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1 Flipping detachments: the kinematics of ultraslow spreading ridges

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- 6

7 Abstract

8 Although the seafloor spreading Hess initially proposed was a virtually amagmatic process, 9 little attention has been paid to that possibility since. We construct a kinematic framework 10 for virtually amagmatic and magma-poor Hess-style seafloor spreading, and successfully 11 apply it to processes operating at the Southwest Indian Ridge (SWIR). The kinematic model is based on symmetric divergence about a rift axis at depth, with a repeating cycle in which a 12 13 fault propagates up from the rift axis, develops into a detachment fault accommodating the 14 plate divergence, migrates beyond the rift axis and is abandoned when a new fault 15 propagates up through the footwall from the rift axis. We rigorously explore the controls on 16 the depth, dip and timing of fault initiation and abandonment and use the kinematic framework to reconstruct the evolution of smooth mantle-dominated seafloor at the SWIR 17 18 through symmetric divergence about a fixed rift axis. The model predicts the development of 19 successive detachments of flipping polarity, as observed, each rooting along a narrow and fixed rift axis at 20 km depth, the base of the seismically defined brittle lithosphere. The 20 detachments root at 80° (consistent with constraints on seismicity-defined detachment 21 22 orientation at oceanic core complexes), and exhume mantle. Based on the continuity of 23 basement ridges, of magnetic anomalies and of the seismic activity at the base of the lithosphere, it appears that these exhumation detachments transition laterally into rafting 24 detachments, transporting fault-bounded volcanic slices up and away from the spreading 25

26 axis to form the rougher volcanic seafloor found between mantle-dominated domains. The 27 kinematic framework shows that increased magmatic divergence requires the detachments 28 to root at shallower depths, consistent with the seismicity-defined shallowing of the base of 29 the brittle lithosphere moving along the ridge axis towards the volcanic centres. Only in the 30 immediate vicinity of volcanic centres, where the seismicity dies out, may magmatism 31 dominate. We conclude that detachment tectonics dominate the process of ultraslow 32 seafloor spreading as well as much of slow seafloor spreading, totalling about one third of 33 the global ridge system, and present the first 3D tectonic model for ultraslow seafloor 34 spreading.

35

36 Keywords: seafloor spreading, detachment faults, plate tectonics,

37

38 **1.** Introduction:

39 Seafloor spreading as first proposed by Hess (1962) was virtually amagmatic, leading to the unroofing of large tracts of mantle at the seafloor, but the dredging of dominantly basaltic 40 41 crust and the structure of ophiolites led to the adoption of a more magmatic model, like that 42 proposed by Dietz (1961). However, the interpretation of oceanic core complexes (OCCs -43 Cann et al., 1996) as plutonic and mantle rocks exhumed in the footwall of large offset 44 normal faults has re-emphasised the importance of faulting in seafloor spreading. These 45 oceanic detachment faults are believed to root steeply (deMartin et al., 2007; Figure 1), causing the exhumed footwall to be rotated by at least 60° about a ridge-parallel horizontal 46 axis (Morris et al., 2009), as in a rolling hinge model (Lavier et al., 1999 – Figure 1). 47 MacLeod et al., (2009) proposed that individual oceanic detachment faults develop through 48 49 runaway weakening of normal faults, allowing the detachment to accommodate more than half the plate divergence and hence to migrate across the ridge axis, to be cut by dikes and 50 51 abandoned (Figure 1 D, F, G – Escartin et al., 2017).

52 The observation (Dick et al., 2003) that ultraslow spreading ridges such as the Southwest Indian Ridge (SWIR) and the Gakkel ridge are dominated by long-lived volcanic centres and 53 intervening zones of exhumed mantle, is in keeping with the reduced magmatism expected 54 as full spreading rates drop below 20 mm/yr (Bown and White, 1994), but Dick et al. did not 55 56 investigate the kinematics of mantle exhumation. Building on the MacLeod model for individual OCCs, Reston and McDermott (2011) suggested that successive detachments. 57 each migrating across the rift axis to be cut by a new detachment, could explain the 58 59 unroofing of large expanses of mantle both at magma-poor margins (where it explained the 60 unroofing of mantle, the dominance of landward-dipping root zones on each margin and the large scale symmetry of conjugate margins - Reston, 2007; 2009) and at ultraslow spreading 61 62 ridges (Figure 2), suggesting that the polarity of successive faults would be "likely to alternate if flexure of the exhuming footwall induces strain weakening antithetic to the old 63 64 fault". This "flip-flop" detachment model was subsequently applied by Sauter et al. (2013) to mantle-dominated parts of the SWIR. Here we develop the flip-flop concept into a rigorous 65 66 kinematic model for Hess-style seafloor spreading, exploring the controls on detachment abandonment and initiation, and the along strike transition from mantle-dominated to 67 68 volcanic seafloor. We develop a 3D model for ultraslow seafloor spreading, in which detachment faulting controls both virtually amagmatic seafloor spreading (VASS), exhuming 69 70 the mantle of the smooth seafloor, and much of the neighbouring expanses of volcanic seafloor formed by partially magmatic seafloor spreading (PMSS). Our results have 71 profound implications not just for the spreading mechanism operating at ultraslow ridges but 72 also for the development of oceanic core complexes found along most of the slow-spreading 73 74 Mid-Atlantic Ridge, and thus in total perhaps one third of the active spreading ridge system.

75

76 2. The Southwest Indian Ridge

77 The SWIR, spreading at an ultraslow full rate of 14 mm/yr, exhibits irregular bands in the flowline direction, of "smooth seafloor" - dominantly exhumed mantle - separated by rougher 78 bands of dominantly volcanic seafloor (Sauter et al., 2013). Sparse wide-angle data suggest 79 that the volcanics are up to a few km thick, and widely-spaced Moho reflections a couple of 80 81 km deeper (Minshull et al., 2006 – Figure 3A), whereas the smooth seafloor exhibits 82 pervasive but downward-decreasing serpentinisation to a depth of 6 km below seafloor 83 (Momoh et al., 2017) where the Moho marks a transition to unserpentinised mantle. Most 84 seismic activity occurs along a continuous band that can be traced from 20±5 km depth 85 beneath the smooth seafloor to ~5 km as volcanic centres are approached, tracking just above the 700°C isotherm thought to mark the downdip extent of brittle faulting (Schlindwein 86 87 and Schmidt, 2016 – Figure 3A). The lack of shallower seismicity may result from serpentinisation and hydration of the fractured mantle by the passage of water along the 88 89 faults (Reston and Perez-Gussinye, 2007); serpentinites form up to temperatures between 400 and 500°C (Emmanuel and Berkowitz, 2006), consistent with the upper limit of the 90 91 seismicity. Schlindwein and Schmidt (2016) suggest that the considerable thickness of the 92 brittle layer results from cooling by the circulation of the serpentinising water.

