UNIVERSITY OF BIRMINGHAM
University of Birmingham Research at Birmingham

Flipping detachments

Reston, Timothy

DOI:
10.1016/j.epsl.2018.09.032

License:
Creative Commons: Attribution-NonCommercial-NoDerivs (CC BY-NC-ND)

Document Version
Peer reviewed version

Citation for published version (Harvard):
Reston, T 2018, 'Flipping detachments: the kinematics of ultraslow spreading ridges', *Earth and Planetary Science Letters*, vol. 503, pp. 144-157. https://doi.org/10.1016/j.epsl.2018.09.032

Link to publication on Research at Birmingham portal

Publisher Rights Statement:
Checked for eligibility: 10/10/2018

General rights
Unless a licence is specified above, all rights (including copyright and moral rights) in this document are retained by the authors and/or the copyright holders. The express permission of the copyright holder must be obtained for any use of this material other than for purposes permitted by law.

•Users may freely distribute the URL that is used to identify this publication.
•Users may download and/or print one copy of the publication from the University of Birmingham research portal for the purpose of private study or non-commercial research.
•User may use extracts from the document in line with the concept of ‘fair dealing’ under the Copyright, Designs and Patents Act 1988 (?)
•Users may not further distribute the material nor use it for the purposes of commercial gain.

Where a licence is displayed above, please note the terms and conditions of the licence govern your use of this document.

When citing, please reference the published version.

Take down policy
While the University of Birmingham exercises care and attention in making items available there are rare occasions when an item has been uploaded in error or has been deemed to be commercially or otherwise sensitive.

If you believe that this is the case for this document, please contact UBIRA@lists.bham.ac.uk providing details and we will remove access to the work immediately and investigate.

Download date: 19. Apr. 2024

Flipping detachments: the kinematics of ultraslow spreading ridges

Tim Reston

School of Geography, Earth and Environmental Sciences, University of Birmingham

Birmingham UK, B15 2TT

t.j.reston@bham.ac.uk

Abstract

Although the seafloor spreading Hess initially proposed was a virtually amagmatic process, little attention has been paid to that possibility since. We construct a kinematic framework for virtually amagmatic and magma-poor Hess-style seafloor spreading, and successfully 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 fault propagates up from the rift axis, develops into a detachment fault accommodating the plate divergence, migrates beyond the rift axis and is abandoned when a new fault propagates up through the footwall from the rift axis. We rigorously explore the controls on 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 through symmetric divergence about a fixed rift axis. The model predicts the development of 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 detachments root at 80˚ (consistent with constraints on seismicity-defined detachment orientation at oceanic core complexes), and exhume mantle. Based on the continuity of 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 detachments,* transporting fault-bounded volcanic slices up and away from the spreading axis to form the rougher volcanic seafloor found between mantle-dominated domains. The kinematic framework shows that increased magmatic divergence requires the detachments to root at shallower depths, consistent with the seismicity-defined shallowing of the base of the brittle lithosphere moving along the ridge axis towards the volcanic centres. Only in the immediate vicinity of volcanic centres, where the seismicity dies out, may magmatism dominate. We conclude that detachment tectonics dominate the process of ultraslow seafloor spreading as well as much of slow seafloor spreading, totalling about one third of the global ridge system, and present the first 3D tectonic model for ultraslow seafloor spreading.

Keywords: seafloor spreading, detachment faults, plate tectonics,

1. Introduction:

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 crust and the structure of ophiolites led to the adoption of a more magmatic model, like that proposed by Dietz (1961). However, the interpretation of oceanic core complexes (OCCs - Cann et al., 1996) as plutonic and mantle rocks exhumed in the footwall of large offset normal faults has re-emphasised the importance of faulting in seafloor spreading. These 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 axis (Morris et al., 2009), as in a rolling hinge model (Lavier et al., 1999 – Figure 1). MacLeod et al., (2009) proposed that individual oceanic detachment faults develop through 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 abandoned (Figure 1 D, F, G – Escartin et al., 2017).

