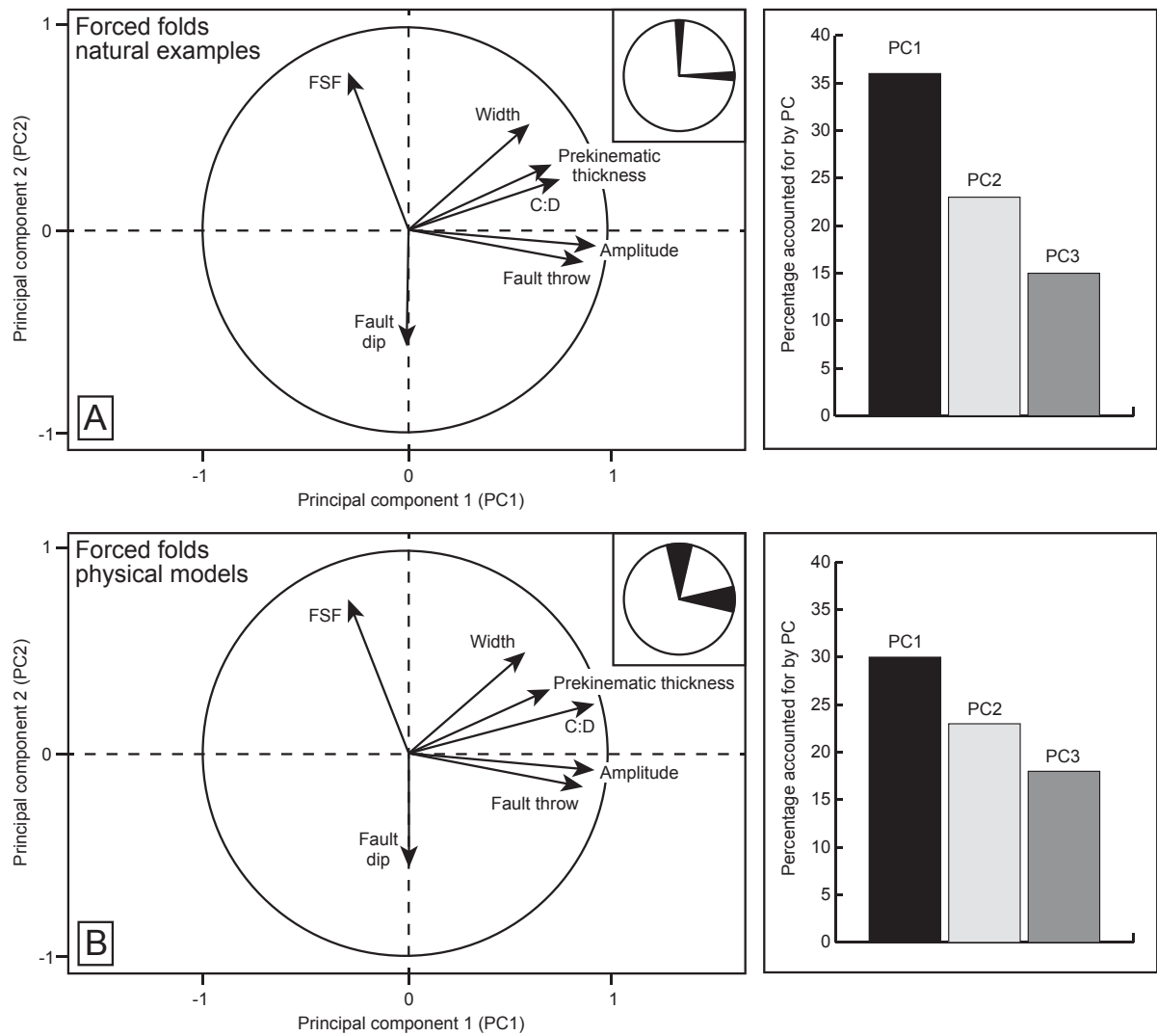


Figure 14 - Principal component analysis (PCA) for forced folds in nature (A) and physical models (B). The percentage of the data variation accounted for by each principal component (PC) and uncertainty associated with missing values is shown in each case. PCA was not undertaken for numerical models as there only Hardy (2018) explicitly model a forced fold. See Fig. 2 for parameters.



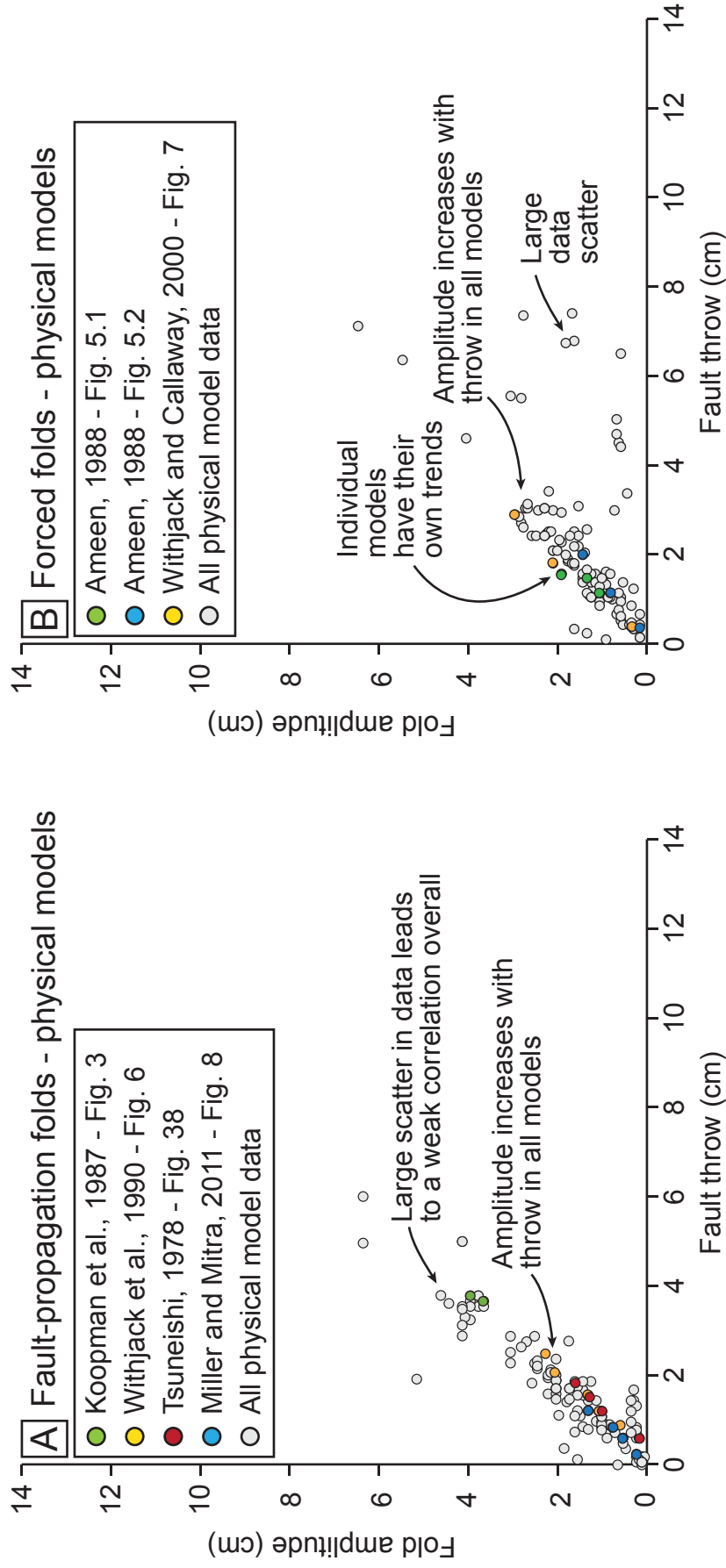


Figure 15 - Physical models of fault-propagation and forced folds show an overall weak-to-moderate correlation. However, individual models in isolation, show similar trends as observed in nature e.g. increased amplitude with throw. These relationships are often hidden within the data are likely due to the large amount of variance introduced by different model setups and material properties.

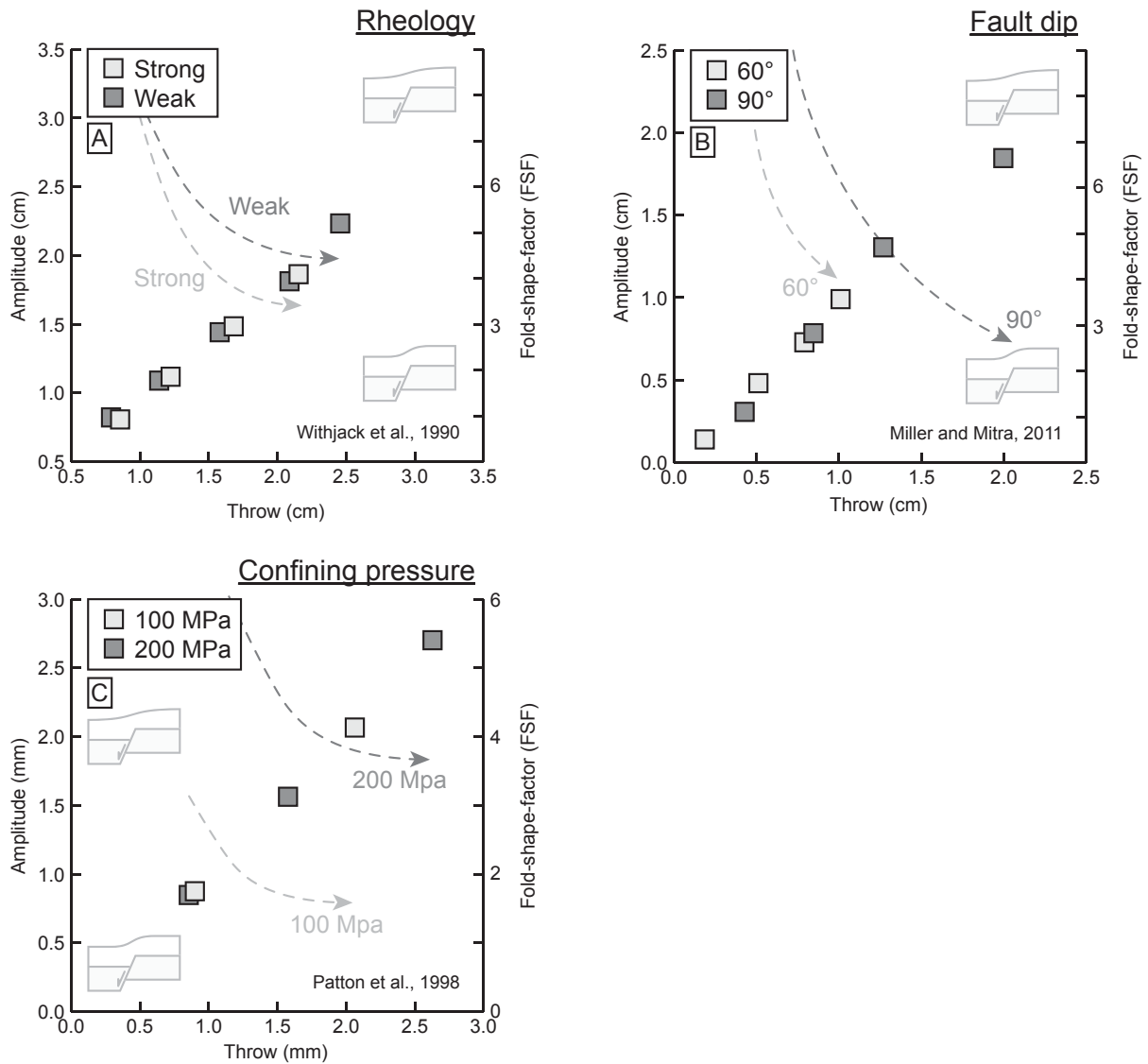


Figure 16 - Predictions of fault-propagation fold growth from physical models due to changes in (A) cover rheology, (B) fault dip, and (C) confining pressure. Fold-shape-factor (FSF) is represented by the dashed line and decreases with increased throw. A schematic of the fold shape is also shown. Amplitude is on the left-y-axis, while FSF is on the right-y-axis for panels A - C. Only in-tact fault-propagation fold measurements are plotted. FSF and amplitude values are taken from the same model at the same time. The reference for each plot is also shown.

