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DOI: 10.1016/j.epsl.2019.03.018

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Document Version Peer reviewed version

Citation for published version (Harvard):

Lymer, G, Cresswell, D, Reston, T, Bull, JM, Sawyer, DS, Morgan, JK, Stevenson, C, Causer, A, Minshull, T & Shillington, DJ 2019, '3D development of detachment faulting during continental breakup', *Earth and Planetary Science Letters*, vol. 515, pp. 90-99. https://doi.org/10.1016/j.epsl.2019.03.018

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- 1 **3D** development of detachment faulting during continental breakup
- 2

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12 ABSTRACT

13 The developing asymmetry of rifting and continental breakup to form rifted margins has been 14 much debated, as has the formation, mechanics and role of extensional detachments. Bespoke 15 3D seismic reflection data across the Galicia margin, west of Spain, image in unprecedented 16 detail an asymmetric detachment (the S reflector). Mapping S in 3D reveals its surface is 17 corrugated, proving that the overlying crustal blocks slipped on S surface during the rifting. 18 Crucially, the 3D data show that the corrugations on S perfectly match the corrugations 19 observed on the present-day block-bounding faults, demonstrating that S is a composite 20 surface, comprising the juxtaposed rotated roots of block-bounding faults as in a rolling hinge 21 system with each new fault propagation moving rifting oceanward; changes in the orientation 22 of the corrugations record the same oceanward migration. However, in contrast to previous 23 rolling hinge models, the slip of the crustal blocks on S occurred at angles as low as $\sim 20^{\circ}$, requiring that S was unusually weak, consistent with the hydration of the underlying mantle 24

25 by seawater ingress following the embrittlement of the entire crust. As the crust only becomes 26 entirely brittle once thinned to ~10 km, the asymmetric S detachment and the hyper-extension 27 of the continental crust only developed late in the rifting process, which is consistent with the 28 observed development of asymmetry between conjugate magma poor margin pairs. The 3D 29 volume allows analysis of the heaves and along strike architecture of the normal faults, whose 30 planes laterally die or spatially link together, implying overlaps in faults activity during 31 hyper-extension. Our results thus reveal for the first time the 3D mechanics and timing of 32 detachment faulting growth, the relationship between the detachment and the network of 33 block-bounding faults above it and the key processes controlling the asymmetrical 34 development of conjugate rifted margins.

35 KEY WORDS

36 Rifting processes; Galicia margin; North Atlantic Ocean; Detachment fault; Assymetry;
37 3D seismic reflection

38

39 1 INTRODUCTION

40 The rifting and breakup of the continents to form new ocean basins (Bullard et al, 1965; Le 41 Pichon and Sibuet, 1981; Lister et al., 1986) is a first order tectonic process at the surface of 42 the Earth that changes ocean circulation by opening new oceanographic gateways (Barker and Burrell, 1977; Reston, 2010), leads to evolutionary divergence through biotic diaspora (Fortey 43 44 and Cocks, 2003) and creates the environment for the accumulation of thick piles of 45 sediments that host important resources (e.g. Lentini et al., 2010). Yet the processes of hyperextension and asymmetrical development of conjugate margins leading to eventual 46 continental breakup remain poorly understood (Reston et al., 2007; Ranero and Pérez-47 48 Gussinyé, 2010; Brune et al. 2014).

49 Much recent debate has centred on the importance of sequential faulting (Goldsworthy and 50 Jackson, 2001; Ranero and Pérez-Gussinvé, 2010; Brune et al., 2014), in which extension 51 occurs along a succession of individual faults, which develop, rotate and lock before the 52 succeeding fault initiates by slicing ever farther into one side of the rift, thus creating the asymmetry of the resulting conjugate margins (Ranero and Pérez-Gussinyé, 2010). Sequential 53 54 faulting and the resulting asymmetry has been proposed to develop early in the rifting process 55 when the continental crust is still >20 km thick (Ranero and Pérez-Gussinyé, 2010), but 56 dynamic models (Brune et al., 2014) allow a later onset, more consistent with observations 57 from North Atlantic magma-poor conjugate margins (Reston, 2010), which show that the 58 asymmetry only developed when the crust had thinned to <10 km to become entirely brittle (Reston and Pérez-Gussinyé, 2007; Reston, 2010). Related questions concern the 59 60 development and mechanics of apparently low-angle, large-displacement "detachment" faults 61 (Lister et al., 1986; Hoffmann and Reston, 1992; Sibuet, 1992): how and when these detachments formed and whether they slipped at low-angles (Figure 1a) or developed by a 62 63 rolling hinge mechanism (Buck, 1988; Figure 1b). The rolling hinge model itself is a form of 64 sequential faulting in which the "detachment" comprises segments of successive steep faults 65 (Buck, 1988; Reston et al., 2007; Choi et al., 2013), each active individually and in turn, each 66 abandoned when a new fault cuts through the hanging wall of the previous fault, and each 67 rotated by slip on subsequent faults propagating up from a steep root zone to form an 68 apparently continuous sub-horizontal surface (Figure 1b).