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 intervening zones of exhumed mantle, is in keeping with the reduced magmatism expected as full spreading rates drop below 20 mm/yr (Bown and White, 1994), but Dick et al. did not investigate the kinematics of mantle exhumation. Building on the MacLeod model for individual OCCs, Reston and McDermott (2011) suggested that *successive* detachments, each migrating across the rift axis to be cut by a new detachment, could explain the unroofing of large expanses of mantle both at magma-poor margins (where it explained the 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 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 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 kinematic model for Hess-style seafloor spreading, exploring the controls on detachment abandonment and initiation, and the along strike transition from mantle-dominated to volcanic seafloor. We develop a 3D model for ultraslow seafloor spreading, in which detachment faulting controls both virtually amagmatic seafloor spreading (VASS), exhuming 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 profound implications not just for the spreading mechanism operating at ultraslow ridges but also for the development of oceanic core complexes found along most of the slow-spreading Mid-Atlantic Ridge, and thus in total perhaps one third of the active spreading ridge system.

2. The Southwest Indian Ridge

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 bands of dominantly volcanic seafloor (Sauter et al., 2013). Sparse wide-angle data suggest that the volcanics are up to a few km thick, and widely-spaced Moho reflections a couple of km deeper (Minshull et al., 2006 – Figure 3A), whereas the smooth seafloor exhibits pervasive but downward-decreasing serpentinisation to a depth of 6 km below seafloor (Momoh et al., 2017) where the Moho marks a transition to unserpentinised mantle. Most seismic activity occurs along a continuous band that can be traced from 20±5 km depth 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 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 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 seismicity. Schlindwein and Schmidt (2016) suggest that the considerable thickness of the brittle layer results from cooling by the circulation of the serpentinising water.

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 slip surfaces of major faults (Sauter et al., 2013). Inward-facing faults can be traced from the top of each elongate high down to the base of the inward-facing flanks where they are cut by 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 successive detachment faults of alternating polarity (Reston and McDermott, 2011 – Figure 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 root, and the seafloor observations of fault extent and orientation.

3. A kinematic model for amagmatic spreading

The concept of mantle exhumation and VASS through successive detachments (Reston and McDermott, 2011) is based on three assumptions: divergence is amagmatic (magmatism may thicken the lithosphere but does not accommodate significant horizontal displacements), divergence is symmetric about a deep rift axis, and successive faults 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 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 hanging wall, the fault root migrates with the hanging wall away from the rift axis at half the spreading rate until the next fault propagates up from the rift axis through the footwall (Figure 2). The footwall, including the breakaway, migrates at the same half-spreading rate in the opposite direction.

The kinematic model can be presented in two ways: a simple geometrical approach (Figure 4C), based on reducing the curvature of the flexing footwall to a sharp hinge and assuming that the system is kinematically stable, i.e. a fixed rift axis, and a graphical approach (Figure 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 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 original fault and hence the rift axis at the depth of fault initiation, assuming symmetric 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 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. Furthermore, the image is only to a depth of 5-6 km below the seafloor, and as rolling hinge detachments are flexed to be convex-up, the detachment is likely to steepen towards the depth of the brittle-ductile transition close to the 700°C isotherm (Schlindwein and Schmidt, 2016; Figure 3). We thus suspect that the image significantly underestimates the dip of the detachment at depth. The depth of fault initiation is constrained by the depth of seismicity observed (Schlindwein and Schmidt, 2016), and the fault dip θ is constrained by the 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 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), 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 depth for the next fault (Figure 4D): we discuss the possible explanations below.

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., 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 ultraslow spreading ridges. From the model in Figure 4C, and defining e as divergence (= 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 fault dip, and z as the depth of fault initiation, we have:

$$(e/2) - c = 2z/\tan\theta \qquad [1]$$

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:

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

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°.

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

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

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 (Parnell-Turner et al., 2017), but is considerably greater than that expected from simple Mohr-Coulomb criteria and may indicate that faults partly follow sub-vertical dikes (Olive et 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 structures at angles steeper than optimum. Sauter et al. (2013) note that the exhumed slip surfaces are cut and offset by minor high-angle faults and fissures that act as conduits for shallow magma intrusion and eruption of lavas that cover parts of the seafloor even in the smooth sections of the SWIR.