93 The smooth seafloor on both sides of the spreading axis (Figure 3B) exhibits a series of axis-parallel elongate highs, with both inward- and outward-facing flanks formed by exhumed 94 slip surfaces of major faults (Sauter et al., 2013). Inward-facing faults can be traced from the 95 96 top of each elongate high down to the base of the inward-facing flanks where they are cut by 97 outward-dipping faults (forming the outward flank of the high immediately inboard) which pass into the subsurface. The pattern was interpreted by Sauter et al., (2013) in terms of 98 successive detachment faults of alternating polarity (Reston and McDermott, 2011 - Figure 99 100 4C). We start by considering the kinematics of these faults, given the constraints imposed by the observed seismicity (Schlindwein and Schmidt, 2016) on the depths at which faults 101 root, and the seafloor observations of fault extent and orientation. 102

103

104 **3.** A kinematic model for amagmatic spreading

105 The concept of mantle exhumation and VASS through successive detachments (Reston and 106 McDermott, 2011) is based on three assumptions: divergence is amagmatic (magmatism may thicken the lithosphere but does not accommodate significant horizontal 107 108 displacements), divergence is symmetric about a deep rift axis, and successive faults 109 propagate up from that rift axis, exploiting weakness of the footwall where it has been flexed and faulted near the rolling hinge. (We use the term "rift axis" to describe the axis of 110 111 divergence at the depth of fault initiation, distinct from the surface expression of divergence, the spreading axis). As extension proceeds and the footwall is pulled out from beneath the 112 hanging wall, the fault root migrates with the hanging wall away from the rift axis at half the 113 spreading rate until the next fault propagates up from the rift axis through the footwall (Figure 114 2). The footwall, including the breakaway, migrates at the same half-spreading rate in the 115 opposite direction. 116

117 The kinematic model can be presented in two ways: a simple geometrical approach (Figure 118 4C), based on reducing the curvature of the flexing footwall to a sharp hinge and assuming 119 that the system is kinematically stable, i.e. a fixed rift axis, and a graphical approach (Figure 120 4A and B) that explores the implications of seafloor observations. The graphical approach (Figure 4B) defines the linear extrapolation of the fault root to the surface as the edge of the 121 122 original hanging wall, a parallel line through the breakaway as the edge of the original footwall prior to divergence and flexure, and the midpoint of the two as the location of the 123 original fault and hence the rift axis at the depth of fault initiation, assuming symmetric 124 125 spreading.

To analyse the detachments graphically, we must first reconstruct them (Figure 4D) from the seafloor observations, revealing the heave of each detachment immediately prior to its truncation, and where each detachment was truncated by the next. A seismic study at the SWIR (Momoh et al., 2017) imaged basement reflections interpreted as from the detachment 130 root dipping at 60° and, but the Kirchhoff time migration used does not handle steep dips well and the depth conversion by vertical stretch does not include ray-path bending. 131 132 Furthermore, the image is only to a depth of 5-6 km below the seafloor, and as rolling hinge 133 detachments are flexed to be convex-up, the detachment is likely to steepen towards the 134 depth of the brittle-ductile transition close to the 700°C isotherm (Schlindwein and Schmidt, 135 2016; Figure 3). We thus suspect that the image significantly underestimates the dip of the 136 detachment at depth. The depth of fault initiation is constrained by the depth of seismicity 137 observed (Schlindwein and Schmidt, 2016), and the fault dip θ is constrained by the 138 geometry of oceanic detachments elsewhere: in Figure 4D, we assumed that at depth faults dip at 75°, similar to the dip observed at the MAR at TAG (deMartin et al., 2007), meaning 139 140 that for four of the six detachments interpreted in Figure 3, the original fault position and the new fault intersect at the rift axis at a depth of ~ 10 km below the seafloor (Figure 4D), 141 142 somewhat shallower than the observed SWIR seismicity. For the same 75° fault dip, the small heaves of two detachments (ϵ and ϕ) however predict an even shallower initiation 143 depth for the next fault (Figure 4D): we discuss the possible explanations below. 144

145 Parameters such as heave, truncation point and fault dip are more efficiently analysed using the geometric model. While considerably simpler than numerical models (e.g., Buck et al., 146 147 2005; Tucholke et al., 2008; Behn and Ito, 2008), the geometrical approach allows testing of the key controlling parameters and hence provides insight into the processes occurring at 148 149 ultraslow spreading ridges. From the model in Figure 4C, and defining e as divergence (= 150 heave h for amagmatic divergence along a single fault), c as the distance between the idealised surface trace of the old fault and where it is truncated by the new fault, θ as the 151 fault dip, and z as the depth of fault initiation, we have: 152

153 $(e/2) - c = 2z/\tan\theta$

[1]

relating the observable timing (in terms of divergence) and location of the truncation point to the fault parameters of dip and initiation depth. This equation can be rewritten to give the fault initiation depth:

157
$$\tan\theta.((e/2) - c)/2 = z$$
 [2]

Plotting heave (divergence *e* for amagmatic spreading) against fault initiation depth for a wide range of fault dips, and two different truncation distances (3 and 5 km in broken and solid lines respectively) shows that as the heave or the fault dip increases, so does the depth of fault initiation (Figure 4E). Comparing the results for the range of fault heaves observed along the smooth 64.5°E transect (Table 1) with the 15-25 km depths of seismicity observed just to the east (Schlindwein and Schmidt, 2016) suggests that the faults must have initiated as steep structures dipping at least 80°.