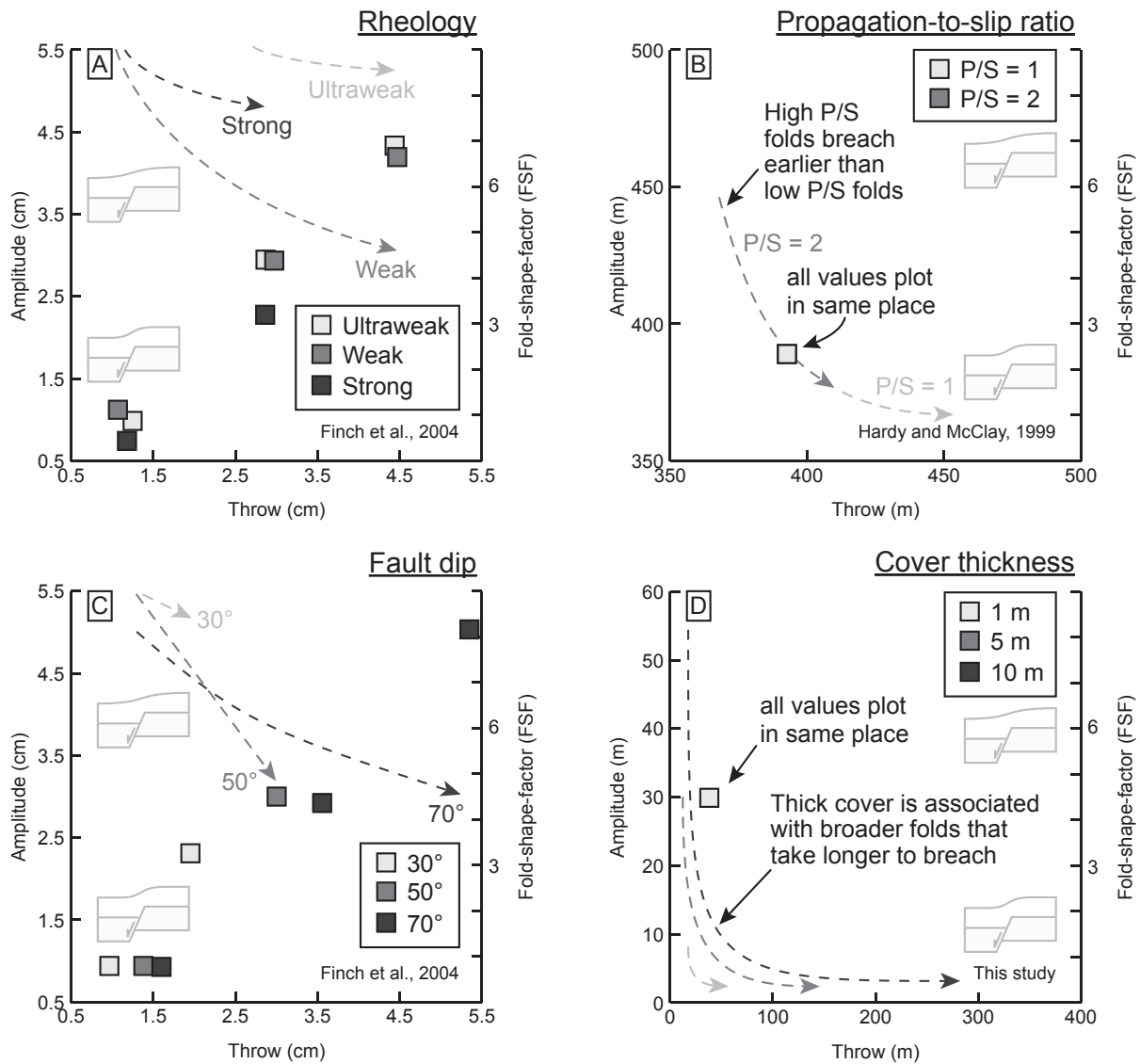


Figure 17 - Predictions of fault-propagation fold growth from numerical models due to changes in (A) cover rheology, (B) propagation-to-slip ratio, (C) fault dip, (D) cover thickness. Fold-shape-factor (FSF) is represented by the dashed line and decreases with increased throw. Amplitude is on the left-y-axis, while FSF is on the right-y-axis for panels A - D. Only in-tact forced fold measurements are plotted. The reference for each plot is also shown. Cover thickness (D) was calculated in this study using forward trishear models (after Allmendinger, 1998).

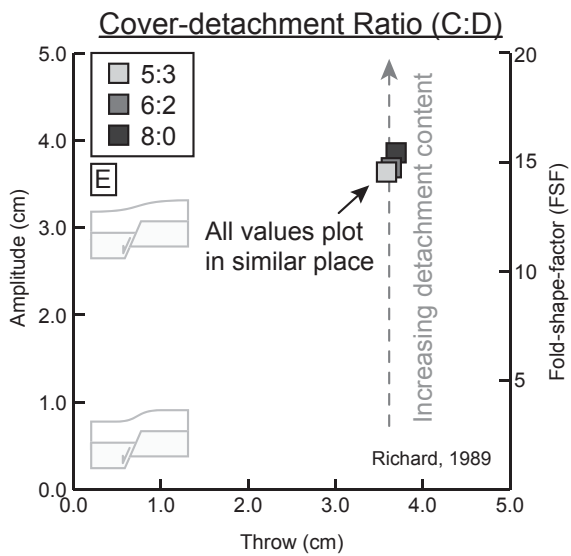
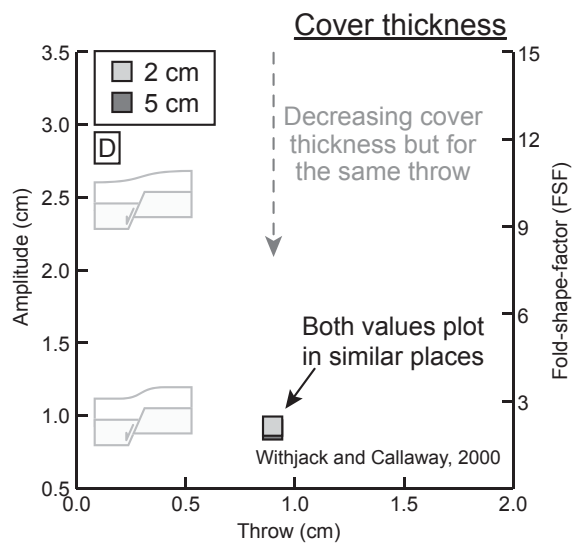
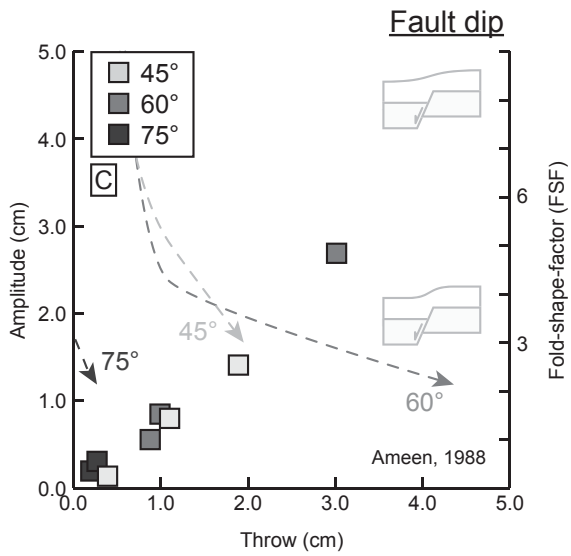
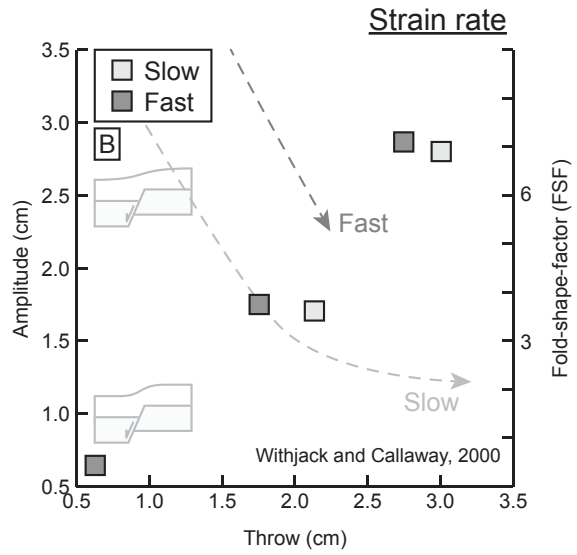
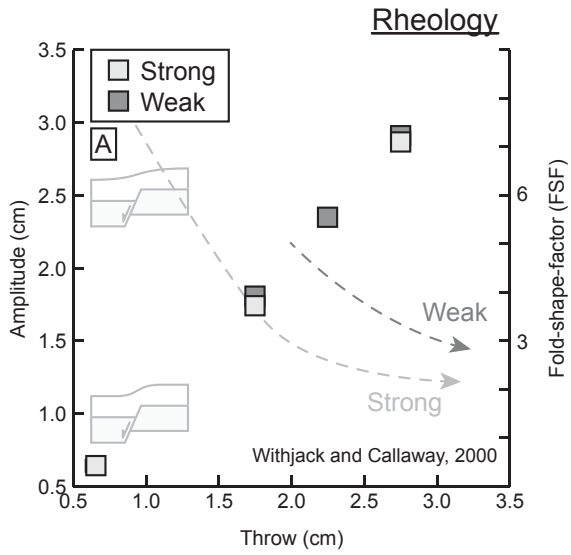


Figure 18 (previous page) - Predictions of forced fold growth from physical models due to changes in (A) cover rheology, (B) strain rate, (C) fault dip, (D) cover thickness, and (E) cover-detachment ratio. Fold-shape-factor (FSF) is represented by the dashed line and decreases with increased throw. A schematic of the fold shape is also shown. Amplitude is on the left-y-axis, while FSF is on the right-y-axis for panels A - E. Fold amplitude data on panels D – E are largely similar but the fold width and hence the FSF, is different. Only in-tact forced fold measurements are plotted. References for each plot are also shown. FSF and amplitude values are taken from the same model at the same time. Note that the strain rate and displacement rate are linked in Withjack and Callaway (2000).

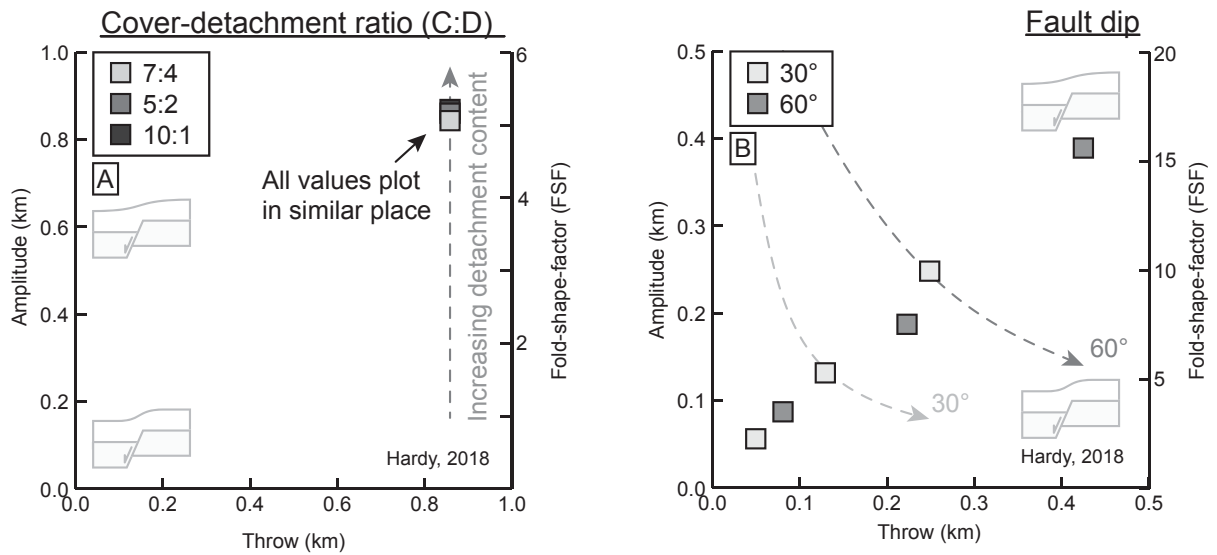


Figure 19 - Predictions of forced fold growth from numerical models (from Hardy, 2018) due to changes in (A) cover-detachment ratio, (B) fault dip. Fold-shape-factor (FSF) is represented by the dashed line and decreases with increased throw. Amplitude is on the left-y-axis, while FSF is on the right-y-axis for panels A - B. Only in-tact forced fold measurements are plotted.