3.1 Incorporating asymmetry

The small heaves of the ε and φ detachments would appear (Figure 4D) to suggest that the succeeding fault would either have to initiate much shallower than the other detachments, or if also initiating at the depth of the seismicity, would need to have developed from near-vertical fissures or dikes (Olive et al., 2010). The anomalous heaves of the ε and φ 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 can be introduced by allowing the rift axis to move by a proportion K of the divergence. Positive values of K move the rift axis in the direction of the hangingwall, negative values in the direction of the footwall, giving us new expressions for the distance from the original edge of the footwall to the rift axis of

$$e.K + e/2 \qquad [3]$$

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

$$c = e - (0.5.e + e.K) - 2z/\tan\theta = e(0.5 - K) - 2z/\tan\theta \qquad [4]$$

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

The depth of initiation can be found from:

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

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

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

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 later in the cycle, i.e. at larger heaves (Figure 4F). In one scenario, where the rift axis is controlled by the location of the detachment root, the rift axis moves with that root, K = 0.5, 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 develop very large offsets, as observed for the OCC within the Ascension double transform system (Grevemeyer et al., 2013), and for the Godzilla OCC (Tani et al., 2015). Conversely, a negative K would result in the fault developing earlier in the cycle (i.e. at a smaller heave – Figure 4F)): a K of -0.3 would suffice to shift the initiation point of the ε to depths similar to the other four detachments.

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 the initiation of the next fault. A simpler way of looking at the same events is to suggest that the rift axis stayed fixed but that a single fault, the ε detachment, rooted off axis on the 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 well back in the footwall of the developing ε detachment, thus also truncating ε at relatively low heaves. To illustrate this interpretation we have reconstructed the evolution of the 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.

3.2 Incorporating magmatic divergence

In the kinematic model for VASS developed above, we have related four parameters: the depth of fault initiation (constrained by seismicity), the dip of fault initiation (partially constrained by observations elsewhere), the point where a detachment cuts the preceding 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 have formed, and crucially ignore any contribution of magmatism to plate divergence. This assumption would appear reasonable for smooth-seafloor parts of the SWIR where mantle dominates and the fraction of magmatic divergence M may be close to 0, but is probably less valid where the amount of volcanics increases.

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 above, and increased magmatism accompanied by a hotter, thinner lithosphere, and a 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 thicken the crust, and magmatism that actually extends rather than thickens part of one plate (Figure 6A, B), taking up a proportion M of the divergence (Buck et al., 2005; Behn and Ito, 2008). Magma is likely to be trapped deep in the ductile asthenosphere (Olive et al., 2010) 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 increases crustal thickness but does not actually extend the system. How much magma is trapped in this way is the subject for another debate, but may range from very little (e.g. 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 accommodates some divergence (partially magmatic seafloor spreading, PMSS) we need to modify the kinematic model.

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

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

Or from a process perspective:

$$((e/2) - c - e.M) = 2z/\tan\theta \qquad [8]$$

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.

The above analysis can be applied to oceanic core complexes such as 5°S (Reston et al., 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 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 to the NE and SW as the rift axis, the active magmatism deflects to the northwest around the OCC. The rift axis is closer to the breakaway identified by deMartin et al. than it is to the root zone (Figure 1E), requiring an impossible negative M value or markedly asymmetric spreading. Instead we propose that the deMartin breakaway is the edge of a rafted rider block rafted with the true breakaway at the next scarp to the east. The rift axis now lies 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 antithetic faulting (deMartin et al., 2007) may be compressional related to the bending of the exhuming footwall; if this band of seismicity were to mark an incipient fault cutting across the active detachment near the hanging wall cutoff, the dimensions would imply an M of about 0.05.

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 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 was cut (Figure 6E); in the rarer case where the active fault dips in the same direction as its predecessor, the magmatic divergence extends the structurally deeper portion of the preceding footwall between the root zone and the point where that fault was cut. By 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 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 preceding fault must be estimated and removed from the observed geometries before the kinematics of the original detachment can be analysed. The truncation distance *c* (Figure 6) is given for each numbered phase of faulting by:

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

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

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

and for the next phase of faulting:

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

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

$$h_1 = e_1 - e_1.M_1 + e_2.M_2 \quad = e_1(1-M_1) + e_2.M_2 \qquad [12]$$

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:

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

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 (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 and Ito, 2008): for a given heave (Figure 6F) or fault dip (Figure 6G) as M increases, the kinematically stable (i.e. above a fixed rift axis) depth of fault initiation decreases, but in a manner also related to *c*, meaning that lateral variations in temperature and rheology and hence the depth of fault initiation, can be accommodated in part by variation in the place where the new fault cuts the old.