	SWIR at		MAR at					
Location	64.5°E	64.5°E	64.5°E	64.5°E	64.5°E	64.5°E	5°S	TAG
Detachment	β	Х	δ	3	ф	Y	5S	TAG
dip of root °	?	?	?	?	?	?	75°	73°
polarity: down								
to	N	S	N	S	Ν	S	E	W
heave [km]	24	17	18	10	11	20	23	12
truncation [km]	6	3	4	2	3	4	6	3 assumed

165 Table 1: Detachment parameters

The specific truncation points and heaves of the detachments observed (Table 1) can also be used to predict fault depth vs dip (Figure 4G), effectively duplicating the analysis in Figure 4D but over a wide range of fault angles. The β , χ , δ and γ detachments plot in virtually the same space, despite different heaves and truncation points (Table 1), suggesting a common depth and dip of formation; for all four an initial dip of 80-83° predicts that the detachments initiated at the 15-25 km depths of seismicity observed at magma-starved portions of the 172 SWIR (Figure 3). This dip is the same as the best constrained dip at depth of an oceanic detachment fault, traced to ~10 km below the seafloor using microseismicity at 13°20'N 173 (Parnell-Turner et al., 2017), but is considerably greater than that expected from simple 174 Mohr-Coulomb criteria and may indicate that faults partly follow sub-vertical dikes (Olive et 175 176 al., 2010) or hydrofractures weakened by serpentinisation; while it is generally recognised that serpentinites allow normal slip at low-angles, they also allow slip on pre-existing 177 structures at angles steeper than optimum. Sauter et al. (2013) note that the exhumed slip 178 179 surfaces are cut and offset by minor high-angle faults and fissures that act as conduits for 180 shallow magma intrusion and eruption of lavas that cover parts of the seafloor even in the 181 smooth sections of the SWIR.

182

183 3.1 Incorporating asymmetry

The small heaves of the ε and φ detachments would appear (Figure 4D) to suggest that the 184 succeeding fault would either have to initiate much shallower than the other detachments, or 185 if also initiating at the depth of the seismicity, would need to have developed from near-186 vertical fissures or dikes (Olive et al., 2010). The anomalous heaves of the ε and ϕ 187 188 detachments may alternatively involve a departure from the assumption that rifting is symmetric about a deep rift axis and that all faults root on this axis. A degree of asymmetry 189 can be introduced by allowing the rift axis to move by a proportion K of the divergence. 190 Positive values of K move the rift axis in the direction of the hangingwall, negative values in 191 192 the direction of the footwall, giving us new expressions for the distance from the original edge of the footwall to the rift axis of 193

194
$$e.K + e/2$$
 [3]

195 which means that the distance *c* from the HW cutoff to the truncation point becomes

196

 $c = e - (0.5.e + e.K) - 2z/tan\theta = e(0.5 - K) - 2z/tan\theta$

[4]

197
$$K = 0.5 - (c + 2z/tan\theta)/e$$

198 The depth of initiation can be found from:

199
$$z = tan\theta.(0.5e - e.K - c)/2$$
 [5]

and the amount of divergence before the new fault develops by:

201
$$e = (c + 2z/tan\theta)/(0.5-K)$$
 [6]

202 For a given angle and depth of fault initiation, positive K either reduces the distance c between the truncation point and the HW cutoff, or means that the new fault only develops 203 later in the cycle, i.e. at larger heaves (Figure 4F). In one scenario, where the rift axis is 204 controlled by the location of the detachment root, the rift axis moves with that root, K = 0.5, 205 206 the detachment is never abandoned, and no new fault develops. In this manner a fault that runs the whole length of a segment - and thus controls the location of the rift axis - might 207 develop very large offsets, as observed for the OCC within the Ascension double transform 208 system (Grevemeyer et al., 2013), and for the Godzilla OCC (Tani et al., 2015). 209 210 Conversely, a negative K would result in the fault developing earlier in the cycle (i.e. at a

211 smaller heave – Figure 4F)): a K of -0.3 would suffice to shift the initiation point of the ε to 212 depths similar to the other four detachments.

213 It does not, however, seem likely that a generally stable rift axis would suddenly jump several km to the footwall for the initiation of one fault and then back by the same amount for 214 the initiation of the next fault. A simpler way of looking at the same events is to suggest that 215 the rift axis stayed fixed but that a single fault, the ε detachment, rooted off axis on the 216 217 footwall side, and propagated up through the φ detachment before that had achieved the expected heaves. The subsequent δ detachment propagated up from the rift axis, located 218 well back in the footwall of the developing ε detachment, thus also truncating ε at relatively 219 220 low heaves. To illustrate this interpretation we have reconstructed the evolution of the 221 smooth seafloor along the 64.5° E transect (Figure 5). All faults initiate at the same depth,

and apart from the ε detachment, all faults initiate at the rift axis, about which spreading is symmetric. Given that we have simply adopted the seafloor interpretation of Sauter et al. (2013), the stability of the reconstruction is remarkable, with the off-axis formation of a single detachment (ε) being the proverbial "exception that proves the rule". We thus conclude that development of successive flip-flop detachments, initiating at 15-20 km depth and at an angle of ~80° during overall symmetric VASS produced the smooth seafloor along the 64.5° E transect.

229

230 3.2 Incorporating magmatic divergence

231 In the kinematic model for VASS developed above, we have related four parameters: the 232 depth of fault initiation (constrained by seismicity), the dip of fault initiation (partially 233 constrained by observations elsewhere), the point where a detachment cuts the preceding 234 one and the amount of divergence accommodated by each detachment (both from seafloor observations). However, we observe the current extent of the detachment, not how it may 235 have formed, and crucially ignore any contribution of magmatism to plate divergence. This 236 assumption would appear reasonable for smooth-seafloor parts of the SWIR where mantle 237 238 dominates and the fraction of magmatic divergence M may be close to 0, but is probably less valid where the amount of volcanics increases. 239

240 The interplay between magmatism and faulting is likely complex (e.g. Olive et al., 2010), with faults providing conduits for magma and dikes potentially evolving into faults as discussed 241 above, and increased magmatism accompanied by a hotter, thinner lithosphere, and a 242 243 shallower brittle-ductile transition (Behn and Ito, 2008). For this kinematic analysis we distinguish between magmatism that does not contribute directly to plate divergence but may 244 thicken the crust, and magmatism that actually extends rather than thickens part of one plate 245 (Figure 6A, B), taking up a proportion M of the divergence (Buck et al., 2005; Behn and Ito, 246 2008). Magma is likely to be trapped deep in the ductile asthenosphere (Olive et al., 2010) 247

248 or beneath the footwall (Kelemen et al., 2007; Dick et al., 2008; MacLeod et al., 2009) as it is uplifted beneath the detachment and migrates across the deep rift axis; this magma 249 increases crustal thickness but does not actually extend the system. How much magma is 250 trapped in this way is the subject for another debate, but may range from very little (e.g. 251 252 during truly amagmatic spreading) to considerable, trapped by upside-down magmatic growth faulting beneath the footwall (Kelemen et al., 2007; Dick et al., 2008), but if intrusion 253 accommodates some divergence (partially magmatic seafloor spreading, PMSS) we need to 254 255 modify the kinematic model.