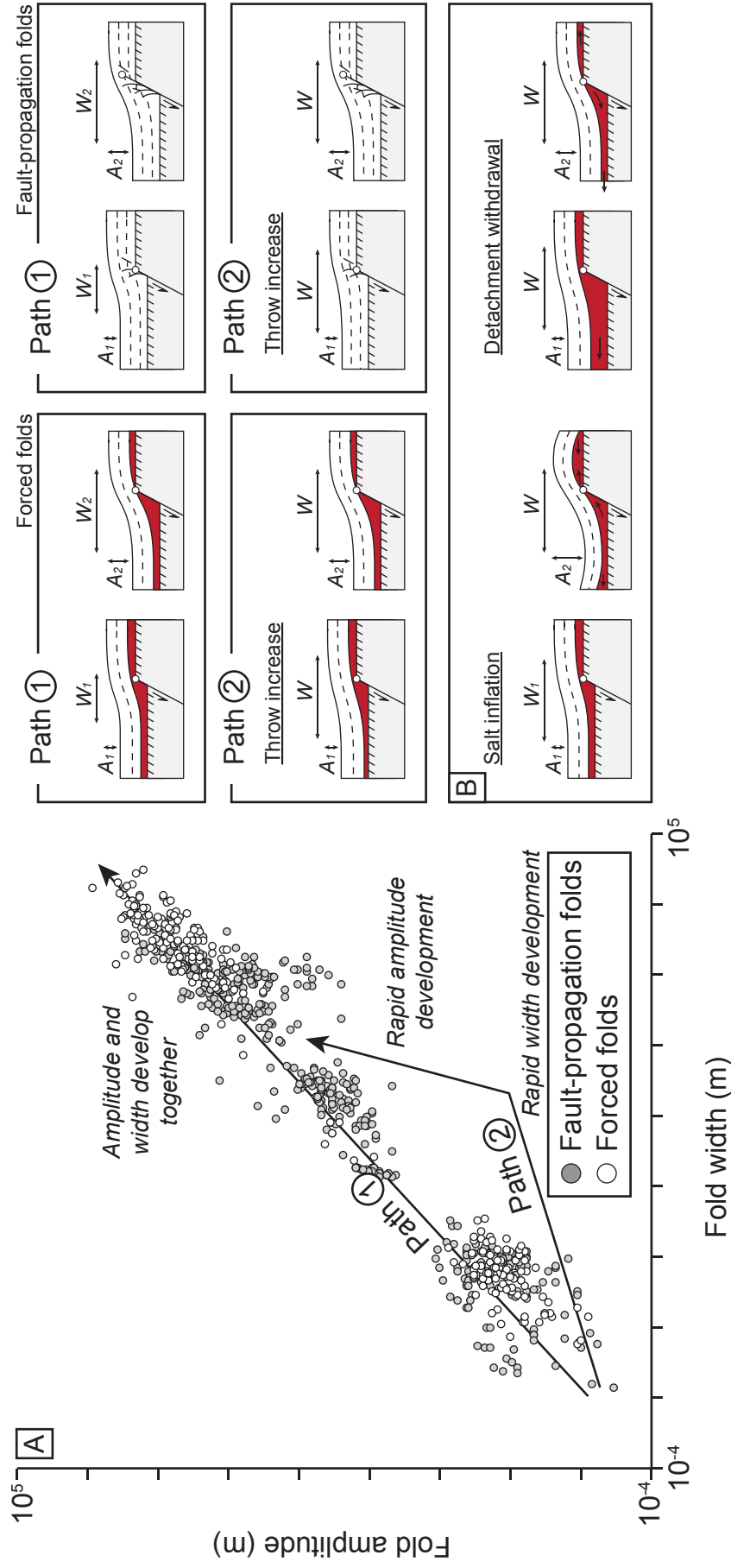


Figure 20. Growth of fault-propagation and forced folds (A). Two schematic paths for the growth fold evolution are plotted (path 1 and path 2). Folds following path 1 amplify and widen at a similar, gradual rate. Folds following path 2 widen early and amplify relatively late during fold growth. Amplitude and width variations due to salt flow are also shown (B).

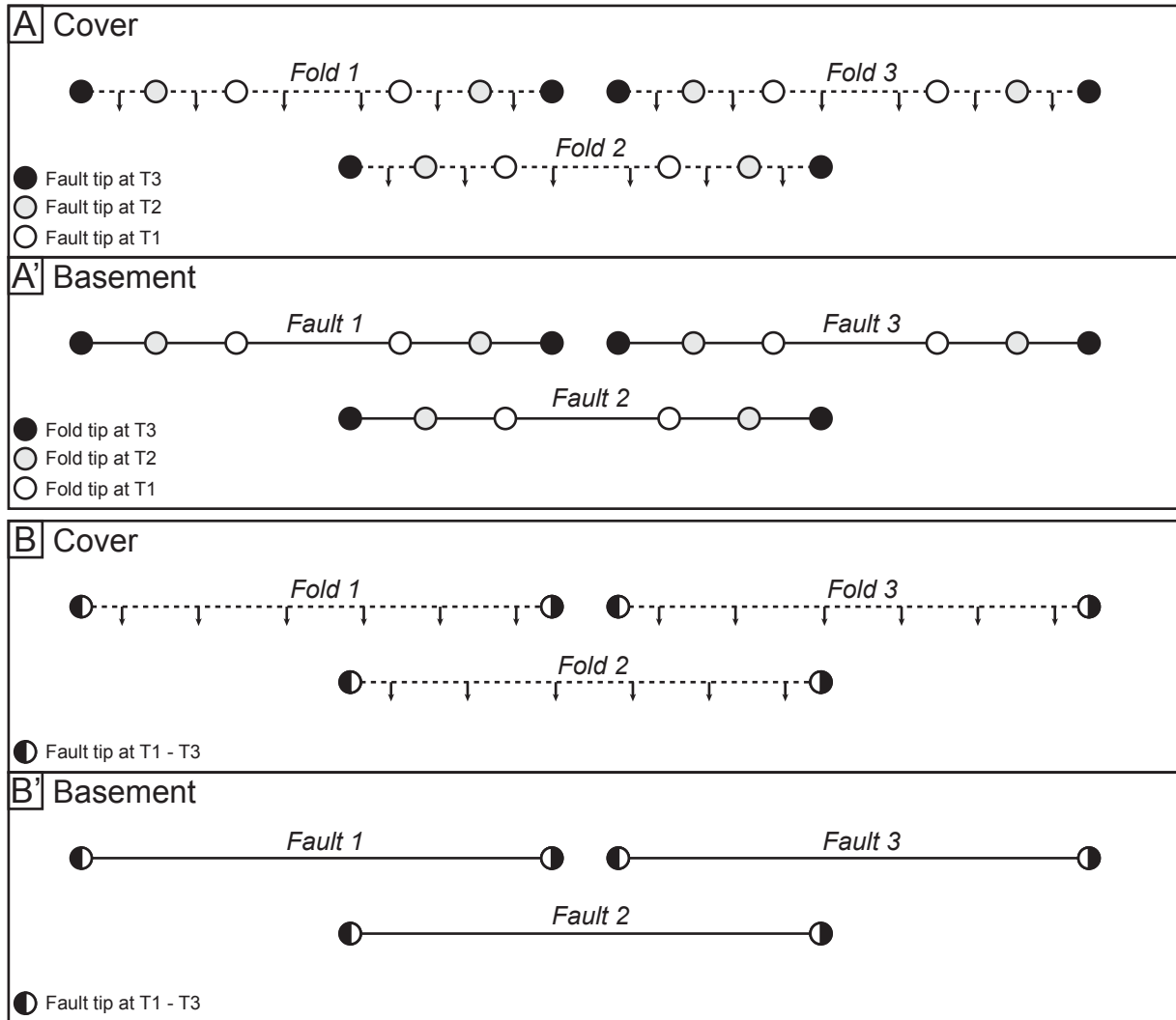


Figure 21. - Evolution of cover growth folds above growing basement-involved normal faults. (A) Isolated fault growth model. The basement normal faults get incrementally longer through time and accumulate displacement gradually; growth folds develop their along-strike width gradually and attain their amplitude as displacement is accrued. (B) Coherent fault growth model. The basement normal faults establish their lengths very rapidly before attaining displacement gradually; growth folds attain their along-strike width rapidly and then amplify as displacement is accrued. The across-strike width of fold is established early during fold growth in both models, and increases very slowly. Modified from Jackson and Rotevatn, 2013; Jackson et al. 2017. The direction of the dipping growth fold limb is indicated by the direction of the black arrows in (A) and (B).



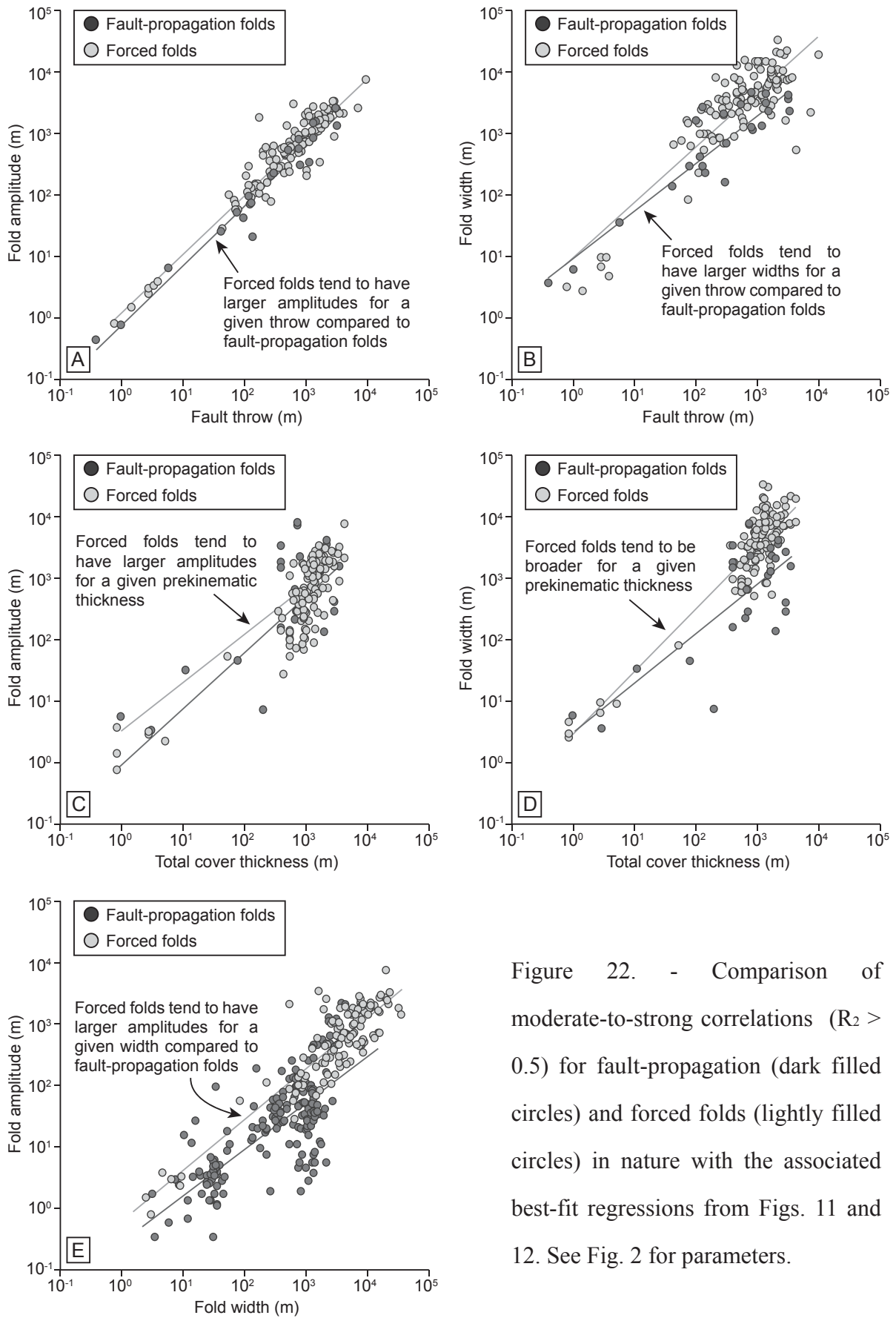


Figure 22. - Comparison of moderate-to-strong correlations ( $R_2 > 0.5$ ) for fault-propagation (dark filled circles) and forced folds (lightly filled circles) in nature with the associated best-fit regressions from Figs. 11 and 12. See Fig. 2 for parameters.