69

Many of the key concepts of rifting processes have been developed and/or tested at the Galicia margin, west of Spain, where the now widely observed characteristics (Reston, 2010) of reduced mantle velocities beneath thin crust, the crust thinning toward zero, and mantle unroofing (Boillot and Winterer, 1988), were first recognised. This margin is both sediment74 starved and magma-poor (Boillot and Winterer, 1988), allowing an optimal image of the 75 margin structure, including well-defined extensional faults (Reston et al., 2007; Ranero and 76 Pérez-Gussinyé, 2010) which appear to detach onto a band of bright discontinuous reflections 77 termed collectively the S reflector (de Charpal et al., 1978; Boillot and Winterer, 1988), and identified as a possible detachment fault (Sibuet, 1992; Reston et al., 2007). The final root of 78 79 S is believed to be currently located on the conjugate Flemish Cap margin (Reston et al., 80 2007; Ranero and Pérez-Gussinyé, 2010), where it forms a bright reflection dipping 81 landwards at 30° (Hopper et al., 2004).

82

83 Studies of continental rifts (Cowie et al., 2005; Nixon et al., 2016) and of seafloor spreading 84 (Cann et al., 1997) have shown that the process of continental rifting and eventual breakup is 85 complex and three-dimensional (3D). However, current understanding of the Galicia margin 86 and of continental breakup in general has been based on 2D numerical models (Huismans and Beaumont, 2003; Brune et al., 2014), 2D datasets particularly seismic reflection profiles (e.g. 87 88 de Charpal et al., 1978; Reston et al., 2007; Ranero and Pérez-Gussinyé, 2010), drilling 89 transects (Boillot and Winterer, 1988; Whitmarsh et al., 1998) and industry data not designed 90 or located to address the key scientific questions. In this paper, we present results from the 91 interpretation of a 3D seismic volume located offshore Spain (Figure 2), designed specifically 92 to reveal for the first time the 3D structures generated during the rifting of the Galicia margin. 93 The 3D data uncover the timing and mechanics of faulting and of asymmetric detachment 94 development, and show that both are compatible with the inferred onset of asymmetry at other 95 magma-poor margins (Reston, 2010), thus providing important new insights into the 96 mechanisms of continental breakup at magma-poor margins worldwide.

98 2 THE GALICIA 3D VOLUME

99 The seismic data were collected in 2013 (Figure 2) with the RV Marcus Langseth, towing two 100 3300 cu in tuned airgun arrays, firing alternately every 37.5 m. The data were received by 101 four digital hydrophone streamers, each 6 km in length, containing 480 channels and towed 102 with a 200 m spacing, producing a 68.5km x 20 km volume down to 14s TWT with a nominal 103 inline spacing of 6.25 m and a cross-line spacing of 50m. Processing was carried out by 104 Repsol and consisted of editing, despiking and low cut filtering, wavelet shaping including 105 zero phase conversion, multiple suppression (surface related multiple elimination and radon 106 demultiple), static correction to correct for variation in water velocity during the experiment, 107 offset plane Fourier regularisation and binning to 12.5 m inline and 25 m crossline spacing, 108 3D prestack time migration after tomographic and residual moveout velocity analysis, and 109 bandpass filtering. Relative amplitudes were preserved in the data shown here, although an 110 amplitude balanced version was also used for interpretation. The time migrated image was 111 converted to depth using a velocity model constructed from the interpretation of the fault 112 block structure, using velocities from wide-angle data and from 2D prestack depth migrations: 113 the depth image was compared with coincident images produced by 2D prestack depth 114 migration to ratify the depth conversion (Supplementary Figure S1). Interpretation was via the 115 Kingdom suite: uninterpreted versions of the seismic sections presented are shown in 116 Supplementary Figure S2.

117

118 3 MARGIN STRUCTURE

The 3D volume (Figure 3) provides spectacular new images and observations of the 3D structure of the Galicia margin, including sedimentary layering tilted, folded and faulted within the fault blocks by complex intrablock faulting, the architecture of the block-bounding faults network, whose deepest juxtaposed segments successively form the oceanward continuity of the S reflector, confirming that S is some form of detachment fault. We number the faults F3 through F6 following the 2D classification of Ranero and Pérez-Gussinyé (2010), but as the faults splay and die out laterally in 3D, we have added suffixes, thus keeping the same basic numbering scheme but distinguishing between the many faults. The block-bounding faults also bound wedges of sediment that splay towards the faults which we identify as synrift and discuss further below.