The kinematic model for VASS (Figure 4C) is easily modified for PMSS (Figure 6C). As the 256 amount of magmatic divergence by intrusion of the hanging wall increases, the proportion of 257 divergence taken up on the fault drops and the active fault no longer follows the original 258 edge of the hanging wall but is closer to the rift axis; when M reaches 0.5 (Behn and Ito, 259 2008), the active fault is at the rift axis (Tucholke et al., 2008) and follows the original fault 260 position, halfway between the original HW and FW edges. The kinematically stable depth of 261 262 initiation z (i.e. above a fixed rift axis during symmetric spreading) can be related to the 263 divergence e, the truncation distance c and the angle of fault initiation θ by

$$z = \tan\theta.((e/2) - c - e.M)/2$$
 [7]

[8]

265 Or from a process perspective:

266

 $((e/2) - c - e.M) = 2z/\tan\theta$

which is the equivalent of equations [1] and [2] when M = 0. Note that these relationships are the same as for the element of asymmetry in [*3-6*], only replacing the asymmetric proportion K with M and noting that unlike K, M can only be positive.

270 The above analysis can be applied to oceanic core complexes such as 5°S (Reston et al.,

271 2002) where the detachment was abandoned following the migration of the fault root beyond

the rift axis. The heaves, truncations points, and a suitable fault dip (Table 1) can be

compared with the seismicity observed nearby to estimate the amount of magmatic divergence in these systems. At 5°S, the few days seismicity recorded (Tilmann et al., 2004) is insufficient to map out fault dips but does suggest a maximum seismogenic depth of ~7 km below the seafloor. Inputting the detachment parameters into the kinematic model, suggests an M factor of ~0.15 for 5°S (although there is considerable uncertainty - Figure 6D), which is not unreasonable since for the fault to migrate across the rift axis M < 0.5 (Tucholke et al., 2008).

Although the oceanic detachment at TAG (deMartin et al., 2007) is still active, the same sort 280 281 of analysis is instructive there. In map view (Figure 1D) the TAG OCC bulges markedly across the median valley. Taking a narrow box linking the well-defined neo-volcanic zones 282 to the NE and SW as the rift axis, the active magmatism deflects to the northwest around the 283 OCC. The rift axis is closer to the breakaway identified by deMartin et al. than it is to the 284 root zone (Figure 1E), requiring an impossible negative M value or markedly asymmetric 285 spreading. Instead we propose that the deMartin breakaway is the edge of a rafted rider 286 287 block rafted with the true breakaway at the next scarp to the east. The rift axis now lies 288 approximately halfway between the root and the breakaway, implying that M must be small unless spreading is slightly asymmetric. We speculate that bands of seismicity identified as 289 290 antithetic faulting (deMartin et al., 2007) may be compressional related to the bending of the 291 exhuming footwall; if this band of seismicity were to mark an incipient fault cutting across the 292 active detachment near the hanging wall cutoff, the dimensions would imply an M of about 293 0.05.

294

3.3 Incorporating magmatism for successive detachments

The OCCs at TAG and 5°S each formed by slip on a single detachment fault. When successive detachments are present, intrusion (magmatic divergence) in the hanging wall of the active fault is in the footwall of the immediately preceding fault (Figure 6E). Where the 299 active fault dips in the opposite direction to the preceding fault, the magmatic divergence increases the distance between the breakaway of that fault and the point where that fault 300 was cut (Figure 6E); in the rarer case where the active fault dips in the same direction as its 301 302 predecessor, the magmatic divergence extends the structurally deeper portion of the 303 preceding footwall between the root zone and the point where that fault was cut. By 304 affecting the geometry and dimensions of the preceding detachment, in both cases the magmatic divergence influences the relative positions of the rift axis and the root zone and 305 306 hence affects the next fault's initiation depth. Thus to analyse the kinematics of successive detachments in the presence of magmatism, the effect of magmatic extension of the 307 preceding fault must be estimated and removed from the observed geometries before the 308 309 kinematics of the original detachment can be analysed. The truncation distance c (Figure 6) 310 is given for each numbered phase of faulting by:

311
$$c_1 = e_1(1 - M_1) - (2z_1/tan\theta_1) - e_1/2$$
 [9]

which can be re-arranged to express divergence *e* in terms of *c*, *z*, θ and *M*:

313
$$e_1 = (c_1 + 2z_1/tan\theta_1)/(0.5 - M_1)$$
 [10]

and for the next phase of faulting:

315
$$e_2 = (c_2 + 2z_2/tan\theta_2)/(0.5 - M_2)$$
 [11]

and the measured heave *h* (based on current geometry), extended by the subsequent magmatic divergence $e_2.M_2$ is given by:

318
$$h_1 = e_1 - e_1 \cdot M_1 + e_2 \cdot M_2 = e_1(1 - M_1) + e_2 \cdot M_2$$
 [12]

which indicates that the measured heave is the divergence reduced by the magmatic
divergence occurring at the same time as the fault slip, but increased by the subsequent
magmatic divergence that lengthened the exposed slip surface and footwall through diking.
Substituting in [12] for *e* (equations [10] and [11]) gives an expression relating the measured

heave *h* of a fault to the measured truncation distance *c*, *z* (fault initiation depth), θ (the fault dip) and *M* (the proportion of magmatic divergence) of that fault and of the next fault:

325
$$h_1 = (c_1 + 2z_1/\tan\theta_1)(1-M_1)/(0.5-M_1) + (c_2 + 2z_2/\tan\theta_2).M_2/(0.5-M_2)$$
[13]

326 For the sake of simplicity, in Figures 6F and 6G we have assumed that M, h, e, z, c and θ are the same for successive faults, and have investigated the effect of varying M and heave 327 328 (Figure 6F) and of varying M, fault dip and the truncation distance c (Figure 6G) on the fault initiation depth. The results are consistent with thermal and rheological expectations (Behn 329 and Ito, 2008): for a given heave (Figure 6F) or fault dip (Figure 6G) as M increases, the 330 kinematically stable (i.e. above a fixed rift axis) depth of fault initiation decreases, but in a 331 332 manner also related to c, meaning that lateral variations in temperature and rheology and 333 hence the depth of fault initiation, can be accommodated in part by variation in the place 334 where the new fault cuts the old.

335 Moving along the axis of the SWIR from smooth seafloor towards the volcanic centres, the observed shallowing of the seismicity (Figure 6H), controlled by rheology and temperature, 336 (Figure 3) is kinematically compatible with an increase of M from close to zero beneath the 337 smooth seafloor to 0.25, or to 0.4 if the truncation point migrates closer to the hinge, as the 338 339 volcanic centres are approached. As these values remain below M=0.5, flip-flop kinematics remain viable, and together with the continuity in the seismicity raises the possibility that the 340 same basic tectonic system may continue laterally beneath more volcanic seafloor. To 341 342 consider this idea further, we return to the structure and morphology of seafloor created at 343 the SWIR.