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, (Figure 3) is kinematically compatible with an increase of M from close to zero beneath the smooth seafloor to 0.25, or to 0.4 if the truncation point migrates closer to the hinge, as the 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 same basic tectonic system may continue laterally beneath more volcanic seafloor. To consider this idea further, we return to the structure and morphology of seafloor created at the SWIR.

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 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 scarps dominate, suggesting a very different style of spreading. Indeed the volcanic seafloor and the dominance of inward-facing faults is reminiscent of normal slow-spreading crust (Sinton and Detrick, 1992), formed by magmatic processes and only moderately affected by faulting as that magmatic crust is lifted up and out of the median valley. The magmatic/amagmatic dichotomy appears long-lived as both the rough, magmatic seafloor and the smoother, long-wavelength, ridge-parallel topography of the exhumed mantle can be traced off axis for > 100 km (Cannat et al., 2006; Sauter et al., 2013).

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 considerable structural continuity between them. First, the seismicity observed beneath peridotitic seafloor continues beneath volcanic seafloor, climbing steadily from >20 km to <10 km as the volcanic centre is approached, but is only absent 10 km either side of the volcanic centre (Schlindwein and Schmidt, 2016 – Figure 3A). The continuity of the seismicity suggests that faulting remains important except actually at the volcanic centres; 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 (Figure 3B) continue along strike from smooth to rough seafloor with no obvious distortion reflecting a change in spreading mechanism. Third, sub-parallel to the magnetic anomalies, 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 smooth regions (Figure 3B).

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.

4.1 Rolling hinge models

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 both are covered with a series of fault blocks, sliced off the hanging wall by successive faults and rafted up and out of the median valley with the footwall (Buck, 1988). Reston and 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 from “exhumation detachments” to “rafting detachments” as the point where the fault was 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 coefficient) would favour riderless exhumation detachments that form oceanic core complexes, but increasing the fault strength or increasing the amount of fill (or volcanic cover 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 block we have identified through our kinematic analysis in the TAG area (Figure 1) may have formed in this way.

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.

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 up and out of the median valley (Figure 7 A,B). At the same time, the active root zone migrates beyond the axis (Figure 7B), until a new fault propagates up from depth, cutting through the footwall close to the point of maximum curvature, the part of the footwall most 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, and a new set of fault blocks are produced, all bounded by ridgeward dipping faults (Figure 7D). As the new fault cuts the preceding system near the preceding hinge, virtually all rafted blocks are bounded by inward-dipping faults, producing a seafloor structure in marked contrast to seafloor produced by the laterally equivalent exhumation detachments and characterised by widely spaced ridges of smooth seafloor bounded by faults rooting outwards.

The smooth seafloor of the SWIR is marked by patches of rafted volcanics (Sauter et al., 2013); we suggest that the same process also occurs on a largescale, so that the majority of 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 (Figure 3B) are unlikely to have formed by vastly different processes to their surrounds but 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 8) to illustrate the possibility that successive detachments may continue beyond the smooth 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 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 inward-facing as predicted, but an outward-dipping fault near anomaly C3A corresponds to an exposure of dominantly peridotites within the volcanic segment. The presence of 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.

The reconstruction in Figure 8 is necessarily interpretative: we do not know the geometry 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 volcanics are ~3km thick (Minshull et al., 2006) and a magmatic divergence of 4.5 km for 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 of lavas that form the fault blocks rafted with successive detachments (Figure 9). The results are however instructive. Although not as kinematically stable as the amagmatic reconstruction (Figure 5) as the rift axis is wider, that axis is still only ~5 km wide and could be narrowed by varying the amount of magmatism, the fault dip or the truncation point. The inward-facing faults between the volcanic blocks are completely compatible with outward-dipping detachment roots. Incorporating magmatism requires the detachments to either be 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 accompany laterally increasing magmatism and temperature, but probably not at the same rate. As small variations in the location of fault truncation and in the dip of the faults have a large effect on the depth of kinematically stable fault initiation, we suggest that these may vary along strike to reconcile the kinematics with the controlling rheology.