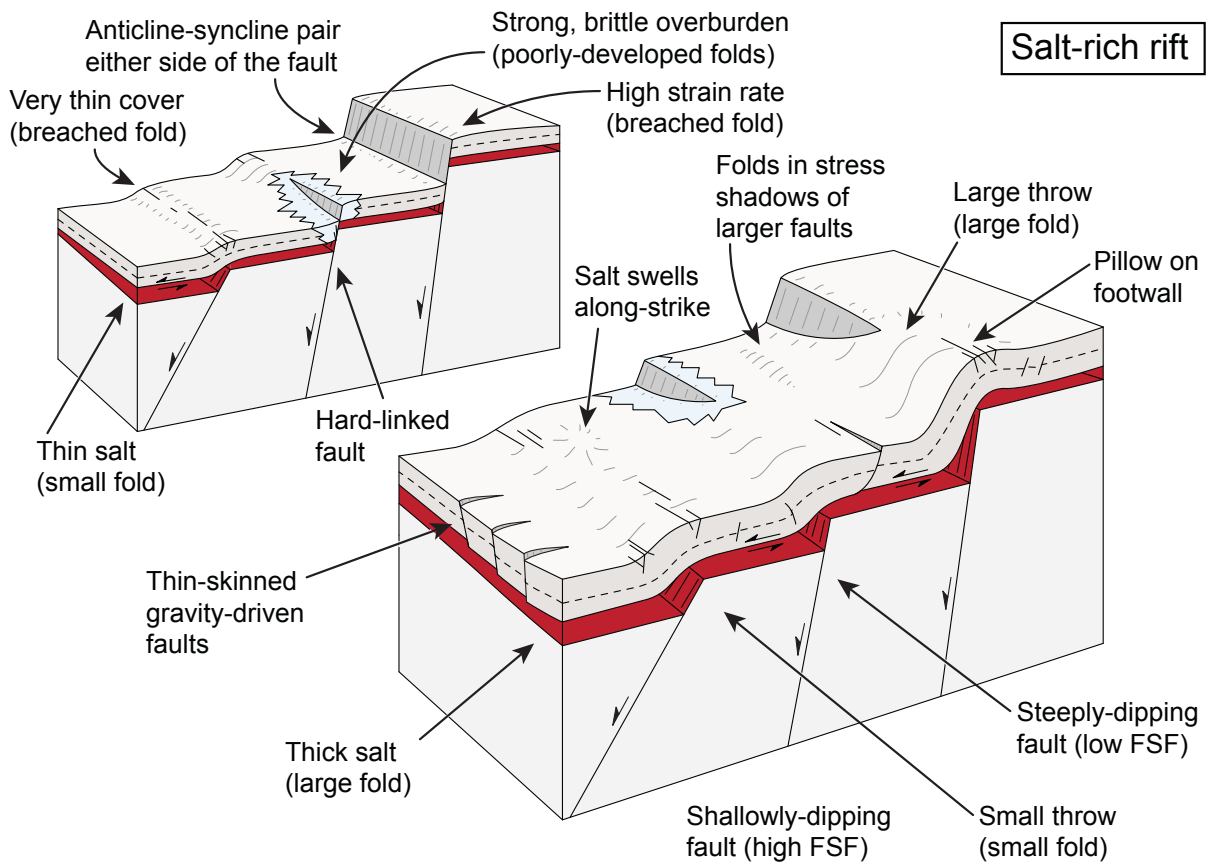
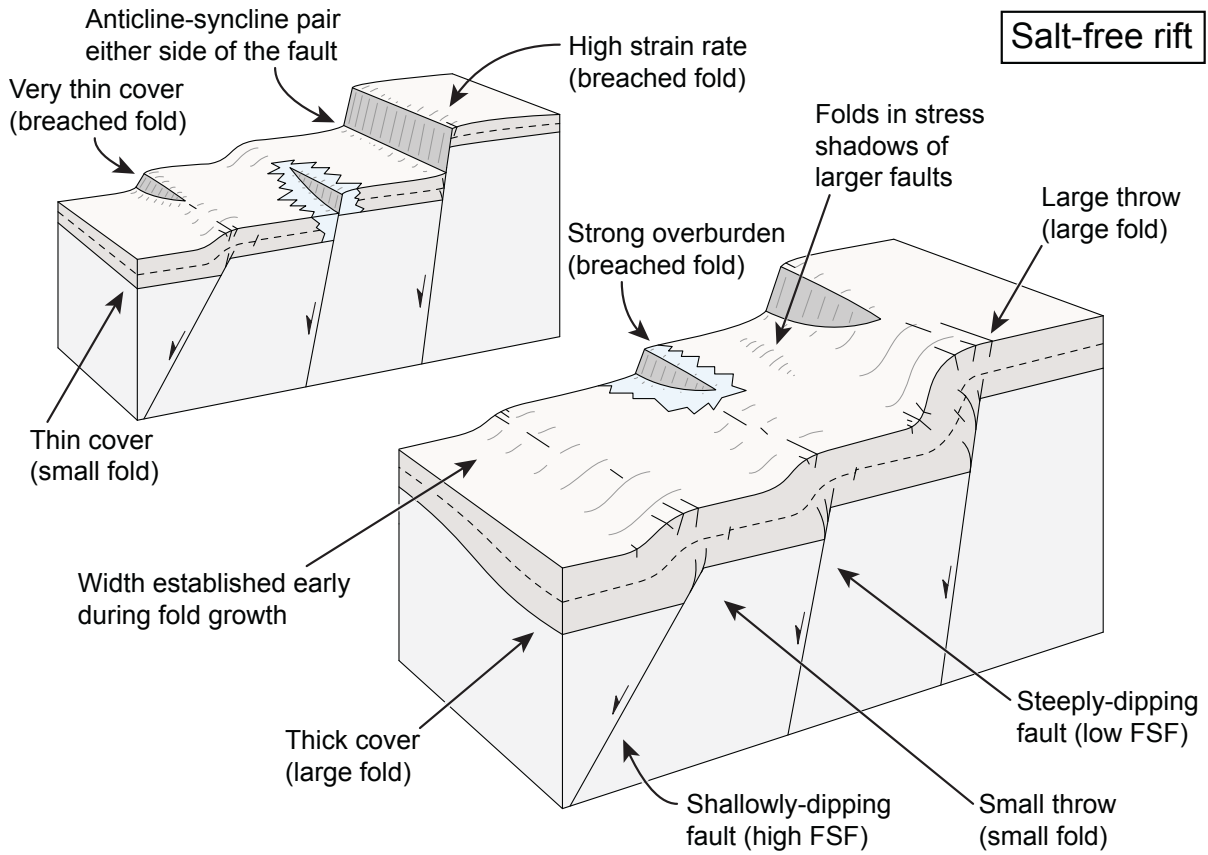
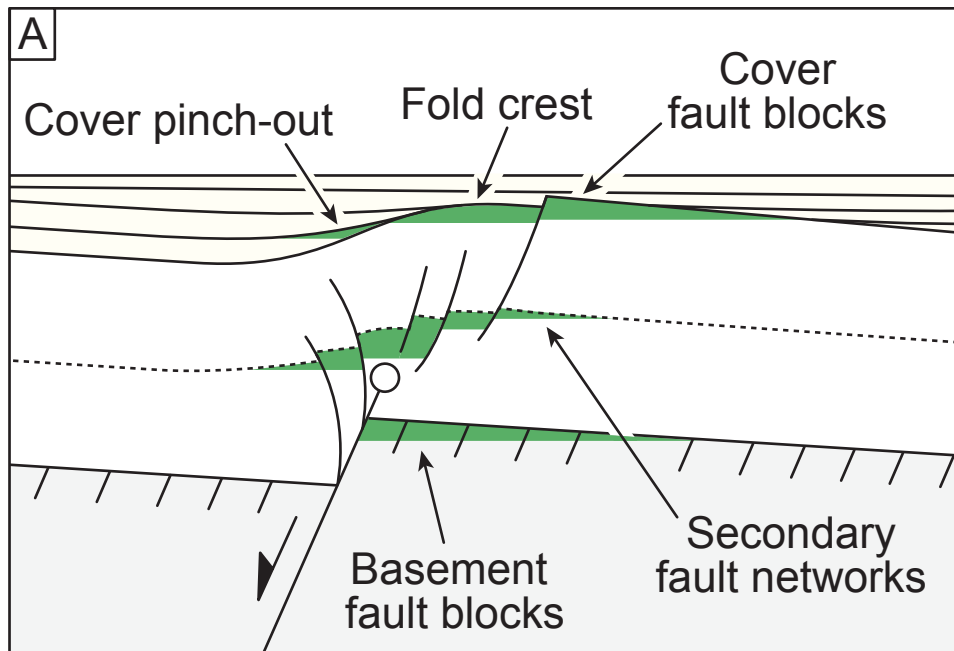


Figure 23. (previous page) - Growth fold geometry in salt-free (top) and salt-rich (bottom) sedimentary basins. Brittle, rheologically strong cover is shown in blue. Note how the width and amplitude of growth folds in salt-rich settings may be considerably different to those developed in salt-free settings. Salt may also create additional fault and fracture populations related to diapirism, independent of regional extension. Cover thickness decreases towards the background in both salt-free and salt-rich settings, which in turn, affects fold geometry.

## Fault-propagation fold petroleum plays



## Forced fold petroleum plays

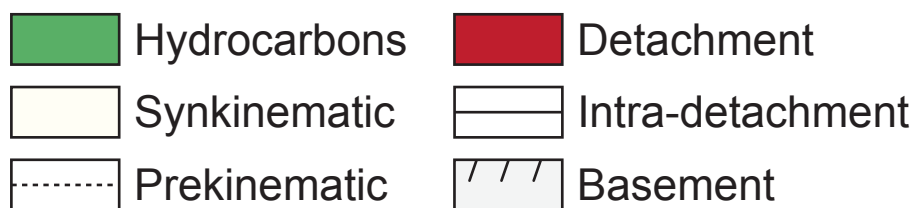
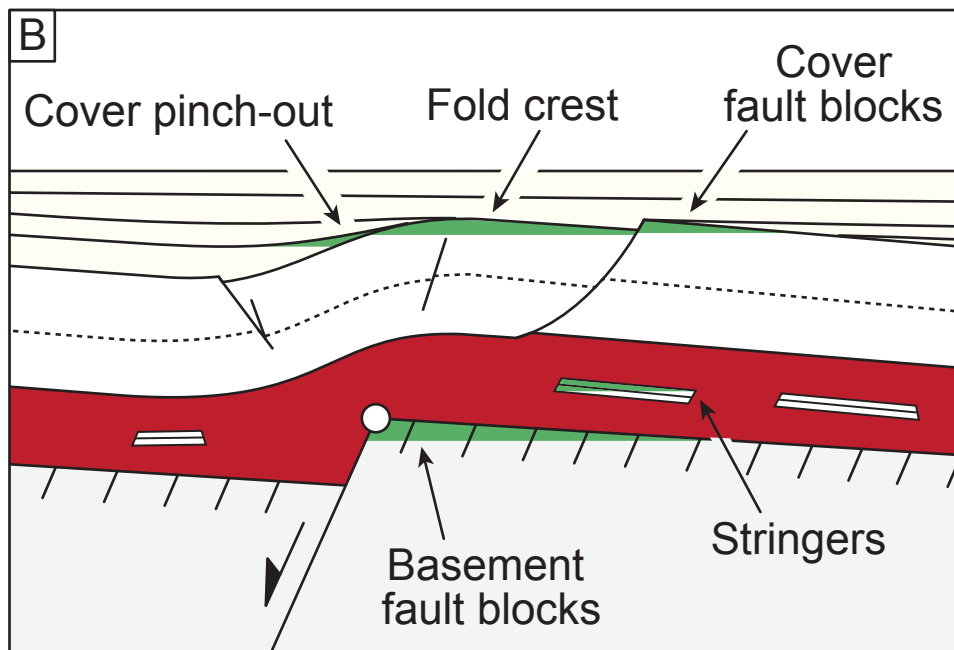


Figure 24. (previous page) - Petroleum plays associated with fault-propagation folds (A) and forced folds (B). Hydrocarbons may be trapped at all stratigraphic levels creating vertically stacked hydrocarbon play potential. Given that the plays are not necessarily formed at the same time, the hydrocarbon composition and hydrocarbon-water contacts within individual compartments may be different. As the fold grows different compartments may be charged and the volume may change as the shape and size changes.

Parameter	Fault-propagation folds (FPF)			Forced folds (FF)		
	Natural examples	Physical models	Numerical models	Natural examples	Physical models	Numerical models
Fold amplitude (A)	10 cm – 2.5 km	3 mm – 8.6 cm	4 mm – 965 m	75 cm – 3.2 km	7 mm – 6.6 cm	50 m – 820 m
Fold width (W)	10 cm – 7.5 km	1.5 mm – 16 cm	7 mm – 4.6 km	2.4 m – 20 km	6 mm – 38 cm	2 km – 3.4 km
Fold-shape-factor (FSF)	0.3 – 357	0.2 – 79	1.2 – 50	0.25 - 24	0.93 - 25	2.8 – 14
Fault throw (TH)	41 cm – 3.3 km	6 mm – 12 cm	4 mm – 1 km	81 cm – 9.8 km	1 mm – 7 cm	50 m – 910 m
Fault dip (fd)	45° - 85°	45° - 90°	30° - 90°	13° – 90°	30° - 90°	30° – 65°
Prekinematic thickness (T <sub>P</sub> )	2.8 m – 3.5 km	1 cm – 26 cm	6 cm – 9.7 km	43 cm – 2.3 km	3.5 mm – 7 cm	1.75 km – 2.75 km
Detachment thickness (T <sub>D</sub> )	-	-	-	42 cm – 2.1 km	5 mm – 7 cm	250 m – 1 km
Cover-detachment ratio (C:D)	-	-	-	0.6 - 9	0.9 - 26	1.5 - 10

Table 1 – Ranges for the growth fold parameters identified in Fig. 2 Values are approximate based on measurements from global data compilation in Appendix D and E.