129 **3.1** The 3D geometry of the S detachment

130 In the volume, S is a strong, simple, apparently continuous reflection at \sim 9s TWT marking 131 the base of a probable damage zone (Leythaeuser et al., 2005; Schuba et al., 2018) at the main 132 fault interface. Mapped in time (Figure 4a), S shows long-wavelength undulations that are due 133 to velocity pull-up effects of the overlying fault blocks. S also shows pronounced 134 corrugations that are oblique to the sail-lines and thus are not acquisition artefacts. The 135 corrugations correspond to ~ 10 ms lineations in a filtered map of S (Figure 4b), persist after 136 depth conversion (Figure 4c) and match high-amplitude lineations on the amplitude map of S 137 (Figure 4d). Corrugations observed on major slip surfaces, such as on oceanic detachment 138 faults (Cann et al., 1997), are believed to form at depth and to parallel the displacement 139 direction (Resor and Meer, 2009; Edwards et al., 2018), but have never previously been 140 observed on a major extensional detachment buried beneath fault blocks at a rifted margin 141 before the acquisition of the Galicia 3D volume. In both time and depth, the corrugations 142 exhibit an oceanward change in orientation from E-W to ESE-WNW; the identification and 143 changing orientation of the corrugations on S demonstrate that the overlying extended 144 continental crust slipped on S and that the direction of extension changed oceanwards, 145 remaining parallel to the corrugations (Figure 4), during the rifting. The dominant strike of 146 the faults also changes oceanwards from N-S to SSW-NNE, remaining approximately

perpendicular to the corrugations and suggesting that the corrugations formed at the sametime as the faults overlying them.

149 A spectacular observation from the Galicia 3D volume is that the corrugations of the S 150 surface align with corrugations observed on some of the block-bounding fault planes (Figure 151 3, F6.0): many of the block-bounding fault surfaces were subject to mass-wasting when 152 exposed at the seafloor, obscuring any corrugations that may have formed, but some fault 153 planes, such as F6.0, display preserved corrugations (Figure 3) where they juxtapose 154 hangingwall and footwall basement (and so were never subject to mass-wasting); corrugations 155 on fault F6.0 (Figure 3) do not just align with the corrugations on S, but accurately match 156 ridge and trough with the corrugations on S, suggesting that both fault F6.0 and S represented 157 a single slip surface when F6.0 was active and the corrugations formed. The close relationship 158 between the activity of one fault and the development of S, emphasized by the matching of 159 the corrugations on both surfaces, strongly supports the development of S following a rolling 160 hinge model in which the basal detachment is composed of root segments of block-bounding 161 faults. Another characteristic of the rolling-hinge model (Buck, 1988; Choi et al., 2013) is 162 the upward propagation of the faults from a deep root zone, and we interpret the continuity of 163 corrugations on S and overlying faults (Figure 3) as evidence that both surfaces have 164 slipped together, suggesting that the block-bounding faults propagated up from S, consistent 165 with the rolling-hinge model. Nucleation of the faults on S and upward propagation 166 are further supported by the upward decrease in fault displacements (Figure 5) and the 167 increase in geometric complexity of the fault network between the S and the top basement 168 surfaces (Figures 4 and 6) that we interpret as resulting from the splitting of fault branches as 169 they propagated up in the shallower units.

171 Depth conversion removes the pull-up effects of the overlying fault blocks (Figure 4c) but pronounced topography on S remains where S meets the crust-mantle boundary (green-dotted 172 173 line on Figure 4) and where the deep segments of some of the block-bounding faults form the 174 oceanward propagation of S (solid coloured lines on Figure 4). Fault-related distortions of S 175 are also apparent on the time sections (Figure 5; Schuba et al., 2018), on the time structure 176 map (Figure 4a), and on the depth map of S, especially after removing the long-wavelength 177 topography related to velocity pull-up effects (Figure 4c), and thus are not products of the 178 depth conversion but genuine features of S. Uninterpreted maps showing fault-related 179 distortions on the S surface both in time and depth are presented in Supplementary Figure S3.