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:

1. 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.
2. Apart from two detachments affected by a single fault forming off axis, the heaves occur in a narrow range (24-17 km, with a mean of 20 km and a standard deviation 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.

We are now in a position to consider the primary controls on the process of ultraslow seafloor spreading. Point 2 confirms the basic premise of the model that increasing heave 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 (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 the analyses also appears important, and presumably constrained by the mechanics of fracture propagation towards the surface. Perhaps surprisingly, the analyses suggest that 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 considerable variation in the precise location of that truncation, accommodating variation in the other parameters. The whole process is thus driven by processes at depth not near the surface.

Incorporating magmatism predicts that the depth of fault initiation should shallow if all other 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 remain active longer.

- Applied to abandoned OCCs at the MAR, the detachment geometries can be combined with observed seismicity to deduce that the OCC at 5°S had an M value of ~0.15. After re-interpretation of the structure of the TAG detachment system, we suggest that the previously identified breakaway is a rider block, that the actual 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.
- the continuity of basement ridges, of magnetic anomalies, and observed axial seismicity, coupled with the lack of obvious transform and other ridge normal discontinuities, raises the possibility that the detachment systems also continue laterally beneath the volcanic cover of the rougher volcanic seafloor, evolving from *exhumation detachments* to *rafting detachments* as increasing amounts of volcanics are transported up and out of the median valley
- For successive detachments accompanied by a component of magmatic divergence, the kinematic model predicts that increasing magmatism results in shallower fault initiation. As thermal and rheological constraints also predict such a shallowing, further evidenced by the shallowing of seismicity observed at the SWIR moving along strike from smooth to volcanic seafloor, to within ~10 km of volcanic centres (Figure 3A), the kinematic shallowing may be essential in allowing detachments to continue laterally. As temperature and rheology are likely to remain the primary

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.

- moving from mantle-dominated smooth seafloor to rougher volcanic seafloor, a lateral change from virtually amagmatic spreading by successive exhumation detachments to partly magmatic spreading by successive rafting detachments and diking explains the apparent paradox of outward- vs inward-facing faults, the overall symmetrical spreading of the SWIR, the along strike continuity of structures and magnetic anomalies, and the shallowing of the axial seismicity.
- 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 in a flip-flop manner not only explain the unroofing of mantle to form smooth seafloor, but 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 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 deepening of the detachment root moving towards cooler more amagmatic sections of the ridge, consistent with the observed seismicity and inferred temperature structure. We thus conclude that successive detachment faults (Figure 9) are the fundamental mechanism in ultraslow seafloor spreading, as well as at the magma-poor margins where they were initially proposed. Ultraslow seafloor spreading may thus be more akin to the model advocated by Hess (1962) than to that of Dietz (1961).

Acknowledgements: This research has benefitted from funding by the Natural Environment Research Council of the UK (NERC). Comments by Steve Jones, Marco Maffione and Ian Fairchild and helpful reviews from Roger Buck and Luc Lavier helped improve the manuscript.

References

Behn MD, Ito, G, 2008. Magmatic and tectonic extension at mid-ocean ridges: 1. Controls on fault characteristics. Geochem. Geophys. Geosyst., 9, Q08O10, doi:10.1029/2008GC001965

Bown, J. W. & White, R. S. Variation with spreading rate of oceanic crustal thickness and geochemistry. Earth Planet. Sci. Lett. 121, 435–449 (1994).

Buck, W. R. (1988), Flexural rotation of normal faults, Tectonics, 7, 959-973.

Buck, W. R., L. L. Lavier, and A. N. B. Poliakov (2005), Modes of faulting at mid-ocean ridges, Nature, 434, 719–723, doi:10.1038/nature03358.

Cann, J. R., Blackman, D.K., Smith, D.K., McAllister, E., Janssen, B., Mello, S., Avgerinos, E., Pascoe, A.R., Escartin, J, 1997. Corrugated slip surfaces formed at North Atlantic ridge-transform intersections. Nature 385, 329–332.