344

345 4. Volcanic and smooth seafloor

The SWIR and Gakkel Ridge (in the Arctic) are not amagmatic: between broad expanses of
smooth seafloor, corresponding mainly to unroofed mantle and characterised at the SWIR by

348 outward-facing faults, are rougher regions where dredges mainly recover basalts and gabbros (Sauter et al., 2013) and where at the SWIR inward- rather than outward-facing fault 349 scarps dominate, suggesting a very different style of spreading. Indeed the volcanic seafloor 350 351 and the dominance of inward-facing faults is reminiscent of normal slow-spreading crust 352 (Sinton and Detrick, 1992), formed by magmatic processes and only moderately affected by 353 faulting as that magmatic crust is lifted up and out of the median valley. The 354 magmatic/amagmatic dichotomy appears long-lived as both the rough, magmatic seafloor 355 and the smoother, long-wavelength, ridge-parallel topography of the exhumed mantle can be 356 traced off axis for > 100 km (Cannat et al., 2006; Sauter et al., 2013).

357 The amagmatic and volcanic swathes are not obviously separated by transform faults or by non-transform discontinuities (Figure 3B), and several lines of evidence suggest that there is 358 considerable structural continuity between them. First, the seismicity observed beneath 359 peridotitic seafloor continues beneath volcanic seafloor, climbing steadily from >20 km to 360 <10 km as the volcanic centre is approached, but is only absent 10 km either side of the 361 362 volcanic centre (Schlindwein and Schmidt, 2016 – Figure 3A). The continuity of the 363 seismicity suggests that faulting remains important except actually at the volcanic centres: 364 the observed shallowing of the seismicity is compatible with an increase from amagmatic to moderate amounts of magmatic divergence (Figure 3A). Second, the magnetic anomalies 365 (Figure 3B) continue along strike from smooth to rough seafloor with no obvious distortion 366 367 reflecting a change in spreading mechanism. Third, sub-parallel to the magnetic anomalies, 368 ridges can be traced across the boundary between the rough and smooth seafloor, including some of the prominent ridges that mark the breakaways of successive detachments in the 369 smooth regions (Figure 3B). 370

The continuity of the magnetic anomalies, of some of the long wavelength seafloor topography and of the band of seismicity at depth all suggest that the tectonic process forming the smooth seafloor may extend laterally beneath the rougher volcanic seafloor. But such continuity is apparently in conflict with the switch from smooth exhumed mantle to rough volcanic seafloor, and from outward-facing to inward-facing faults. To resolve this
paradox, it is necessary to consider possible variants on the rolling hinge models and the
controls on the mode of detachment faulting that develops.

378

379 4.1 Rolling hinge models

380 There are two variants of the rolling hinge model for detachment faulting: that in which the footwall and slip surface are exhumed to the seafloor (Lavier et al., 1999), and that in which 381 382 both are covered with a series of fault blocks, sliced off the hanging wall by successive faults 383 and rafted up and out of the median valley with the footwall (Buck, 1988). Reston and 384 Ranero (2011 – Figure 7A) suggested that at slow-spreading ridges, the increase in volcanic fill and in fault strength moving from segment end to segment middle resulted in a switch 385 386 from "exhumation detachments" to "rafting detachments" as the point where the fault was 387 rotated sufficiently to lock up migrated from above to below the seafloor. From numerical modelling Choi and Buck (2013) concluded that weak faults (low cohesion and low friction 388 coefficient) would favour riderless exhumation detachments that form oceanic core 389 complexes, but increasing the fault strength or increasing the amount of fill (or volcanic cover 390 391 in a ridge setting) would favour the development of fault-bound riders above a rafting detachment, as observed at the Atlantis Massif (Reston and Ranero, 2011). The large rider 392 block we have identified through our kinematic analysis in the TAG area (Figure 1) may have 393 formed in this way. 394

If an exhumation detachment at an OCC such as the Atlantis Massif can transition laterally into a rafting detachment, the same along strike transition might be expected at ultraslow ridges. The breakaway ridges of the smooth seafloor detachments can be traced some distance into the volcanic domains, raising the question whether these flip-flop detachments also continue laterally, changing from exhumation to rafting detachments as the volcanism increases. 401 Using Choi and Buck's results as the template, as divergence progresses successive slices are carved off the volcanic-fill in the hanging wall and transferred to the footwall to be rafted 402 up and out of the median valley (Figure 7 A,B). At the same time, the active root zone 403 migrates beyond the axis (Figure 7B), until a new fault propagates up from depth, cutting 404 405 through the footwall close to the point of maximum curvature, the part of the footwall most 406 flexurally strained and thus likely weakest (Figure 7B.C) and crucially on the ridgeward side of the array of rafted blocks. A new rafting system with the opposite polarity then initiates, 407 408 and a new set of fault blocks are produced, all bounded by ridgeward dipping faults (Figure 409 7D). As the new fault cuts the preceding system near the preceding hinge, virtually all rafted 410 blocks are bounded by inward-dipping faults, producing a seafloor structure in marked 411 contrast to seafloor produced by the laterally equivalent exhumation detachments and 412 characterised by widely spaced ridges of smooth seafloor bounded by faults rooting 413 outwards.

The smooth seafloor of the SWIR is marked by patches of rafted volcanics (Sauter et al., 414 415 2013); we suggest that the same process also occurs on a largescale, so that the majority of 416 the volcanic seafloor is allochthonous, transported up and out of the ridge axis by successive rafting detachments. Similarly, patches of smooth seafloor within the volcanic regions 417 418 (Figure 3B) are unlikely to have formed by vastly different processes to their surrounds but 419 are instead simply windows to the underlying detachment. To illustrate the concept, we have interpreted the section through the rough volcanic seafloor at 64°E (Figure 3D; Figure 420 421 8) to illustrate the possibility that successive detachments may continue beyond the smooth 422 seafloor into the rougher, volcanic regions. Although we have used basement ridges and magnetic anomalies as a guide, it is unlikely that each detachment on the 64.5°E transect 423 424 can be traced 50 km to the south, and so in each case assign the interpreted detachments a different letter. Although the detachment roots dip outward, the majority of the faults are 425 inward-facing as predicted, but an outward-dipping fault near anomaly C3A corresponds to 426 an exposure of dominantly peridotites within the volcanic segment. The presence of 427

peridotites is further evidence that some form of detachment fault does occur even in the
volcanic segments, and is specifically consistent with the unroofing of mantle rocks in the
footwall of an outward-dipping detachment.