Correlation	Fault-propagation folds (FPF)			Forced folds (FF)	
	Natural examples	Physical models	Numerical models	Natural examples	Physical models
Fold amplitude vs fold width	A=22.319(W) <sup>0.7659</sup> [R <sup>2</sup> = 0.63]	No correlation [R <sup>2</sup> < 0.1]	A=6.5446(W) <sup>1.0078</sup> [R <sup>2</sup> = 0.8941]	A=0.6116(W) <sup>0.8356</sup> [R <sup>2</sup> = 0.7965]	<i>Weak correlation</i> [R <sup>2</sup> = 0.3451]
Fold amplitude vs fault dip	<i>Weak correlation</i> [R <sup>2</sup> = 0.1024]	No correlation [R <sup>2</sup> < 0.1]	<i>Weak correlation</i> [R <sup>2</sup> = 0.2566]	No correlation [R <sup>2</sup> < 0.1]	No correlation [R <sup>2</sup> < 0.1]
Fold amplitude vs fault throw	A=8.0074(TH) <sup>0.8.021</sup> [R <sup>2</sup> = 0.63]	A=0.3536(TH) <sup>0.7647</sup> [R <sup>2</sup> = 0.72]	A=0.9585(TH) <sup>0.9219</sup> [R <sup>2</sup> = 0.8912]	A=1.2063(TH) <sup>0.9513</sup> [R <sup>2</sup> = 0.8912]	<i>Weak correlation</i> [R <sup>2</sup> = 0.4355]
Fold amplitude vs prekinematic thickness	A=0.7508(T <sub>P</sub> ) <sup>0.85</sup> [R <sup>2</sup> = 0.71]	<i>Weak correlation</i> [R <sup>2</sup> = 0.1658]	A=0.2152(T <sub>P</sub> ) <sup>0.8076</sup> [R <sup>2</sup> = 0.8652]	A=2.4864(T <sub>P</sub> ) <sup>0.8271</sup> [R <sup>2</sup> = 0.6996]	<i>Weak correlation</i> [R <sup>2</sup> = 0.1032]
Fold width vs fault dip	<i>Weak correlation</i> [R <sup>2</sup> = 0.1063]	No correlation [R <sup>2</sup> < 0.1]	<i>Weak correlation</i> [R <sup>2</sup> = 0.1125]	No correlation [R <sup>2</sup> < 0.1]	No correlation [R <sup>2</sup> < 0.1]
Fold width vs fault throw	W=7.5487(TH) <sup>0.7922</sup> [R <sup>2</sup> = 0.835]	No correlation [R <sup>2</sup> < 0.1]	W=6.4602(T <sub>P</sub> ) <sup>0.9246</sup> [R <sup>2</sup> = 0.9038]	W=8.8228(TH) <sup>0.9178</sup> [R <sup>2</sup> = 0.7229]	<i>Weak correlation</i> [R <sup>2</sup> = 0.3061]
Fold width vs prekinematic thickness	W=3.5994(T <sub>P</sub> ) <sup>0.7879</sup> [R <sup>2</sup> = 0.7226]	<i>Weak correlation</i> [R <sup>2</sup> = 0.1567]	W=0.2883(T <sub>P</sub> ) <sup>0.8501</sup> [R <sup>2</sup> = 0.8303]	W=7.7147(T <sub>P</sub> ) <sup>0.9318</sup> [R <sup>2</sup> = 0.7784]	<i>Weak correlation</i> [R <sup>2</sup> = 0.2485]
Fold-shape-factor vs fault dip	No correlation [R <sup>2</sup> < 0.1]	No correlation [R <sup>2</sup> < 0.1]	No correlation [R <sup>2</sup> < 0.1]	No correlation [R <sup>2</sup> < 0.1]	No correlation [R <sup>2</sup> < 0.1]

Table 2 - Correlations for for fault-propagation and forced folds in nature, physical models and numerical models. Where Moderate-to-strong correlations ( $R_2 > 0.5$ ) are present, the best-fit parametric equation has been provided. The  $R_2$  value is shown in all cases. A = fold amplitude. W = fold width. TH = fault throw. T<sub>P</sub> = prekinematic cover thickness. T<sub>D</sub> = detachment thickness. Regression analysis was not undertaken for numerical models of forced folds.

Correlation	Fault-propagation folds (FPF)			Forced folds (FF)	
	Natural examples	Physical models	Numerical models	Natural examples	Physical models
Fold-shape-factor vs fault throw	<i>Weak correlation</i> [ $R^2 = 0.1214$ ]	<i>Weak correlation</i> [ $R^2 = 0.3898$ ]	No correlation [ $R^2 < 0.1$ ]	No correlation [ $R^2 < 0.1$ ]	No correlation [ $R^2 < 0.1$ ]
Fold-shape-factor vs prekinematic thickness	<i>Weak correlation</i> [ $R^2 = 0.1488$ ]	No correlation [ $R^2 < 0.1$ ]	No correlation [ $R^2 < 0.1$ ]	No correlation [ $R^2 < 0.1$ ]	No correlation [ $R^2 < 0.1$ ]
Detachment thickness vs fold amplitude	-	-	-	$A=2.6853(T_D)^{0.9065}$ [ $R^2 = 0.6226$ ]	<i>Weak correlation</i> [ $R^2 = 0.1179$ ]
Detachment thickness vs fold width	-	-	-	$W=8.914(T_D)^{1.0151}$ [ $R^2 = 0.7248$ ]	<i>Weak correlation</i> [ $R^2 = 0.4058$ ]
Detachment thickness vs fold-shape-factor	-	-	-	No correlation [ $R^2 < 0.1$ ]	<i>Weak correlation</i> [ $R^2 = 0.133$ ]
Cover-detachment ratio vs fold amplitude	-	-	-	No correlation [ $R^2 < 0.1$ ]	No correlation [ $R^2 < 0.1$ ]
Cover-detachment ratio vs fold width	-	-	-	No correlation [ $R^2 < 0.1$ ]	No correlation [ $R^2 < 0.1$ ]
Cover-detachment ratio vs fold-shape-factor	-	-	-	No correlation [ $R^2 < 0.1$ ]	No correlation [ $R^2 < 0.1$ ]

Table 2 continued - Correlations for for fault-propagation and forced folds in nature, physical models and numerical models. Where Moderate-to-strong correlations ( $R_2 > 0.5$ ) are present, the best-fit parametric equation has been provided. The  $R_2$  value is shown in all cases. A = fold amplitude. W = fold width. TH = fault throw.  $T_P$  = prekinematic cover thickness.  $T_D$  = detachment thickness. Regression analysis was not undertaken for numerical models of forced folds.



## **Appendix A - Genesis of fault-related folds**

Forced fold – As a fault propagates towards the surface, folding occurs above the upper fault. Deformation is principally faulted at depth, but abruptly transitions to folding at shallower levels. This abrupt change between faulting below and folding above is facilitated due to a detachment or ductile lithology, such as salt or overpressured shale (e.g. Laubscher, 1982; Withjack and Callaway, 2000; Ford et al., 2007; Duffy et al., 2013; Lewis et al., 2013; Jackson and Lewis, 2016; Coleman et al., 2017). A breached forced fold resembles that of a breached fault-propagation fold.

Fault-propagation fold – As a fault propagates towards the surface, folding occurs above the upper fault tip. Deformation is manifested as faulting at depth but gradually transitions to folding at shallow levels (e.g. Withjack et al., 1990; Gawthorpe et al., 1997; Sharp et al., 2000; Jackson et al., 2006; Lewis et al., 2015).

Fault-propagation folds (breached) – Following fault-propagation folding, the underlying fault may propagate through its cover and folding ceases. The fold may then be preserved in the footwall and hangingwall, typically as an anticline and syncline, respectively (e.g. Withjack et al., 1990; Gawthorpe et al., 1997; Lewis et al., 2015). Forced folds that are breached appear similar to breached fault-propagation folds (e.g. Withjack and Callaway, 2000; Ford et al., 2007; Lewis et al., 2013).

Compactional drape – Differential compaction either side of a fault plane creates folding with sub-vertical fold axes (e.g. Thomson and Underhill, 1993; Skuce, 1996; Faereth and Lien, 2002).

Withdrawal drape – Prekinematic strata may become folded above a pre-existing basement fault step as an underlying mobile unit, such as salt or shale, is evacuated. The withdrawal drape fold is geometrically similar to a forced fold, however, is *not* due to a propagating upper fault tip (e.g. Withjack and Callaway, 2000). Withdrawal drape folds are typically associated with nearby ‘leakage points’ such as salt or shale diapirs.

Frictional drag – The deflection of beds adjacent to a fault into folds that are convex in the direction of relative slip due to frictional sliding along a fault and progressive tilting of beds

with increased amount of sliding along a fault (e.g. Billings, 1972; Resor, 2008; Spahic et al., 2013). Their origin has been recently called into question (cf. Reches and Eidelman, 1995; Graseman et al., 2005; Ferril et al., 2012).

**Inversion** – The compressional reactivation of pre-existing extensional structures, so that an initial structural low is uplifted, and subsequently inverted, to form a structural high (e.g. Badley et al., 1989; Mitra, 1993; Mitra and Islam, 1994; Turner and Williams, 2004; Jackson et al., 2013).

**Fault-line deflection (recess)** – Folding due to along-strike corrugations in fault plane geometry. Recess features are created at concave fault segments (e.g. Wheeler, 1939; Stewart and Hancock, 1991; Ehrlich and Gabrielsen, 2004).

**Fault-line deflection (salient)** – Folding due to along-strike corrugations in fault plane geometry. Salient features are created at convex fault segments (e.g. Wheeler, 1939; Machette et al., 1991; Stewart and Hancock, 1991; Ehrlich and Gabrielsen, 2004; cf. Claringbould et al., 2017).

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**Appendix B - Fault-propagation fold locations**

Locality	Country	Fault System	Basin	Reference(s)	Published	Confidence
1	Libya		Sirte Basin	Fodor et al., 2005; Skuce, 1996	Yes	High
2	Egypt		Gulf of Suez	Jackson et al., 2006; Khalil and McClay, 2002; Khalil and McClay, 2016	Yes	High
3	US		Newark Basin	Olsen et al., 1996; Schlische et al., 1992	Yes	Low
4	Egypt		Northern Gulf of Suez	Jackson et al., 2006; Sharp et al., 2000a; b; Garfunkel and Bartov, 1977; Moustafa, 1993	Yes	High
5	Egypt		Central Gulf of Suez	Sharp et al., 2000b; Garfunkel and Bartov, 1977; Moustafa, 1993	Yes	High
6	Egypt		Southern Gulf of Suez	Sharp et al., 2000a; Garfunkel and Bartov, 1977; Moustafa, 1993	Yes	High
7	US	Balcones Fault System	Gulf Coast Basin	Ferrill et al., 2011; Ferrill et al., 2012	Yes	High
8	US	Nopolo Fault	Loreto Basin	Willsey et al., 2002	Yes	High
9	Iceland		Vogar	Grant and Kattenhorn, 2004; Hardy et al., 2013; Trippanera et al., 2015	Yes	High
10	Iceland		Grindavik	Grant and Kattenhorn, 2004; Hardy et al., 2013	Yes	High
11	Iceland		Thingvellir	Grant and Kattenhorn, 2004; Hardy et al., 2013; Trippanera et al., 2015; Smart and Ferrill, 2018	Yes	High
12	Spain		Jiloca Graben	Lafuente et al., 2011	Yes	High

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13	US		Canyonlands Graben	Cartwright and Mansfield, 1998	Yes	High
14	US	Koa'e Fault System	Kilauea Southwest and East Rift Zone	Martel and Langley, 2006; Kaven and Martel, 2007; Bubeck et al., 2018	Yes	High
15	US	Hat Creek System	Hat Creek Graben	Blakeslee and Kattenhorn, 2013	Yes	High
16	Israel	Galilee and Zurim Escarpment	Dead Sea	Matmon et al., 2010	Yes	High
17	US	White Rabbit Fault System	Kilauea Southwest Rift Zone	Podolsky and Roberts, 2008	Yes	High
18	Taiwan	Shanchiao Fault System	Taipei Basin	Chu et al., 2015	Yes	High
19	Saudi Arabia		Jebel Hafeet	van Gent et al., 2010	Yes	High
20	Norway	Oseburg East	Horda Platform	Finch et al., 2004; Jackson et al., 2018	Yes/No	High
21	Norway	Smorbukk	Halten Terrace	Corfield and Sharp, 2000; Bell et al., 2014; Færseth and Lien, 2002	Yes	High
22	Norway	Fjerritslev Fault System	Farsund Basin	Phillips et al., 2018	No	High
23	Israel		Levant Basin	Baudon and Cartwright, 2008a; b; c	Yes	Low
24	Norway	Strathspey-Brent-Statfjord Fault Zone	Eastern Shetland Basin	McLeod et al., 2000	Yes	Mid
25	US		Modoc Plateau	White and Crider, 2006	Yes	High
26	Gabon	Mikouloungou; Kiene; Mounana; Kaya; Magna faults	Franceville Basin	Ndongo et al., 2016	Yes	High
27	Norway		Vøring Basin	Færseth and Lien, 2002	Yes	Mid