180

181 The continuity of the corrugations between faults and S (Figure 3), and the topographic 182 distortions on S where the faults root on it (Figures 4 and 5) both emphasize the partitioned 183 nature of S, i.e. that S comprises the downdip portions of successive fault planes, consistent 184 with the rolling hinge model (Buck, 1988; Reston et al., 2007; Choi et al., 2013). In the 2D 185 rolling hinge model (Buck, 1988; Choi et al., 2013), extension over any one-time interval is 186 along a single fault, rooting steeply at depth, that flexurally rotates as the crust beneath the 187 fault is gradually pulled out from beneath the hangingwall. When rotated sufficiently, the 188 fault is abandoned and replaced by a single new fault that initiates after the previous fault is 189 locked (Buck, 1988; Choi et al., 2013) cutting up from the same root zone and across the 190 preceding fault, now part of S, at a slight angle to transfer a slice of the hangingwall to the 191 footwall. However, only some of the block-bounding faults (e.g., faults 3.1; 5.1; 5.4; 6.1; 6.4 192 on Figure 5) appear to distort and cut across the more landward portions of S, but others just 193 merge with or stop abruptly at S. We suggest that those faults which cut at a low-angle across 194 the more landward portion of S bound groups or families of faults active over the same time, 195 as supported by fault heave analysis (see next section).

3.2 3D relationships between faults

197 To investigate the relationship between faults in 3D and to identify which faults must have 198 been active over the same time, we mapped the spatial relationships between the fault planes 199 of the main block-bounding faults and measured their heaves at top basement level (Figure 6). 200 Heaves were measured in the displacement direction (i.e. parallel to the corrugations -201 compare corrugations on Figure 4 with direction of heaves measurements on Figure 6a). The 202 block-bounding faults exhibiting both geometrical linkages (i.e. overlapping and merging of 203 the slip surfaces, Figure 6a) and complementary heaves are likely to have accommodated the 204 same episode of regional extension and so were likely active over the same time interval 205 (Cartwright et al., 1995; Cowie et al., 2005) as observed from the distribution of extension 206 over multiple faults during the progressive strain localization in the Corinth Rift system 207 (Nixon et al., 2016). Three main sets of faults (Figure 6) can be identified within the 3D 208 volume, each outlined on the depth and amplitude maps of S (coloured solid lines on Figure 209 4) by narrow distortions in the topography of S, changes in the orientations of the 210 corrugations on S and related change in the orientation of the strike of the faults remaining 211 approximately orthogonal to the corrugations. The easternmost set (closest to Iberia) consists 212 of four directly linked main faults (F3.0, F3.1, F3.2 and F4.0 on Figures 6a). The blocks 213 between F4.0 and F3.0 and between F3.0 and F3.1 pinch out southwards and northwards 214 respectively: these faults probably developed separately but became geometrically linked 215 when increasing displacement led to merger (Gupta and Scholz, 2000; Cowie et al., 2005) and 216 to form a single slip surface (Figure 6a, b). Within the entire fault set 3/4, as the heave on one 217 fault decreases, it increases elsewhere, but the sum of the heaves remains steady, even though 218 it decreases slightly to the north (Figure 6c), consistent with a general northward propagation 219 of rifting (Whitmarsh and Miles, 1995).

220 The geometrical linkages between the fault planes F3.0, F3.1, F3.2 and F4.0 (Figure 6a), and 221 the complementarity of the heaves within fault set 3/4 (Figure 6c), suggest that at times 222 during their evolution, F3.0, F3.1, F3.2 and F4.0 were active concurrently (Figure 6b), not 223 sequentially as previously suggested on the basis of 2D data (F3.0 then F4.0 - Ranero and 224 Pérez-Gussinyé, 2010). Although the 3D data require that Fault 3.1 was active over the same 225 time intervals as both Fault 3.0 and Fault 4.0, when looking at the fault system in 2D it might 226 be considered that F3.0 died abruptly when F4.0 initiated so that F3.0 and F4.0 were never 227 active at the same time, as in a 2D sequential faulting mechanism where a fault must lock-up 228 before the next fault forms (Ranero and Pérez-Gussinyé, 2010). However, it is generally 229 accepted that faults initiate as laterally restricted structures which grow both in length and in 230 displacement (Figure 6b) through repeated slip events (e.g. Cartwright et al., 1995; Cowie et 231 al., 2005; Nixon et al., 2016), making it unlikely that when F3.0 ceased to slip F4.0 was 232 instantly of sufficient extent to take up all the divergence accommodated further south by 233 F3.1. The 3D nature of rift fault network development thus far more likely implies that 234 activity on F4.0 and F3.0 overlapped in time (Figure 6b), probably substantially, as the 235 accommodation of the extension was progressively transferred from F3.0 to F4.0 as the locus 236 of extension migrated gradually oceanward. In short, the way faults grow, their linkages and 237 limited lateral extent, and the 3D nature of extension require modification of the 2D rolling 238 hinge model (Buck, 1988) as multiple faults have slipped at once (Figure 6b), and not in the 239 sequential way as defined by Ranero and Pérez-Gussinyé (2010) where two faults can not be 240 active at the same time, even if late extension migrated oceanwards. We note that overlap in 241 the activity of individual faults seems to be a common feature observed in natural 3D fault 242 systems even where faulting migrates asymmetrically (Colletini et al., 2009; Nixon et al., 243 2016).