431 The reconstruction in Figure 8 is necessarily interpretative: we do not know the geometry 432 and spacing of the detachments here, the thickness of the volcanics, or the magmatic divergence. We simply assume the same basic structure as on the smooth transect, that the 433 434 volcanics are ~3km thick (Minshull et al., 2006) and a magmatic divergence of 4.5 km for 435 each detachment; this magmatism, although represented in the reconstruction as a simple block added to the crust, is likely to have been through numerous dikes feeding the 2-3 km 436 of lavas that form the fault blocks rafted with successive detachments (Figure 9). The 437 results are however instructive. Although not as kinematically stable as the amagmatic 438 reconstruction (Figure 5) as the rift axis is wider, that axis is still only ~5 km wide and could 439 be narrowed by varying the amount of magmatism, the fault dip or the truncation point. The 440 inward-facing faults between the volcanic blocks are completely compatible with outward-441 442 dipping detachment roots. Incorporating magmatism requires the detachments to either be 443 steeper still or, more probably, to root at shallower depths than for amagmatic spreading (Figure 5), a result compatible with the rise in the brittle-ductile transition expected to 444 accompany laterally increasing magmatism and temperature, but probably not at the same 445 rate. As small variations in the location of fault truncation and in the dip of the faults have a 446 447 large effect on the depth of kinematically stable fault initiation, we suggest that these may 448 vary along strike to reconcile the kinematics with the controlling rheology.

449

450 **5. Discussion and conclusions**

In this paper, we have explored the kinematics of detachment faulting at the Southwest
Indian Ridge and abandoned OCCs at the Mid-Atlantic Ridge, and tested the predictions
against observations. The model, summarised in Figure 9, is fundamentally based on the

initiation of successive faults at a fixed rift axis midway between the two diverging plates,
allowing simple kinematic analysis in terms of heave, the point where one faults cuts the
previous one, initial fault dip and the proportion of divergence taken up by magmatism. An
amagmatic kinematic model of successive detachment faulting successfully duplicates the
observations made over the smooth, mantle-dominated seafloor:

- Symmetric divergence about a fixed rift axis and the initiation of successive
 detachment faults, in a flip-flop alternation, explains the formation of the smooth
 seafloor observed along the 64.5°E transect.
- 462 2. Apart from two detachments affected by a single fault forming off axis, the heaves
 463 occur in a narrow range (24-17 km, with a mean of 20 km and a standard deviation
 464 of 3 km).
- 3. For a given dip, the depth of fault initiation is remarkably constant; for a given depth,
 the fault dip is remarkably constant; applying the best constrained detachment dip at
 depth of ~80°, indicates a depth consistent with the seismicity observed beneath the
 least magmatic portions of the SWIR. We thus consider the model robust and a
 valid representation of the processes occurring at the most magma-poor regions of
 the SWIR.

471 We are now in a position to consider the primary controls on the process of ultraslow 472 seafloor spreading. Point 2 confirms the basic premise of the model that increasing heave 473 and distance between the fault root and the rift axis is the primary control on the abandonment of each detachment. However, given the consistency of fault/seismicity depth 474 475 (and the relationship of the latter to temperature), the primary control on the formation of the new detachment would appear to be rheology. The consistently steep fault dip indicated by 476 the analyses also appears important, and presumably constrained by the mechanics of 477 fracture propagation towards the surface. Perhaps surprisingly, the analyses suggest that 478 479 the location of the truncation point is the least important control; although truncation generally occurs where the footwall has been fractured and weakened by bending, there is 480

481 considerable variation in the precise location of that truncation, accommodating variation in 482 the other parameters. The whole process is thus driven by processes at depth not near the 483 surface.

484 Incorporating magmatism predicts that the depth of fault initiation should shallow if all other 485 parameters stay the same; conversely if the fault initiation depth remains constant, increasing the amount of magmatic divergence towards M=0.5 will allow the detachment to 486 remain active longer. 487

Applied to abandoned OCCs at the MAR, the detachment geometries can be 488 combined with observed seismicity to deduce that the OCC at 5°S had an M value of 489 \sim 0.15. After re-interpretation of the structure of the TAG detachment system, we 490 491 suggest that the previously identified breakaway is a rider block, that the actual 492 breakaway is further to the SW, and that the detachment will soon be cut by one propagating up from the rift axis and dipping to the southeast. 493

the continuity of basement ridges, of magnetic anomalies, and observed axial 494 495 seismicity, coupled with the lack of obvious transform and other ridge normal 496 discontinuities, raises the possibility that the detachment systems also continue laterally beneath the volcanic cover of the rougher volcanic seafloor, evolving from 497 exhumation detachments to rafting detachments as increasing amounts of volcanics 498 499 are transported up and out of the median valley

For successive detachments accompanied by a component of magmatic divergence, 500 • the kinematic model predicts that increasing magmatism results in shallower fault 501 initiation. As thermal and rheological constraints also predict such a shallowing, 502 further evidenced by the shallowing of seismicity observed at the SWIR moving 503 504 along strike from smooth to volcanic seafloor, to within ~10 km of volcanic centres 505 (Figure 3A), the kinematic shallowing may be essential in allowing detachments to continue laterally. As temperature and rheology are likely to remain the primary 506

507 control on fault initiation depth, it is likely that the fault dip and especially the cut point will vary to accommodate the changing kinematics as magmatism increases. 508 moving from mantle-dominated smooth seafloor to rougher volcanic seafloor, a 509 lateral change from virtually amagmatic spreading by successive exhumation 510 511 detachments to partly magmatic spreading by successive rafting detachments and diking explains the apparent paradox of outward- vs inward-facing faults, the overall 512 513 symmetrical spreading of the SWIR, the along strike continuity of structures and magnetic anomalies, and the shallowing of the axial seismicity. 514

Within ~10 km of the volcanic centres, where 80° faults initiate at 5-10 km below the seafloor, magmatic divergence may be between 25 and 40% of the total divergence.
 While the volcanic centres influence the spreading of volcanic seafloor through dike injection and the emplacement of lava flows, subsequently dissected by faulting and rafted out of the median valley (Figure 9), detachment tectonics dominate ultra-slow seafloor spreading.