Cannat, , Sauter, D, Mendel, V, Ruellan, E Okino, K Escartin,J, Combier V, Baala, M, 2006. Modes of seafloor generation at a melt-poor ultraslow-spreading ridge, Geology 2006;34;605-608

Choi. E, Buck WR, Lavier, LC, Petersen, KD, 2013. Using core complex geometry to constrain fault strength. Geophysical Research Letters, 40, 3863–3867, doi:10.1002/grl.50732, 2013.

deMartin, B., R. A. Sohn, J. P. Canales, S. E. Humphris (2007), Kinematics and geometry of active detachment faulting beneath the Trans-Atlantic Geotraverse (TAG) hydrothermal field on the Mid-Atlantic Ridge, Geology, 35, 711-714.

Dick, H.J.B., Lin, J., and Schouten, H., 2003, An ultraslow-spreading class of ocean ridge: Nature, v. 426, p. 405–412.

Dick, H. J. B., M. A. Tivey and B. E. Tucholke (2008), Plutonic foundation of a slow-spreading ridge segment: Oceanic core complex at Kane Mega mullion, 23°30′N, 45°20′W, Geochemistry Geophysics Geosystems, 9, Q05014, doi: 10.1029/2007GC001645.

Dietz, RS, 1961. Continent and ocean basin evolution by spreading of sea floor. Nature, 190, 854-

Emmanuel S and Berkowiz, B, 2006. Suppression and stimulation of seafloor hydrothermal convection by exothermic mineral hydration. Earth and Planetary Science Letters 243 (2006) 657–668

Escartin, J, Smith DK, Cann, J, Schouten, H, Langmuir, CH, Escrig, S, 2008. Central role of detachment faults in accretion of slow-spreading oceanic lithosphere, Nature, 455, doi:10.1038/nature07333

Escartin, J., et al. (2017), Tectonic structure, evolution, and the nature of oceanic core complexes and their detachment fault zones (138200N and 138300N, Mid Atlantic Ridge), Geochem.Geophys. Geosyst., 18, 1451t.t.ophys. Geosyst.onic structure

Grevemeyer, I, Reston TJ, Moeller, S, 2013. Micro-seismicity of oceanic core complexes: the Mid-Atlantic Ridge at 7°S to 8°15'S and at the Logatchev Massif, 14°40'N to 14°50'N. Geochemistry Geophysics Geosystems, 14, 3532-3554

Hess, HH., 1962. History of ocean basins, in Petrologic Studies: A Volume in Honor of A. F. Buddington, edited by A. E. J. Engle, H. L. James, and B. L. Leonard, pp. 599-620, Geological Society of America, New York.

Kelemen, P.B., Kikawa, E., Miller, D.J., Shipboard Scientific Party, 2007. Leg 209 summary: processes in a 20-km-thick conductive boundary layer beneath the Mid- Atlantic Ridge, 14°–16°N. Proc. Ocean Drilling Program, Scientific Results, 209, College Station, Texas, 1–33, doi:10.2973/odp.proc.sr.209.001.2007.

Lavier, L.L., W. R. Buck, and A. N. B. Poliakov (1999), Self-consistent rolling-hinge model for the evolution of large-offset low-angle normal faults, Geology, 27, 1127-1130.

MacLeod, C. J., R. C. Searle, B. J. Murton, J. F. Casey, C. Mallows, S. C. Unsworth, K. L. Achenbach, and M. Harris (2009). Life cycle of oceanic core complexes, Earth Planet. Sci. Lett.. 287, 333-344.

Minshull, TW, Muller, MR, White, RS, 2006. Crustal structure of the Southwest Indian Rdige at 66E: seismic constraints. Geophys. J. Int. (2006) 166, 135–147

Momoh, E., Cannat, M., Watremez, L., Leroy, S., & Singh, S. C. (2017). Quasi-3-D seismic reflection imaging and wide-angle velocity structure of nearly amagmatic oceanic lithosphere at the ultraslow-spreading Southwest Indian Ridge. Journal of Geophysical Research: Solid Earth, 122, 9511–9533. https://doi.org/10.1002/2017JB014754

Morris, A., J. S. Gee, N. Pressling, B. E. John, C. J. MacLeod, C. B. Grimes, and R. C. Searle (2009), Footwall rotation in an oceanic core complex quantified using reoriented Integrated Ocean Drilling Program core samples, Earth Planet. Sci. Lett., 287, 217–228.

Olive J.-A., Behn, M. D., Tucholke, B. E., (2010), The structure of oceanic core complexes controlled by the depth distribution of magma emplacement, Nature Geoscience, 3, 491-495.