The observed geometrical linkages, slip surface merging and heave complementarity within 244 fault set 3/4 is thus a direct consequence of the 3D nature of extension, which also applies to 245 246 other fault sets identified within the 3D volume. Oceanward, F5.1 marks the start of fault set 5 247 (Figure 6d) as F5.1 cuts slightly across the S reflector to the east but is continuous with S to 248 the west (Figure 5a). Faults within set 5 (F5.1, 5.2, 5.3, 5.4) in places merge directly (see F5.3 249 and 5.4 on Figures 4 and 5a), and have complementary heaves (Figure 6d), so again are likely 250 to have been active concurrently. Stepping oceanward once more, within fault set 6 (Figure 251 6e; F6.0, F6.1, F6.4, trending more NNE-SSW), the heaves of the faults are complementary 252 again (Figure 6e), as one fault dies out its displacement is transferred to neighbouring faults 253 (Walsh et al., 2003; Fossen and Rotevatn, 2016) and the sum of the heaves remains 254 approximately constant across the volume.

255 In each fault set, the most landward fault, marking the eastern boundary of the set, (e.g. F5.1, 256 F6.4) appears to cut across the S reflector to the east and to be continuous with S to the west 257 (Figures 3, 5a and 5b), consistent with a rolling hinge model in which each new fault set 258 propagates up from the root zone at an angle to the preceding, more landward fault set. This 259 relationship both indicates that the faulting migrated oceanwards, as in the sequential faulting 260 model (Ranero and Pérez-Gussinyé, 2010), as each set cut across those landwards, and precludes the possibility that all faults were active at the same time (Hoffmann and Reston, 261 262 1992). Conversely, the lack of any distortion of S where intersected by other faults within 263 each set confirms that these faults were active over the same time interval so that S was active 264 beneath the faults within that set, removing any topography on S. Thus, we interpret the 265 margin evolution in terms of a 3D rolling hinge model, with faulting migrating oceanwards, 266 with the limited lateral extent of individual faults requiring that several faults were active over 267 the same time interval. We conclude our analysis by focusing on the mechanics and timing of 268 the development of this three-dimensional rolling hinge system.

269 **3.3** Timing and angle of slip on S

270 On the 2D data, the internal stratigraphy of the fault blocks is not well resolved, leaving 271 considerable uncertainty in the angle at which S slipped (Reston et al., 2007). The improved 272 spatial resolution provided by the 3D volume (Supplementary Figure S1) reveals the internal 273 structure of the fault blocks, showing that S developed late in the rifting evolution and slipped 274 at low-angle (Figure 7). Crystalline basement, sampled by submersible (Boillot et al., 1988) 275 and identified more widely from seismic velocities (Bayrakci et al., 2016; Davy et al., 2018), 276 is overlain by a thin internally poorly reflective package (A), that we interpret as predating the 277 current fault blocks (Figures 5 and 7). Overlying A is a thicker, more ubiquitous and reflective 278 series of sediments (B); small offsets in the fine layering of package B show that this unit is 279 intensely fractured and faulted. Near the bounding faults, B exhibits an internally poorly 280 reflective facies (Figures 7a and 7b), which thins markedly away from the fault scarps, to 281 grade laterally into a reflective, layered facies subparallel to the tops of the fault blocks. The 282 changing facies may be interpreted as wedge-shaped, internally chaotic debris flows resulting 283 from mass-wasting of the emerging fault scarps during seismogenic slip, which grade away 284 from the fault scarps into more layered turbidites (Boillot and Winterer, 1988; Boillot et al., 285 1988) deposited within and along the half-grabens between adjacent block crests. Each 286 occurrence of package B is thus consistent with deposition during slip on the fault 287 immediately landward; where fault activity was diachronous, then so would be the deposition 288 of package B. The uppermost, and hence youngest, package (C) beneath the postrift (Figures 289 5 and 7) in places neither shows syn-tectonic fanning, nor always reaches the fault scarp. 290 Instead, it onlaps the upper portion of B and is thus interpreted as synrift, but post-dating local 291 faulting.