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28	Norway		Møre Basin	Færseth and Lien, 2002	Yes	Mid
29	Brazil		Espirito Santo Basin	Omosanya and Alves, 2014	Yes	High
30	Turkey	Yavansu Fault Zone	Menderes Graben	Hancock and Barka, 1987	Yes	High
31	UK	East Pennine Coalfield	Welbeck Low	Walsh and Watterson, 1987	Yes	High
32	Greece	Southern Corinth Fault System	Corinth Rift	Vita-Finzi and King, 1985	Yes	High
33	Israel		Levant Basin	Ghalayini et al., 2016	Yes	High
34	US	Sandy Creek Fault System	Cat Creek	Mitra, 1993	Yes	High
35	Java	Java	Kangean Basin	Mitra, 1993; Badley, 1989	Yes	High
36	UK		South Hewett Zone	Badley et al., 1989; Mitra, 1993	Yes	Mid
37	New Zealand	Manaia Fault System, Kupe Structure	Southern Taranaki Basin	Mitra, 1993; Knox, 1982; Conneally, 2017	Yes	High
38	UK	Heather; Ninian Structure	North Viking Graben	Paul and Mitra, 2015	Yes	High
39	Morocco		Anti-Atlas Basin	Robert-Charrue and Burkhard, 2008	Yes	Low
40	Nigeria		Maiduguri Basin	Avbovbo et al., 1986	Yes	Mid
41	US	Central Transform Fault	Guaymas Basin	Lonsdale and Lawver, 1980	Yes	High
42	US	Robinson's Bend Coalbed; Taylor Creek	Black Warrior Basin	Groshong et al., 2010	Yes	High
43	UK		Inner Moray Firth	Lapadat et al., 2016; <a href="http://www.seismicatlas.org/uploaded/image/200802/e1d2ebbb-18d7">http://www.seismicatlas.org/uploaded/image/200802/e1d2ebbb-18d7</a>	Yes	High

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44	Greece	Western Corinth Canal	Isthmia Graben	Sletten, 2016	No	High
45	Denmark	Coffee-Soil Fault	Tail-End Graben	Duffy et al., 2013	Yes	High
46	Greece	Milos Fault Zone	Southern Aegian Sea	Angelier, 1979	Yes	Mid
47	Greece	Karpathos Fault Zone	Southern Aegian Sea	Angelier, 1979	Yes	Mid
48	Greece	Samos Fault Zone	Southern Aegian Sea	Angelier, 1979	Yes	Mid
49	Argentina	Tres Cruces	Salta Rift	Monaldi et al., 2008	Yes	Mid
50	US	Slaughter Canyon	Permian Basin	Kosa et al., 2005	Yes	High
51	Bulgaria	Emine Fault System	Burgas Basin	Dogliani et al., 1996	Yes	High
52	Ethiopia	Fantale Magmatic System	Ethiopian Rift	Tripanera et al., 2015	Yes	High
53	Ethiopia	Manda Hararo Rift	Ethiopian Rift	Tripanera et al., 2015	Yes	High
54	Iceland	Eldgjá	Erdja Fissure Swarm	Tripanera et al., 2015	Yes	High
55	Iceland	Sveinar- Sveinagja	Sveinar Graben	Tripanera et al., 2015	Yes	High
56	Faroe Islands		Faroe- Shetland Basin	Walker et al., 2012; Walker et al., 2013	Yes	High

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**Appendix C - Forced fold locations**

Locality	Country	Fault System	Basin	Reference(s)	Published	Confidence
1	Norway	Revfallet	Halten Terrace	Dooley et al., 2003; Dooley et al., 2005; Pascoe et al., 1999; Faerseth and Lien, 2002; Gabrielsen et al., 1999; Grunnaleite and Gabrielsen, 1995	Yes	High
2	Norway	Bremstein	Halten Terrace	Wilson et al., 2013; Wilson et al., 2015; Coleman et al. 2017; Faerseth and Lien, 2002; Gabrielsen et al., 1999; Grunnaleite and Gabrielsen, 1995	Yes	High
3	France	Illfurth	Dannemarie Basin, Rhine Graben	Ford et al., 2007; Maurin and Niviere, 1999	Yes	High
4	Norway	Stavanger	Egersund Basin	Jackson and Lewis, 2016	Yes	High
5	Norway	Sele High	Egersund Basin	Lewis et al., 2013	Yes	High
6	UK	Dowsing Fault Zone	Sole Pit Trough	Coward and Stewart, 1995	Yes	High
7	Belguim	Southern Roer Valley	Roer Valley, Rhine Graben	Deckers, 2015; Deckers et al., 2014	Yes	High
8	US	Jackpot - Tamurian Block	Basin and Range	Howard and John, 1997	Yes	High
9	UK	Buchan Graben	Buchan Graben	Stewart and Clark, 1999; Stewart, 2014	Yes	High
10	Egypt	Ramadan Oil Field	Gulf of Suez	Brown, 1980; Abdine et al., 1992; Withjack et al., 2000	Yes	High
11	Denmark	Horn Graben	Horn Graben	Stewart and Clark, 1999	Yes	High
12	UK	Wright-Bray	Channel Basin	Harvey and Stewart, 1998	Yes	High

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13	Canada	Creignish; Hollow Fault	Maritimes Basin	Keller and Lynch, 1999; Lynch et al., 1998	Yes	High
14	Spain	Ubierna; Saltacaballos	Basque- Cantabrian Basin	Tavani et al., 2018; Tavani et al., 2011; 2013; Tavani and Granado, 2014; Quintana et al., 2006	Yes	High
15	Israel	Ma'aleh Gerofit	Central Dead Sea Rift	Gross et al., 1997	Yes	High
16	US	Balcones	Gulf of Mexico Basin	Ferrill et al., 2012; Ferrill and Morris, 2008	Yes	High
17	US	Balcones	Gulf of Mexico Basin	Ferrill and Morris, 2008	Yes	High
18	US	Big Brushy Canyon	Big Brushy Canyon	Ferrill et al., 2007	Yes	High
19	Norway	Nordkapp Basin	Nordkapp Basin	Nilsen et al., 1995; Koyi et al., 1993; Koyi et al., 1995; Gudlaugson et al., 1998	Yes	High
20	UK	Keys Graben	Keys Graben	Jackson and Mulholland, 1993; Stewart et al., 1997; Penge et al., 1999	Yes	High
21	Denmark	East North Sea High	Norwegian- Danish Basin	Geil, 1991; Petersen et al., 1992; Stewart et al., 1996	Yes	High
22	Norway	Sleipner Basin	South Viking Graben	Kane et al., 2010	Yes	High
23	UK	Fisher Bank Basin	Fisher Bank Basin	Penge et al., 1999	Yes	High
24	UK	Forties- Montrose High	Forties- Montrose High	Penge et al., 1999	Yes	High
25	UK	East Deemster Graben	East Deemster Graben	Penge et al., 1999	Yes	High
26	UK	Dowsing Fault Zone	Swarte Bank Hinge	Stewart and Coward, 1995; Stewart et al., 1996	Yes	High

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27	UK	Machar and Median Diapirs	East Central Trough	Stewart et al., 1996	Yes	High
28	UK	Cleaver Bank High	Cleaver Bank High	Oudmayer and de Jager, 1992	Yes	High
29	Denmark	Hyllebjerg Basin	Hyllebjerg Basin	Koyi and Petersen, 1993	Yes	High
30	Denmark	RÅ,ddung Graben	RÅ,ddung Graben	Koyi and Petersen, 1993	Yes	High
31	UK	Lagman Fault	Lagman Basin	Jackson and Mulholland, 1993	Yes	High
32	UK	Tynwald Fault	Tynwald Basin	Jackson and Mulholland, 1993	Yes	High
33	Denmark	Coffee-Soil Fault	Tail-End Graben	Duffy et al., 2013	Yes	High
34	Portugal		Northern Lusitanian Basin	Alves et al., 2002; Alves et al., 2003	Yes	High
35	Portugal	Arruda subbasin and Bombarral-Alcobaca subbasin	Central Lusitanian Basin	Alves et al., 2002; Alves et al., 2003	Yes	High
36	Canada		Whale Basin	Balkwill and Legall, 1987; Vendeville et al., 1995; Withjack and Callaway, 2000	Yes	High
37	Canada		Jeanne D'Arc Basin	Sinclair, 1995; Withjack and Callaway, 2000; Serano-Saurez et al., 2013	Yes	High
38	Portugal	Porto Basin	Porto Basin	Alves et al., 2006	Yes	High
39	Portugal	Alentejo Basin	Alentejo Basin	Alves et al., 2006	Yes	High
40	Spain	Zarate Fault	Lasarte Basin	Bodego and Agirrezabala, 2013	Yes	High
41	France	Aquitaine Basin	Aquitaine Basin	Bourrouilh et al., 1995	Yes	High



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42	France	Parentis Basin	Parentis Basin	Ferrer et al., 2012; Ferrer et al., 2014	Yes	High
43	Ukraine		Dniepr-Donets Basin	Stovba and Stephenson, 2002; Brown et al., 2012	Yes	Low
44	Poland		Mid Polish Trough	Burliga et al., 2012; Krzywiec, 2010; Lamarche and Scheck-Wenderoth, 2005	Yes	High
45	Canada		Orpheus Basin	Durcanin et al., 2009; Zulfitriadi et al., 2011; Hanafi et al., 2013	No	High
46	Norway		Haapet Dome		No	High
47	Canada		Sverdrup Basin	Harrison and Jackson, 2014	Yes	Low
48	Morocco		Essaquira Basin	Tari et al., 2000; Tari et al., 2013	Yes	Low
49	Morocco		Agadir Basin	Tari et al., 2000; Tari et al., 2013	Yes	Low
50	Morocco		Safi Basin	Tari et al., 2000; Tari et al., 2013	Yes	Low
51	Israel	Sedom Fault	Southern Dead Sea Rift	Smit et al., 2008	Yes	High
52	Spain		Ebro Basin	Salas and Casas, 1993; Alvaro et al., 1979	Yes	Low
53	Canada		Carson Basin	Enachescu, 1992.	Yes	Low
54	Italy		Po Basin	Cardello et al., 2015	Yes	High
55	Norway		Feda Graben	Ge et al., 2016	Yes	High
56	Norway		Steinbit Terrace	Ge et al., 2016	Yes	High
57	Norway		Breiflabb Graben	Ge et al., 2016	Yes	High
58	Norway		Cod Terrace	Ge et al., 2016	Yes	High
59	UK		Josephine High	Ge et al., 2016; Vendeville et al., 1995	Yes	High
60	Norway		Sorvestlandet High	Ge et al., 2016; Stewart et al., 1992; Vendeville et al., 1995	Yes	High
61	Norway		Hidra High	Ge et al., 2016	Yes	High

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62	Poland		Lower Silesian Basin	Mejia-Herrera et al., 2015	Yes	Mid
63	Italy		Radicondoli Basin	Brogi and Liotta, 2008	Yes	Low
64	Czech Republic		Most Basin	Rajchl and Uličný, 2001; 2008; Rajchl et al., 2009	Yes	High
65	Spain	Gargallo Fault	Maestrazgo Basin	Rodriguez-Lopez et al., 2007	Yes	High
66	France	Rhenish Fault	Soult-sous-Forets Area	Place et al., 2010	Yes	High
67	US	Moab Fault Splay	Paradox Basin	Berg and Skar, 2005	Yes	High
68	Iran		Southern Salt Basin	Perotti et al., 2016	Yes	Low
69	UK	Beatrice Fault System	Inner Moray Firth	Lapadat et al., 2016	Yes	High
70	Norway		Hammerfest Basin	Gabrielsen et al., 2016	Yes	High
71	Israel		Levant Basin	Reiche et al., 2014	Yes	Low
72	Russia		Pripyat Basin	Garetskii et al., 2004	Yes	High
73	Saudi Arabia		Rub' Al-Khali Basin	Stewart et al., 2016	Yes	Low
74	US		Rattlesnake Mountain	Stearns, 1978; Weinberg, 1979	Yes	High
75	Norway	Fjerritslev Fault System	Farsund Basin	Phillips et al., 2018	No	High
76	Ireland		Central Ireland Carboniferous Basin	Lewis and Couples, 1999	Yes	Low
77	US		Uinta Mountains	Stearns, 1978	Yes	High
78	US		West Powder River Basin	Sacrison, 1978; Stearns, 1978	Yes	High
79	US		Brady Structure	Sacrison, 1978	Yes	High

“Growth folds above propagating normal faults” - Appendices

80	US		Carter Lake Anticline	Matthews and Work, 1978	Yes	Low
81	US		Bellview Dome	Matthews and Work, 1978	Yes	Mid
82	US		Milner Mountain Anticline	Matthews and Work, 1978	Yes	Mid
83	US		Dowe Pass Anticline	Matthews and Work, 1978	Yes	Mid
84	US	Horn Fault; Tensleep- Beaver Creek Fault	Horn Block	Palmquist, 1978	Yes	Mid
85	US		Piney Creek	Palmquist, 1978	Yes	Low
86	US		Fanny Peak Monocline	Lisenbee, 1978	Yes	Low
87	US		Rapid City Structure	Lisenbee, 1978	Yes	Low
88			Rockerville Quadrangle Area	Lisenbee, 1978	Yes	Low
89	US		Cascade Springs Anticline	Lisenbee, 1978	Yes	Mid
90	US		Stockade Beaver Creek Monocline	Lisenbee, 1978	Yes	Mid
91	US		Red Rock Fold	Cook, 1978	Yes	Low
92	Italy	Zuccale Fault	Elba Basin	Smith et al., 2007	Yes	High
93	Spain		Prebetic Basin	Rubinat et al., 2013	Yes	High
94	France	St Benoit Fault	Annot Basin	Tomasso and Sinclair, 2004	Yes	Mid
95	Borneo		East Barito Fordeep	Satyana and Silitonga, 1994	Yes	Mid
96	New Zealand		Taupo Volcanic Zone	Milner et al., 2002	Yes	Low