In conclusion, rigorous kinematic analysis has shown that successive detachments operating 521 in a flip-flop manner not only explain the unroofing of mantle to form smooth seafloor, but 522 523 intriguingly also explain the majority of the rougher volcanic seafloor, even where dominated by inward-facing fault blocks. Combined with evidence for their importance along 50% of the 524 525 length of slow-spreading ridge system (Escartin et al, 2008), we estimate that detachment faulting controls perhaps one third of spreading ridges. The kinematics require the 526 527 deepening of the detachment root moving towards cooler more amagmatic sections of the 528 ridge, consistent with the observed seismicity and inferred temperature structure. We thus conclude that successive detachment faults (Figure 9) are the fundamental mechanism in 529 ultraslow seafloor spreading, as well as at the magma-poor margins where they were initially 530 531 proposed. Ultraslow seafloor spreading may thus be more akin to the model advocated by Hess (1962) than to that of Dietz (1961). 532

533

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639 **Figure 1**: The formation of oceanic core complexes by the rolling hinge model. A: a steep fault develops rooting on the axis of the rift. As extension continues, the footwall flexes 640 under its own weight: at small offset the flexure is minor (B), but at large offsets, the fault 641 flexes to sub-horizontal (C). The deep crustal and mantle rocks in the footwall of this 642 643 exhumation detachment form a domal oceanic core complex. If extension is symmetric and 644 amagmatic, the active part of the fault migrates with the hangingwall across the rift axis, 645 whereas the breakaway (bky) migrates in the opposite direction at the same rate. The 646 original steep edge of the footwall (prior to flexure) and of the hangingwall (tangential to the 647 active fault), are symmetrically disposed about the original fault position, rooting on the rift 648 axis. The system terminates when either a new fault or a dike propagates up from the rift 649 axis across the footwall. If a fault, it will probably cut through the strained flexed portion of the footwall close to the hangingwall cutoff (bold broken line in C). At the MAR at TAG 650 651 (deMartin et al., 2007), we suggest that the rift axis corresponds to the extrapolation of the neovolcanic zone north and south of the core complex. The antithetic normal faulting 652 identified from a linear cluster of microseisms are probably associated with the bending of 653 the exhuming footwall, and may in future develop into a fault rooting on the rift axis at the 654 655 base of the seismicity. Once an OCC is split in this way, a new spreading axis develops, isolating a fragment of the OCC as observed at 5°S. 656

657 Figure 2: The concept of mantle exhumation on successive detachments (Reston and 658 McDermott, 2011). As a new fault develops (A) it cuts the previous detachment in two, an upper exhumed part including the old breakaway, and a lower root zone, dipping away from 659 the ridge axis. Continued slip exhumes a second expanse of mantle, with the new fault 660 migrating over the ridge axis as it moves with the hangingwall until eventually a third fault 661 662 develops (B, C), propagating up from the rift axis up through the flexed and fractured footwall. Multiple repetitions of the process produce a series of abandoned and cut 663 detachment systems (D – Reston and McDermott, 2011), each with a root zone dipping 664 away from the ridge on the opposite side of the axis from the breakaway. The seafloor 665

generally youngs symmetrically towards the spreading axis, but for the short root zone
segments locally youngs away from the axis. In contrast, if large expanses of seafloor were
unroofed along a single detachment (E) and subsequently dismembered (F), the younging
direction would be asymmetric.

Figure 3: Maps and sections of part of the Southwest Indian Ridge (SWIR) all at the same 670 671 scale. A: Geophysical section running to the north from the edge of the bathymetric map (B). 700°C isotherm marks the bases of a continuous band of seismicity (grey shading with black 672 673 outline) that shallows towards the volcanic centre (Schlindwein and Schmidt, 2016). We propose that this band is the root of detachment faults. Other shallow seismicity (no outline) 674 may be related to diking. Crustal structure (after Minshull et al., 2006) showing inferred 675 layers 2 & 3, the limited raypath control (dark shading) and Moho reflections (bright green). 676 B: high resolution bathymetry (Sauter et al., 2013; Cannat et al., 2006) over strips of rough 677 (volcanic) and smooth (exhumed mantle) seafloor, running ~N-S (left-right) for up to 100km 678 679 away from the current spreading axis (red dashes). White profiles highlight seafloor 680 topography along two transects, fault geometries are those at the seafloor (Sauter et al., 681 2013 and 2018). Magnetic anomalies are marked by coloured dotted lines, showing that 682 spreading is largely symmetric in both the volcanic and smooth domains. Broken white lines 683 mark elongated highs: many can be traced from the smooth seafloor into the rougher, 684 volcanic domains, suggesting that the detachment breakaways and by implication the 685 detachment themselves can be traced laterally from the smooth domain to beneath volcanic 686 fault blocks of the volcanic domain. C: Top: detail of seafloor observations and interpretation (modified after Sauter et al., 2013) along smooth seafloor transect at 64.5°E. Velocity model 687 of Momoh et al (2017) and 7.5 km/s contour (black) showing approximate Moho, the limit of 688 689 intense serpentinisation. D: detail of seafloor observation (Sauter et al., 2018) and possible interpretation across volcanic domain at 64°E. Interpretations discussed in sections 3 and 4. 690

Figure 4: Kinematic model for flip-flop non-volcanic detachment faulting. A: As extensionproceeds, the space beneath the uplifting footwall is filled by a combination of upwelling

693 mantle and magma produced by decompression melting. Substantial volumes of magma may be emplaced in the footwall even if divergence is entirely fault controlled (A, B) and 694 apparently amagmatic (M=0). The resulting kinematics can be summarised as in C: as 695 successive detachments simply cut the preceding one, the kinematics of each detachment 696 697 can be considered separately. Asymmetry is incorporated by shifting the rift axis towards the hanging wall (positive K) or footwall (negative K). D: Graphical approach to the same 698 kinematic analysis assuming 75° initial dip (= 90- θ , see section 3 for description): note that 699 700 the exhumed part of the ε and ϕ detachments are considerably smaller than the other 701 detachments, meaning that the cut point is close to the rift axis, apparently requiring a 702 shallow fault initiation for the next fault. E: Depth of fault initiation vs heave for detachments 703 forming at dips ranging from 60° to 83° for amagmatic divergence, and a truncation point 5 704 km (solid) or 3 km (dashed) from root projection. For the heaves observed on the non-705 volcanic transect, only faults much steeper than 70° predict seismicity at the depths observed for non-volcanic portions of the SWIR . F: plot of the heave vs fault initiation depth 706 707 (truncation point 3 km) for different degrees of asymmetric spreading, represented by K. 708 Bold lines (K=0) correspond to bold lines in E. Circles show initiation depth of detachment x 709 for different fault dips, block arrows the asymmetry necessary to shift the initiation depth of ε or φ to similar depths. **G**: Depth of fault initiation vs fault dip for amagmatic detachments 710 (coded by dying detachment) observed on the 64.5E transect: only faults initiating at >80 ° 711 predict the observed seismicity; the ε and ϕ detachments predict anomalously shallow 712 initiation depths for their successor. Stars are parameters of dying detachments obtained 713 graphically (D) for comparison. Block arrow shows the shift in initiation depth arising from 714 asymmetry K of -0.3. 715