293 Within syn-faulting package B, the more continuously layered beds away from the fault are 294 likely to have been deposited close to horizontal and then rotated during slip on the block-295 bounding faults. Consequently, the angular relationships between the faults and both the base 296 and the top of this part of package B (Figure 7), revealed by the depth conversion, can be used 297 to infer that the faults formed at 55-60°, were rotated to ca. 40° and then abandoned, 298 consistent with standard models of extensional faulting (Anderson, 1905; Sibson, 1985). 299 From the angle between package B (base and top) and the underlying S detachment, the faults 300 initially rooted at ca. 40° but, rotating as the block rotated, the downward continuation of each 301 fault at the level of top mantle (i.e. S) remained active until 20-25° (the angle measured between the top of package B and S – Figure 7). Then a new fault propagated up at ~60° from 302 303 where S dipped at 40° and the process repeated.

304

305 The consistency of the angular relationships between sedimentary package B, S detachment, 306 and the faults within each half-grabens across the volume (Figures 5 and 7) supports the idea 307 that all blocks have been through the same process, as expected for a rolling hinge (Buck, 308 1988; Choi et al., 2013) rooting beneath the conjugate margin (Hopper et al., 2004; Reston 309 and McDermott, 2011) or a similar sequential faulting system (Ranero and Pérez-Gussinyé, 310 2010). However, the angular relationships measured from the 3D volume imply that this 311 system allowed slip on S at angles as low as 20-25°. Slip at such a low angle requires very 312 weak fault rocks such as talc or serpentine (Moore et al., 1996; Escartin et al., 1997; Pérez-313 Gussinyé and Reston, 2001; Reston et al., 2007), high fluid pressures (Floyd et al., 2001) that 314 are difficult to maintain in an extensional environment (Wills and Buck, 1997), or both 315 (Reston et al., 2007). At extensional detachments formed at the base of the crust during Neo-316 Tethyan rifting and exposed in the Alps, the fault rocks consist of serpentine gouge (Picazo et 317 al., 2013) and foliated serpentinites (Manatschal et al., 2006); similar serpentine lithologies

318 have been drilled further west at the Iberian margin (Whitmarsh et al., 1998) and inferred 319 from the reduction in mantle velocity beneath S (Bayrakci et al., 2016), but S itself has not 320 been sampled and other hydrated mantle rocks and even transient high fluid pressures may 321 also be important. Whatever the precise cause of fault weakening at the top of the mantle, the 322 large volumes of water needed (Bayrakci et al., 2016) require that the crust had thinned 323 sufficiently (~10 km) to become entirely brittle (Pérez-Gussinyé and Reston, 2001; Reston 324 and Pérez-Gussinyé, 2007) and so allow the necessary ingress of water (Bayrakci et al., 2016) 325 from above, penetrating several km into the brittle mantle. Subsequent slip and deformation 326 would then result in further water influx and further mantle hydration beneath the thinning 327 crust (Bayrakci et al., 2016; Prada et al., 2017). The development of a late stage asymmetric 328 detachment system during the rifting is compatible with the widely observed asymmetry at 329 conjugate magma-poor margin pairs (Gerlings et al., 2012; Reston, 2010), which is only 330 developed when the crust is thinner than ~10 km (Reston and Pérez-Gussinyé, 2007; Reston, 331 2010), that is where it had become entirely brittle during rifting, allowing serpentinization. 332 The numerical models of Brune et al. (2014) also predicted the development of asymmetry 333 through sequential faulting when the crust was thinned to between 10 and 20 km, depending 334 on lithospheric rheology, but their mechanism relied on the presence of a weak lower crustal 335 channel where temperatures were between 600° and 800°C, incompatible with the inferred 336 presence of serpentinites or similar rocks that only form below ~ 400°C (Emmanuel and 337 Berkowitz, 2006).

338

339 4 CONCLUSIONS

The 3D observations provide new insights into the role of detachment faulting during breakup (Figure 8). The data demonstrate that S was not a throughgoing detachment active simultaneously over a wide area, but rather a detachment fault formed of the root zones of successive normal faults, a result never demonstrated before. In addition, the intersection of
one fault by the next, hence more recent, fault generation along the S reflector prove that
extensional faulting migrated oceanwards, aspects similar to the sequential faulting (Ranero
and Pérez-Gussinyé, 2010) and rolling hinge (Buck, 1988) models.