Parnell-Turner, R., Sohn, R.A., Peirce, C., Reston, T.J., Macleod, C.J., Searle, R.C., Simão, N.M., 2017. Oceanic detachment faults generate compression in extension. Geology. http://dx.doi.org/10.1130/G39232.1.

Reston, TJ., 2009. The structure, evolution and symmetry of the magma-poor rifted margins of the North and Central Atlantic: a Synthesis. Tectonophysics, 468, 6-27

Reston TJ, Pérez Gussinyé M, 2007. Lithospheric extension from rifting to continental breakup at magma-poor margins: rheology, serpentinisation and symmetry. Int J Earth Sci, DOI 10.1007/s00531-006-0161-z

Reston, T. J., W. Weinrebe, I. Grevemeyer, E. R. Flueh, N. C. Mitchell, L. Kirstein, C. Kopp, H. Kopp, and participants of Meteor 47-2 (2002), A Rifted Inside Corner Massif on the Mid-Atlantic Ridge at 5°S., Earth Planet. Sci. Lett., 200, 255-269.

Reston, T. J. & Ranero, C. R. The 3-D geometry of detachment faulting at mid-ocean ridges. Geochem. Geophys. Geosyst. 12, Q0AG05 (2011).

Reston, T.J. & McDermott, K.G., 2011. Successive detachment faults and mantle unroofing at magma-poor rifted margins, Geology, 39, 1071–1074.

Sauter, D. et al., 2013. Continuous exhumation of mantle-derived rocks at the Southwest Indian Ridge for 11 million years, Nat. Geosci., 6, 314–320.

Sauter D, Tugend J, Gillard M, Nirrengarten M, Autin J, Manatschal M, Cannat C, Leroy s, Schaming M, 2018. Oceanic basement roughness alongside magma-poor rifted margins: insight into initial seafloor spreading. Geophys. J. Int. (2018) 212, 900–915

Schlindwein, V. & Schmid, F., 2016. Mid-ocean-ridge seismicity reveals extreme types of ocean lithosphere, Nature, 535 276–279.

Sinton JM and Detrick RS, 1992. Mid-ocean ridge magma chambers. J. Geophys Res., 97, 197-216

Tani, K., Dunkley, DJ, Ohara, Y., 2015. Termination of backarc spreading: Zircon dating of a giant oceanic core complex. Geology, 39, 47-50, doi: 10.1130/G31322.1

Tilmann F, Flueh E, Planert L, Reston TJ, Weinrebe W, 2004. Microearthquake seismicity of the Mid-Atlantic Ridge at 5°S: a view of tectonic extension. J. Geophys Res., 109, B06102, doi:10.1029/2003JB002827

Tucholke B. E., M. D. Behn, W. R. Buck, J. Lin (2008), Role of melt supply in oceanic detachment faulting and formation of megamullions, Geology, 36, p. 455–458.

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 under its own weight: at small offset the flexure is minor (B), but at large offsets, the fault flexes to sub-horizontal (C). The deep crustal and mantle rocks in the footwall of this exhumation detachment form a domal oceanic core complex. If extension is symmetric and amagmatic, the active part of the fault migrates with the hangingwall across the rift axis, whereas the breakaway (bky) migrates in the opposite direction at the same rate. The original steep edge of the footwall (prior to flexure) and of the hangingwall (tangential to the active fault), are symmetrically disposed about the original fault position, rooting on the rift axis. The system terminates when either a new fault or a dike propagates up from the rift 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 (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 identified from a linear cluster of microseisms are probably associated with the bending of the exhuming footwall, and may in future develop into a fault rooting on the rift axis at the 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.

Figure 2: The concept of mantle exhumation on successive detachments (Reston and 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 the ridge axis. Continued slip exhumes a second expanse of mantle, with the new fault migrating over the ridge axis as it moves with the hangingwall until eventually a third fault 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 detachment systems (D – Reston and McDermott, 2011), each with a root zone dipping away from the ridge on the opposite side of the axis from the breakaway. The seafloor