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97	Germany		Gluckstadt Graben	Best et al., 1983; Warsitzka et al., 2017	Yes	Mid
98	Denmark		Step Graben	Rommelts, 1995	Yes	High
99	Denmark	Rifgronden Fault Zone	Terschelling Basin	Rommelts, 1995	Yes	Low
100	UK		West Central Graben	Weston et al., 1993; Hossack, 1995	Yes	High
101	Morocco		Essaouira Basin	Hafid et al., 2000	Yes	Mid
102	Mexico	Rincon de Parangueo Maar	Rincon de Parangueo	Aranda-Gomez et al., 2017	Yes	High
103	Tanzania	Lokichar	Usangu Basin	Morley, 2002	Yes	High

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**Appendix D – Fault-propagation fold database**

Fault-propagation fold database may be downloaded here:

<https://figshare.com/s/c6663901f6ca8c6f6fe4>

**Appendix E – Forced fold database**

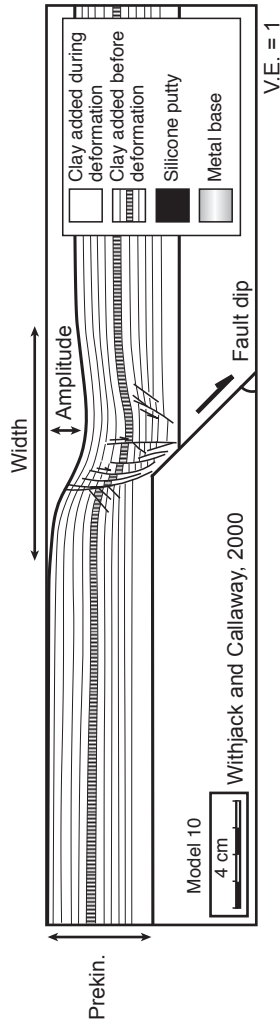
Forced fold database may be downloaded here:

<https://figshare.com/s/c6663901f6ca8c6f6fe4>

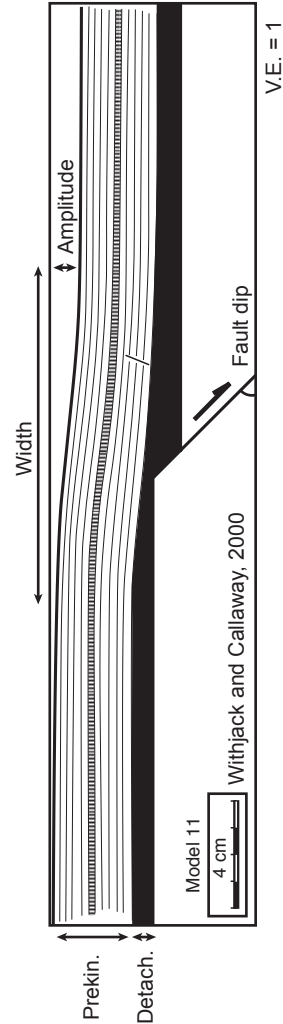
## **Appendix F – Uncertainties**

This study measures growth fold parameters (Fig. 2) from a series of published examples in nature, physical, mechanical and kinematic models. Here, we illustrate using a series of examples how growth fold parameters were measured and their associated errors. As all of the errors are relatively minimal and the data points would still plot in similar locations (for example, on Figs. 11 – 12; 21), the general relationships/trends would remain largely the same. Changes in the measured values would inevitably shift the best-fit regressions and alter the derived parametric equations, but the trends would remain the same. References for each example are also shown.

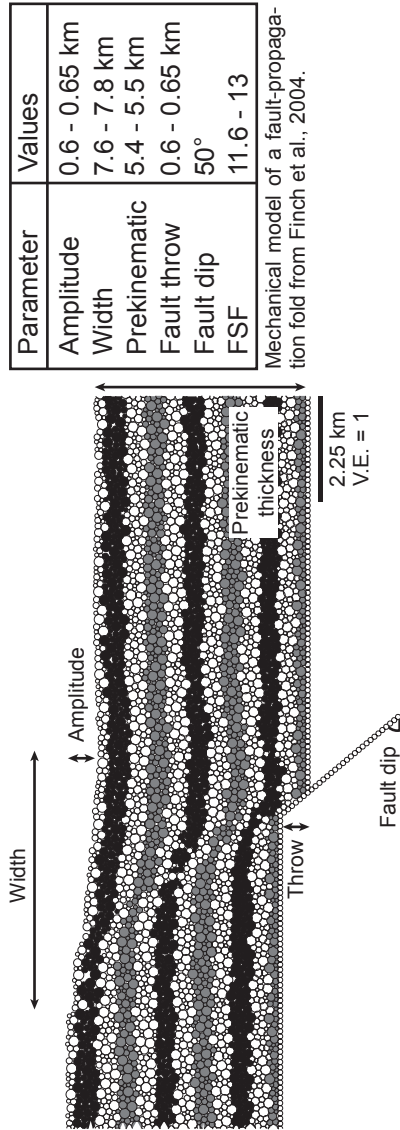
Parameter	Values
Amplitude	10 - 13 mm
Width	96 - 100 mm
Prekinematic	40 - 41 mm
Fault throw	10 - 11 mm
Fault dip	45°
FSF	7 - 10



Parameter	Values
Amplitude	9 - 11 mm
Width	117 - 133 mm
Prekinematic	38 - 40 mm
Fault throw	9 - 11 mm
Fault dip	45°
FSF	11 - 15
Detachment	9 - 12 mm
C:D	3 - 4

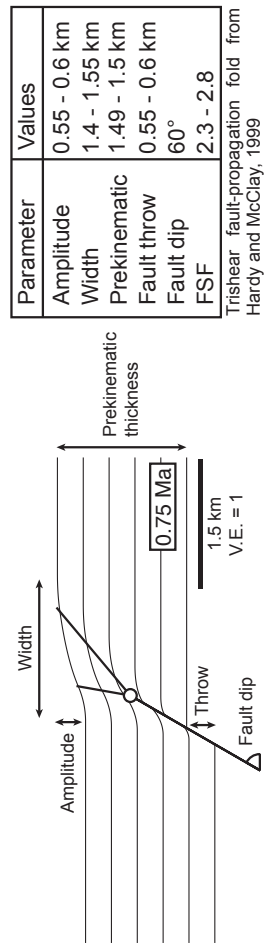






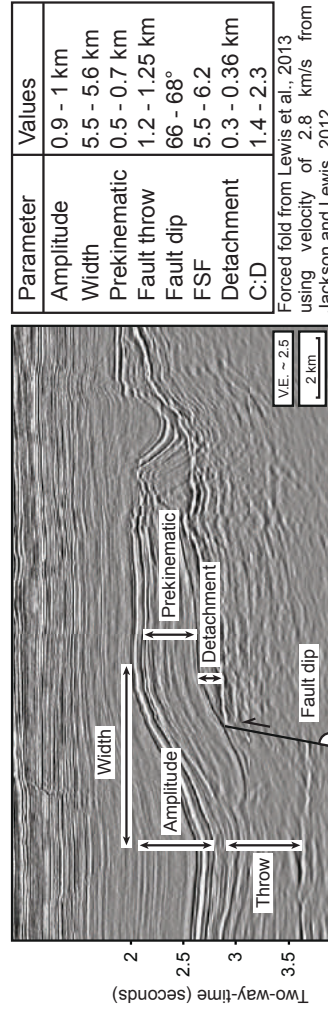
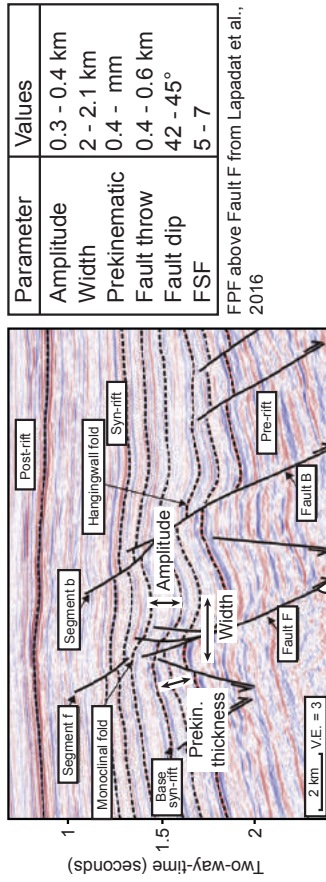
Parameter	Values
Amplitude	0.6 - 0.65 km
Width	7.6 - 7.8 km
Prekinematic	5.4 - 5.5 km
Fault throw	0.6 - 0.65 km
Fault dip	50°
FSF	11.6 - 13

Mechanical model of a fault-propagation fold from Finch et al., 2004.



Parameter	Values
Amplitude	0.55 - 0.6 km
Width	1.4 - 1.55 km
Prekinematic	1.49 - 1.5 km
Fault throw	0.55 - 0.6 km
Fault dip	60°
FSF	2.3 - 2.8

Trishear fault-propagation fold from Hardy and McClay, 1999



## Appendix G - Principal Component Analysis (PCA) Explanation

To demonstrate how PCA works we first consider the following scenario: envision a multi-variate dataset consisting of three measured variables (or ‘dimensions’), x, y and z. If the x- and y- variables are plotted, we can see that they are highly correlated (Fig. G.1A). PCA allows us to represent these data along a best-fit, single axis (PC1 - the black line on Fig. G.1A), termed a ‘principal component’ (PC). This principal axis explains the largest data variation and permits the simplification of two-dimensional data i.e., the x- and y- variables, in this case, to one dimension. By reducing the data to fewer dimensions, the relationship between the x- and y- variables can no longer be explicitly calculated (as in linear regression) but the relationships between the variables are maintained. In other words, when we plot the original data against the principal component, the data is spread along the length of the axis (Fig. G.1B). This suggests that the x- and y- variables are highly correlated, and the principal component explains a large proportion of the data variation, as shown in Fig. G.1A.

Given that we also have a third variable, z, we cannot explain all of the data variance with a single principal component, additional principal components may be calculated to explain further data variance (PC2 - grey line on Fig. G.1A). Each successive principal component introduced into the analysis explains a successively smaller portion of the data (data variance is larger on Fig. G.1B than Fig. G.1C) and is geometrically orthogonal to the others (e.g. Wold et al., 1987; Jolliffe, 1993; Ringner, 2008; Abdi and Williams, 2010; Lever et al., 2017), but together, these principal components cumulatively explain the data variance. The number of principal components can be as large as the number of samples or the number of components. As PC1 and PC2 explain the majority of the data variance, we may project the original data (consisting of the x-, y- and z- values) and their trends onto new axes, comprised of the principle components (black arrows on Fig. G.1D). If particular variables are correlated, they will plot close to one-another. It should be noted that the sign of any principal component, i.e. the direction of the arrows on Fig. G.1D, is completely arbitrary (e.g. Jolliffe, 1987). In our example case, the x- and y- variables plot very close to one-another and the PC1 axis, so are strongly correlated. The z-variable in contrast, is correlated with the PC2 axis, but is also relatively close to the y-variable. We can therefore interpret that the x- and z-variables are both correlated to y variable (Fig. G.1C), and there may be a reason for their correlation, such as the x- and z-variables control the y-variable. Furthermore, principal components identify major trends in highly-dimensional data and the correlated variables. If a data point only has missing values for

particular variables i.e. the data point has an x-, and y- value but not a z-value, the position of the principal components that explains the most data variation may slightly change. Furthermore, the original data may be projected slightly differently.

The PCA method described above can also be applied to our growth fold dataset. However, instead of three variables (e.g. x, y and z), we have more variables or dimensions (e.g. fault dip, fault throw, fold amplitude, fold width etc.). Following the same method, we can thus, determine which parameters are correlated and speculate a geological reasoning for the relationship. Where missing values for particular parameters are missing (i.e. data gaps), then a best-fit, iterative value is used to fill in the record (as discussed in Appendix H). A full description of the PCA method is described in Josse and Husson (2016).