347

348 There are, however, three fundamental differences from existing 2D rolling hinge and 349 sequential faulting models. First, each fault is of limited lateral extent, requiring several 350 linked faults to have been active concurrently rather than only one major fault active at any 351 time. Thus, in 3D (Figure 8), the detachment grows through the complex interaction of 352 several faults at any one time. Second, these faults rooted onto S, which continued to slip at 353 low-angle (although rooting more steeply), requiring the presence of weak hydrated rocks 354 such as serpentinites (Bayrakci et al., 2016) beneath the thin continental crust. Third, the need 355 for mantle hydration indicates that the asymmetric detachment system only developed late in 356 the rifting history as the crust became entirely brittle and thus thinned to <10 km (Reston and 357 Pérez-Gussinyé, 2007; Bayrakci et al., 2016). This result is consistent with the observed 358 asymmetry of conjugate magma poor margin pairs (Reston, 2010) and contrasts with previous 359 models in which sequential faulting and hence asymmetric rifting either developed when the 360 crust was either >20 km thick (Ranero and Pérez-Gussinyé, 2010), or was controlled by a hot, 361 ductile lower crust (Brune et al., 2014), incompatible with the observed mantle 362 serpentinization.

363

364 **5** ACKNOWLEDGMENTS

365 Data acquisition was funded by the National Science Foundation (OCE-257 1031769) and
366 UK Natural Environment Research Council (NERC) awards NE/E015883/1 and
367 NE/E016502/1. TAM was supported by a Wolfson Research Merit award. Data processing by

368	Repsol was funded by NERC through grant NE/E015883/1. We thank the crew of R/V
369	Marcus G. Langseth. We are grateful to Nur Schuba for helpful discussion concerning figure
370	4b. Reviews were by Marta Pérez-Gussinyé and an anonymous but helpful reviewer.
371	

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528 7 FIGURES CAPTIONS

Figure 1. Detachment models. a) 2D model in which detachment slips at low-angle, multiple faults active at once (Sibuet, 1992). b) 2D rolling hinge: detachment comprises the roots of successive faults, active sequentially when steep (Reston et al., 2007; Bayrakci et al., 2016).
Faults are sequentially numbered in the chronological order from the oldest (Fault 1) to the most recent and active one (Fault 4).

Figure 2: Location of the Galicia 3D volume west of Spain across the deep Galicia margin.
White box shows the location of the 3D reflection survey. Black dots show the location of
sites drilled during ODP leg 103. Isocontours show the bathymetry of the study area (in m).

537 Inset map from Google Earth. Bathymetric data consist in Global Multi-Resolution
538 Topography Data Synthesis from the National Oceanic and Atmospheric Administration.

539 Figure 3. The anatomy of the Galicia margin summarising the key structural and stratigraphic 540 elements. The figure displays a perspective view from the north of the 3D volume and has 541 been built by removing the post-rift sequence to expose the top of the faulted layer in the 542 southern part of the volume; similarly, the pre- and syn-rift sequences have been removed to 543 expose the top of the basement and the planes of the block-bounding fault in the northern part 544 of the volume. Two vertical slices generated through the northern and southern parts of the 545 volume respectively display the extended continental basement and the geometry of the pre-546 and syn-rift units (A, B, C). The top of the faulted layer surface, the top basement surface and 547 the vertical slices reveal the lateral discontinuity and interactions of faults above S. 548 Corrugations on S surface (shown at the NW corner of the volume) match the corrugations 549 observed on the plane of the block-bounding faults propagating up from S (Fault 6.0). The 550 seismic data are shown with no vertical exaggeration.

551 Figure 4. Maps of the S reflector. a: Time map displaying corrugations, oblique to the sail-552 lines and shown by three sets of coloured arrows corresponding to the three sets of block-553 bounding faults rooting on S (solid lines). The long wavelength undulation of S in time is due 554 to velocity pull-up effects. Green dotted line underlines where S meets the crust-mantle 555 boundary b: Time filtered map obtained by subtracting the rough interpreted surface of S from 556 the smoothed surface of S in time. The corrugations (arrowed) are highlighted by ~ 10 ms 557 lineations. Traces of the deep segments of the block bounding faults on S (solid lines) are 558 highlighted by ~20 ms lineations. c: Depth map showing corrugations (arrowed) remaining 559 approximately orthogonal to the corresponding fault set and distortions of S where main 560 block-bounding faults (solid lines) root. S also shows a pronounced distortion where it meets 561 the crust-mantle boundary (green dotted line). d: Amplitude map of S, made by slicing through the 3D volume along the peak of the envelope function. The corrugations visible indepth appear as pronounced lineations of high amplitude.