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Figure 5: A: Evolution of the magma-poor transect, interpreting all faults as forming at the same angle and the same depth, showing how all but one faults initiate along the line of symmetry, the rift axis. A: current situation. B-G: reconstruction of successive phases of 720 detachment faulting during overall symmetric spreading (indicated by black block arrows). Only detachment ε (initiating in C and abandoned in D) initiated away from the rift axis, 721 cutting detachment φ off at a relatively small heave. The small heave of the ε detachment 722 itself prior to its abandonment results from the initiation point of the following detachment 723 724 jumping back to the rift axis. Thus both anomalous heaves (φ and ε) result from one fault (ε) 725 initiating off axis; the other five faults analysed all initiated within a km or so of the rift axis. 726 The reconstruction shows that spreading is symmetrical about an axis and that nearly all 727 detachments initiate as steep structures propagating up from this axis. Red: emplacement 728 of volcanics to produce magnetic anomalies.

729 Figure 6: Kinematic model and results incorporating magmatic divergence (M>0). If magma is emplaced as dikes into the HW, it must accommodate some of the divergence, even if 730 731 most of the divergence is taken up on the detachment (A,B). The rate of migration of the fault root across the axis is reduced, and would reach zero if half the divergence is taken up 732 by magmatism. C: kinematic model relating magmatic divergence, expressed as M, to 733 734 detachment location and initiation. D: Using the model in C and assuming 75° fault dip, the 735 observed detachment parameters (heave, cut point, depth of seismicity) can be used to estimate M (proportion of magmatic divergence) for the truncated OCC at 5°S (solid lines), 736 737 and to predict the future development of the TAG OCC (dashed lines). E: For successive 738 detachments, during the next phase of spreading, the purple detachment in C is lengthened 739 between breakaway and cut point by the component of magmatic divergence occurring in 740 the following phase. The process repeats with the earlier system being retrospectively 741 lengthened by magmatic divergence during the succeeding phase. F, G: The kinematic 742 model shown in E is used to test the key factors controlling the initiation and growth of 743 detachments during magma-limited spreading. F: Depth of fault initiation increases with heave but decrease as M increases (cut distance of 4, fault assumed to dip at 80°). G: 744 Depth of fault initiation vs M for fault dips ranging from 63° to 83°. Cut point 0 km 745 (continuous line, the new fault cuts the hinge of the previous fault) and 4 km (dashed) from 746

747 hinge or root projection, total divergence 25 km (fault heaves 12.5-25 km depending on M). As M increases, the predicted depth of fault initiation decreases, but more gradually for 748 smaller values of c. H: calibration of the depth of seismicity in terms of M value, assuming 749 truncation point at the hinge (right hand axis, perhaps more appropriate near the volcanic 750 751 centres) and 4 km inside the hinge (left-hand axis, based on observations from smooth 752 seafloor) and 25 km divergence during each fault phase. These results are used (Figure 3A) 753 to calibrate the SWIR seismicity depths (25 km heave and cut point of 4 km used) in terms of 754 M number: the seismicity beneath the smooth portions of the ridge implies M < 0.1; that 755 beneath the volcanic transects M may approach 0.4. Even beneath the volcanic seafloor, 756 faulting not magmatic divergence dominates except at the volcanic centres themselves.

757 Figure 7: Rolling hinge models revisited. If the flexing fault remains active until the slip surface is exhumed (an exhumation detachment), a large expanse of footwall (plutonic and 758 mantle rocks) will be exposed to form an oceanic core complex (A). However, if the fault 759 locks up in the subsurface, new fault may propagate up from the steep root zone, 760 761 transferring a slice of the hanging wall to the footwall (B). Continued slip does not expose an 762 oceanic core complex but rather a series of wedges sliced off the hangingwall and moving 763 with the footwall A, C). Such a rafting detachment system is favoured if the half-graben is 764 filled with volcanics and if the fault is not too weak (Choi and Buck, 2013), both likely to 765 occur towards the centre of a segment. Thus as seafloor magmatism increases away from 766 the segment end, there may be a switch from exhumation detachments (OCC formation) to 767 rafting detachments (small fault blocks) along strike (Reston and Ranero, 2011 - A). D, E: successive, flip-flop rafting detachments, generating a broad expanse of volcanic blocks 768 769 bounded by inward-dipping faults, but underlain by outward-dipping detachment roots. 770 Lenses (open where new) show schematic intrusion into the detachment footwall and subsequent upward transport in the footwall. 771

Figure 8: Illustrative possible reconstruction of the evolution of the 64°E volcanic transect
during symmetric divergence about a fixed rift axis. During each detachment phase, 4.5 km

774 of horizontal divergence are taken up by magma intruding around the footwall tip, bringing the length of the previous detachment system up to its present-day length. The magmatic 775 divergence means that the active fault is less distance from the rift axis (dashed line box) 776 777 and also changes the relative distance between the breakaway and HW cutoff of each 778 detachment. The consequence is that the point where each detachment is cut by the next is 779 close to the rift axis, meaning that each fault initiates at shallow depth (circles). A: 780 reconstruction at the end of movement on the to detachment. Note that the to detachment 781 has yet to be lengthened by intrusion. B: the end of movement on the π detachment: the ϖ 782 detachment system has now been extended to its full length by magmatic activity. C: end of 783 movement on the ζ detachment. D: end of movement on the σ detachment. E: end of 784 movement on the ξ detachment. F: end of movement on the μ detachment. G: the final section, during movement on the current λ detachment. 785

Figure 9: Tectonic model of ultraslow seafloor spreading, summarising the findings of the 786 paper. Background: mantle is exhumed to form smooth seafloor by slip on successive 787 788 detachments with alternating polarity: yellow/brown then purple then blue. Block arrows 789 show movement direction; outline arrows where detachments are no longer active. The detachments root at steep angles at ~20 km depth, but continue laterally beneath rafted 790 791 volcanic blocks (foreground); increasing magmatic contribution to divergence accompanies a 792 shallowing of the detachment towards the volcanic centres (e.g. towards the foreground at 793 the right edge). For clarity and to emphasise the geometry of the successive detachments, 794 the plutons beneath the detachment and the volcanic centres themselves are omitted for clarity, only the most recent diking is shown, and the mantle is shown transparent. 795

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