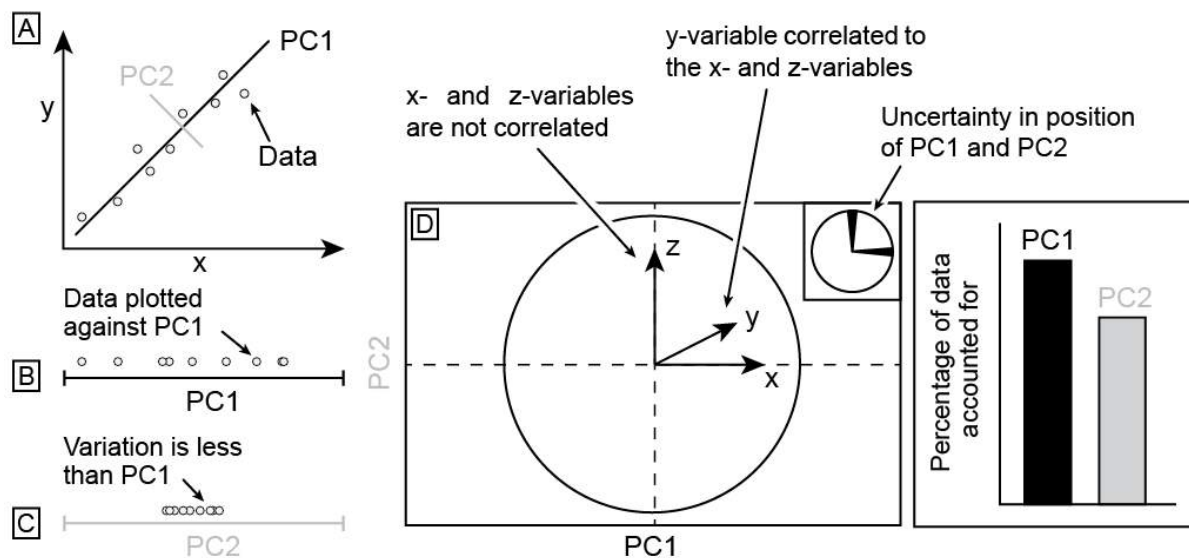


Figure G.1. – Summary of principal component analysis (PCA) method using example data with x-,y- and z-variables. The x-variable is plotted against the y-variable for the example data (A). The most and second-most data variation is described by PC1 and PC2, respectively. By projecting the data onto two new axes, PC1 (B) and PC2 (C), the data can be analysed for clustering and hidden trends. The x-, y- and z-variables are then plotted to see which variables are likely related (D). Where values are missing in the dataset, uncertainty is introduced in the analysis hence the trend and position of PC1 and PC2 (on panel A) may shift. PC1 and PC2 each account a certain amount of the data as shown in the bar chart.

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## Appendix H - Principal component analysis sensitivity

Principal component analysis (PCA) simplifies the complexity of high-dimensional multivariate data, such as our growth fold dataset (Appendices D – E), while retaining trends and patterns (e.g. Jolliffe, 1993; Jolliffe, 2002; Lever et al., 2002). This allows us to identify possible relationships between parameters which are non-linear or very complex.

In an ideal scenario, all structural and stratigraphic parameters (cf. Fig. 2 in the main text) may be measured but this may not be possible in all cases. Therefore, the best-fit position of each principal component (PC) may vary, and an uncertainty is introduced. We explore this uncertainty using two examples: (i) a numerical model, and (ii) a real example from our growth fold database.

### Example 1 – Numerical trishear forward model

To quantitatively investigate the effect of missing parameters within individual examples, we used FaultFold (Allmendinger, 1998) to generate a series of 2D trishear forward models for fault-propagation folds with different structural and stratigraphic parameter variations. As the initial parameters are known, and the fold geometry can be measured, none of the forward models are missing any values and there is no uncertainty in the PCA analysis – ‘*Dataset 1*’, 491 records, each with 5 parameters. We then randomly removed 20% of the values (any parameter from any record) to reflect a dataset with missing values – ‘*Dataset 2*’. We then undertook PCA on *Dataset 2* with the missing values to see how uncertainty affected the strength, and thus, the interpretation of the PCA using three methods (Fig. H.1; cf. Josse and Husson, 2012; Josse et al., 2012; Audiger et al., 2016; Josse and Husson, 2016):

- 1) Ignore incomplete records (and reduce the sample size);
- 2) Replace missing values in individual records with the mean value for an appropriate parameter (sample size remains the same);
- 3) Replace missing values in individual records using a regularised iterative value for the appropriate parameter (sample size remains the same).

We can see that regardless of the PCA method used on *Dataset 2*, the correlations (the directions of the arrows and the relative positions of arrows) are very similar. In this example, we see a correlation between the prekinematic thickness, the total slip, the fold amplitude and to a lesser

extent, the fold width. In addition, we see a correlation between the fold-shape-factor (FSF) and the fault dip, and to a lesser extent, the fold width. The PCA for *Dataset 2* (with missing values) is almost identical to *Dataset 1* (without missing values), suggesting PCA may be used even on incomplete datasets, at least with caution.

It is important to mention that these examples are similar sized, thus, replacing a data gap with a mean value has a negligible effect on the correlation. If the sample contained lots of different sized folds, the replaced variable may be unrealistic and a magnitude larger or smaller. Similarly, removing the record completely (and all of the other parameters, even if only one value is missing), may significantly reduce the sample size, making the dataset susceptible to extremes. An iterative approach tackles both of these issues, giving a parameter that is not out of character with the rest of the record values, and does not remove the record from the sample. This is our preferred method for PCA, but we include the uncertainty associated with the missing value so that correlations can be qualitatively checked in all cases.

### **Example 2 – Natural examples of fault-propagation folds**

Now applying the same sensitivity test to the dataset of natural examples of fault-propagation folds (cf. Appendix D) that already contains missing values. We may compare the results of PCA using the same three methods (Fig. H.2; cf. Josse and Husson, 2012; Josse et al., 2012; Audiger et al., 2016; Josse and Husson, 2016):

- 1) Ignore incomplete records (and reduce the sample size);
- 2) Replace missing values in individual records with the mean value for an appropriate parameter (sample size remains the same);
- 3) Replace missing values in individual records using a regularised iterative value for the appropriate parameter (sample size remains the same).

Similar to Example 1, the PCA results for Example 2 are largely similar irrespective of the method. Our results show there is a correlation between the amplitude and width of the fold, the fault throw and the thickness of the prekinematic cover. The fold-shape-factor is seemingly uncorrelated to the other variables. However, we do see slight changes in the direction of the arrows. In order to not drastically reduce the number of sample records in our analysis, missing values have been replaced using iteration (method 3).

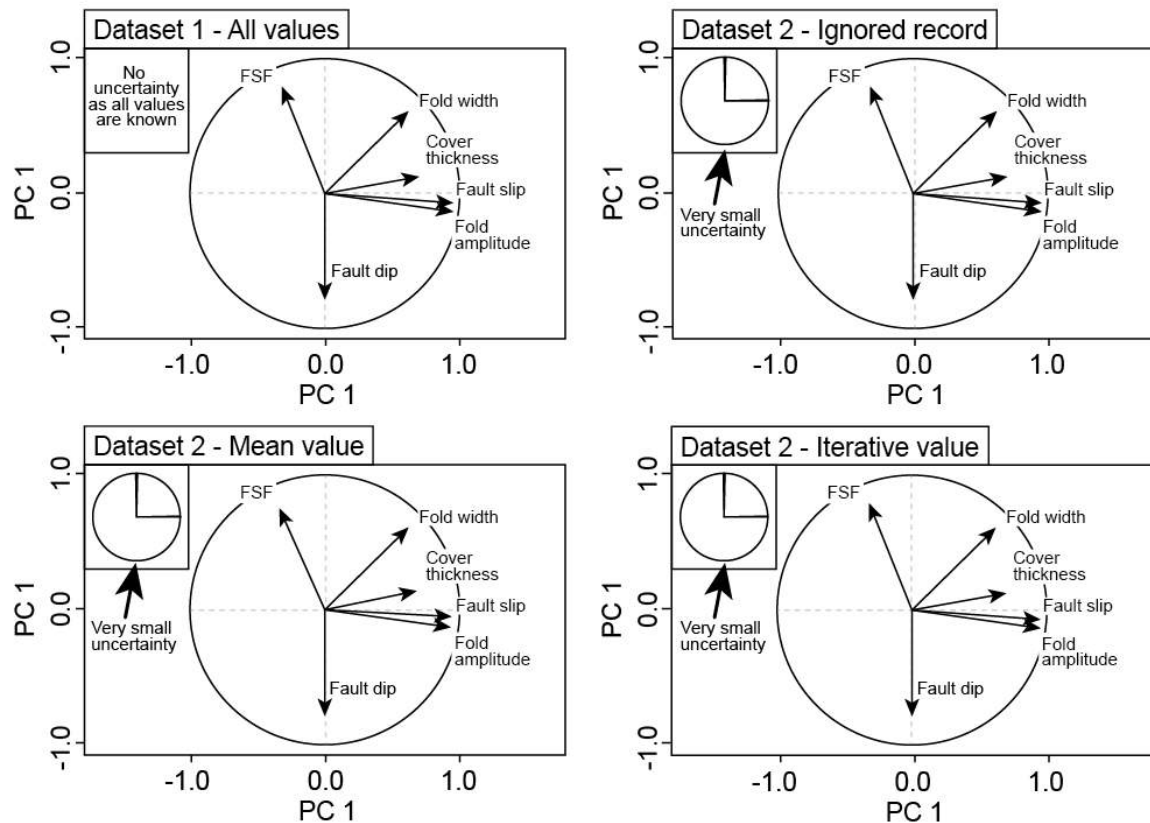


Figure H.1. – Summary of principal component analysis (PCA) sensitivity for the trishear forward model dataset. Top left – Dataset 1 (without missing values). Top right – Dataset 2 (with missing values), where records with missing values are ignored. Bottom left - Dataset 2 (with missing values), where records with missing values for a particular variable are replaced with the mean value for that variable of the entire data. Bottom right - Dataset 2 (with missing values), where records with missing values for a particular variable are replaced with a regularized iterative value for that variable in that record.



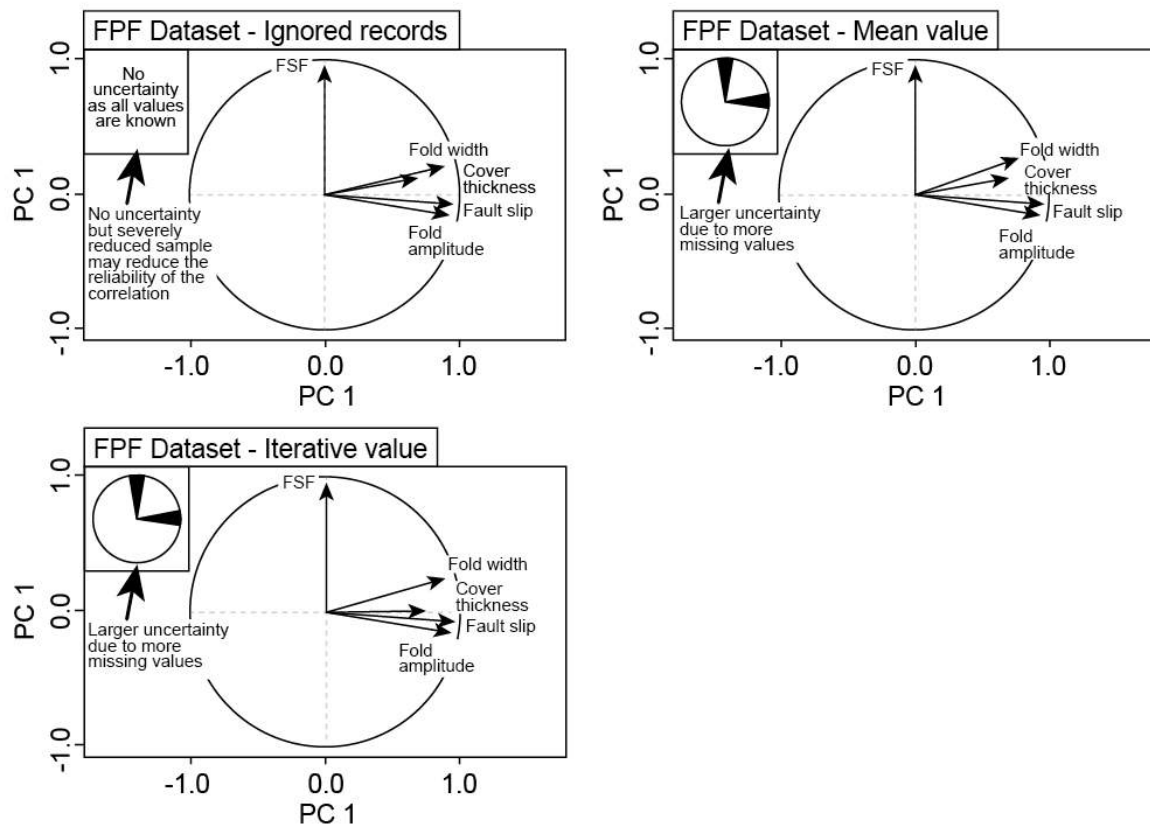


Figure H.2. – Summary of principal component analysis (PCA) sensitivity for the fault-propagation fold dataset of natural examples. Top left – Original dataset of real examples (with missing values). Top right – Dataset 2, where missing values are replaced by the mean value for that particular parameter. Bottom left - Dataset 2 where missing values replaced with a regularized iterative value for that variable in that record.

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