564 Figure 5. Seismic reflection images from the Galicia 3D volume. a, c: Vertical time sections; 565 b, d: Same vertical sections converted to depth. The sections were generated through the 3D 566 volume in the same direction as the corrugations observed on S, thus oriented in the extension 567 and displacement direction (compare direction of sections on Figure 6 with corrugations on 568 Figure 4). The sections show a bright reflection (S) that meets the crust-mantle boundary 569 (white arrows) and runs at the base of the fault blocks. The mantle beneath S has been shown 570 by wide-angle velocities to be serpentinized. S displays distortions where the block-bounding 571 faults root onto it, implying that S is composed of deep segments of faults. Long and short 572 horizontal arrows point the upward decrease in fault displacements (shown in km), 573 respectively between Top Basement and Top A, suggesting the faults propagated up from S. 574 E, f, g, h: Blow ups in time (e, g) and corresponding blow ups in depth (f, h) showing details 575 of relationship between S and overlying faults: F5.1 and F6.4 continue downdip as S, cutting 576 across an older segment of S. Horizontal bars show the heaves (see Figure 6) as, coloured by 577 fault set. Uninterpreted sections are shown in supplementary Figure S2 and details of the 578 analysis of the angle at which S slipped in Figure 7.

579 Figure 6. Heave analysis. a: Top basement map showing block-bounding faults heaves along 580 white flowlines (dashed when only partially covered by the data) defined by corrugations on 581 S; The white arrows point-out spatial linkage between different fault plans. Faults are 582 numbered after line IAM11 from Ranero and Pérez-Gussinyé (2010); b: Map view of fault 583 development in which several faults slip over the same period of time - designed for fault set 584 3/4 but also applicable to fault sets 5 and 6. New faults nucleate, grow and link in the rift-axis 585 area while former faults progressively deactivate, implying several active faults at different stages of their evolution: nucleation, fully active, in process of deactivation and deactivated. 586

Arrows show the relative growth of the different faults. Looking at faults F3.0 and F4.0 on a single 2D line (e.g. IAM11) only provides a glimpse of the full fault system and does not allow to image faults lateral geometry, which form a single slip surface south of IAM11 when merged with fault F3.1, as observed from the 3D data.

591 ; c: Cumulative and individual heaves with uncertainties for fault sets 3/4. Unless F4.0 is 592 included in set 3/4, the heaves drop off suddenly to the north at \sim 7km. Further north as the 593 heave on F4.0 gradually decreases, that on F3.0 gradually increases. Cumulative heave 3/4 594 decreases gradually to the north; all faults in this set were coeval; d: Cumulative and 595 individual heaves with uncertainties for fault set 5. Heave on fault F5.2 is transferred to F5.1, 596 then to F5.3; Cumulative heave 5 remains steady across the volume, all faults in this set were 597 coeval.; e: Cumulative and individual heaves with uncertainties for fault set 6. Moving north, 598 heave on F6.1 increases as that on F6.4 drops, and then transfers abruptly to F6.0; Cumulative 599 heave 6 remains steady across the volume, all faults in this set were coeval.; f: Cumulative 600 heave of all the faults across the dataset decreases slightly to the north.

601 Figure 7: Geometrical analysis of the angle at which faults and S were active based on flow 602 lines through the volume. See Figure 5 for location of data. a, c) current geometry shown in Figure 5c. S dips at 3° to the west whereas the top and base of package B dip 17° and 34° 603 604 respectively to the east, implying that S dipped 37° W at the onset of deposition of package B 605 and 20° W when the top of package B was deposited horizontally, b, d) similar analysis for 606 the data in Figure 5d shows that S dipped 32° and 26° at the onset and end of deposition of 607 package B. e), f) geometry at the end of deposition of package B, not corrected for 608 compaction. g), h) geometry at the end of deposition of package B, corrected for compaction. 609 All show that S was active down to $\sim 20^{\circ}$ and that the faults were active down to $\sim 40^{\circ}$.

610 Figure 8: Our summary model based on 3D observations. Extension migrates oceanwards,

611 but several faults (color-coded by set) were active simultaneously in each set, a 3D innovation

612 of the 2D model shown in figure 1b. The faults rooted on and propagated up from a 613 serpentine detachment (S) at the base of the crust; slip on S occurs at low-angles. The 3D 614 modified rolling hinge system developed only once the entire crust had thinned sufficiently to 615 become brittle allowing mantle hydration.

616

617 Supplementary figures

Figure S1. Comparison of 2D prestack depth migrated images with depth-converted versions of 3D prestack time-migrated images. The close match verifies the accuracy of the depth conversion and highlights the improved imaging resulting from 3D migration. (a) IAM11 prestack depth migrated image and faults numbering from Ranero and Pérez-Gussinyé (2010). (b) corresponding section through the depth conversion of 3D prestack volume. Note also the improved resolution of the sediments in the 3D volume and improved continuity of S.
Figure S2. Uninterpreted versions of the data shown in Figure 5.

625 **Figure S3.** Uninterpreted versions of the data shown in Figure 4.

627 8 FIGURES



628 Graphical Abstract



629

Figure 1















635 Figure 6



637 Figure 7





640 Supplementary Figure S1







644 Supplementary Figure S3