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 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 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) may be related to diking. Crustal structure (after Minshull et al., 2006) showing inferred layers 2 & 3, the limited raypath control (dark shading) and Moho reflections (bright green). B: high resolution bathymetry (Sauter et al., 2013; Cannat et al., 2006) over strips of rough (volcanic) and smooth (exhumed mantle) seafloor, running ~N-S (left-right) for up to 100km away from the current spreading axis (red dashes). White profiles highlight seafloor topography along two transects, fault geometries are those at the seafloor (Sauter et al., 2013 and 2018). Magnetic anomalies are marked by coloured dotted lines, showing that spreading is largely symmetric in both the volcanic and smooth domains. Broken white lines mark elongated highs: many can be traced from the smooth seafloor into the rougher, volcanic domains, suggesting that the detachment breakaways and by implication the detachment themselves can be traced laterally from the smooth domain to beneath volcanic 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 of Momoh et al (2017) and 7.5 km/s contour (black) showing approximate Moho, the limit of 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.

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

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 apparently amagmatic (M=0). The resulting kinematics can be summarised as in **C**: as successive detachments simply cut the preceding one, the kinematics of each detachment 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 kinematic analysis assuming 75° initial dip (= 90-θ, see section 3 for description): note that the exhumed part of the ε and φ detachments are considerably smaller than the other detachments, meaning that the cut point is close to the rift axis, apparently requiring a shallow fault initiation for the next fault. **E**: Depth of fault initiation vs heave for detachments forming at dips ranging from 60° to 83° for amagmatic divergence, and a truncation point 5 km (solid) or 3 km (dashed) from root projection. For the heaves observed on the non-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 (truncation point 3 km) for different degrees of asymmetric spreading, represented by K. Bold lines (K=0) correspond to bold lines in E. Circles show initiation depth of detachment χ 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 (coded by dying detachment) observed on the 64.5E transect: only faults initiating at >80 ° predict the observed seismicity; the ε and φ detachments predict anomalously shallow initiation depths for their successor. Stars are parameters of dying detachments obtained graphically (D) for comparison. Block arrow shows the shift in initiation depth arising from asymmetry K of -0.3.

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

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, cutting detachment φ off at a relatively small heave. The small heave of the ε detachment itself prior to its abandonment results from the initiation point of the following detachment jumping back to the rift axis. Thus both anomalous heaves (φ and ε) result from one fault (ε) initiating off axis; the other five faults analysed all initiated within a km or so of the rift axis. The reconstruction shows that spreading is symmetrical about an axis and that nearly all detachments initiate as steep structures propagating up from this axis. Red: emplacement of volcanics to produce magnetic anomalies.

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 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 by magmatism. **C**: kinematic model relating magmatic divergence, expressed as M, to detachment location and initiation. **D**: Using the model in C and assuming 75° fault dip, the 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), and to predict the future development of the TAG OCC (dashed lines). **E**: For successive detachments, during the next phase of spreading, the purple detachment in C is lengthened between breakaway and cut point by the component of magmatic divergence occurring in the following phase. The process repeats with the earlier system being retrospectively lengthened by magmatic divergence during the succeeding phase. **F, G:** The kinematic model shown in E is used to test the key factors controlling the initiation and growth of 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:** Depth of fault initiation vs M for fault dips ranging from 63° to 83°. Cut point 0 km (continuous line, the new fault cuts the hinge of the previous fault) and 4 km (dashed) from

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 smaller values of c. **H:** calibration of the depth of seismicity in terms of M value, assuming truncation point at the hinge (right hand axis, perhaps more appropriate near the volcanic centres) and 4 km inside the hinge (left-hand axis, based on observations from smooth seafloor) and 25 km divergence during each fault phase. These results are used (Figure 3A) to calibrate the SWIR seismicity depths (25 km heave and cut point of 4 km used) in terms of M number: the seismicity beneath the smooth portions of the ridge implies M <0.1; that beneath the volcanic transects M may approach 0.4. Even beneath the volcanic seafloor, faulting not magmatic divergence dominates except at the volcanic centres themselves.

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 mantle rocks) will be exposed to form an oceanic core complex (A). However, if the fault locks up in the subsurface, new fault may propagate up from the steep root zone, transferring a slice of the hangingwall to the footwall (B). Continued slip does not expose an oceanic core complex but rather a series of wedges sliced off the hangingwall and moving with the footwall A, C). Such a rafting detachment system is favoured if the half-graben is filled with volcanics and if the fault is not too weak (Choi and Buck, 2013), both likely to occur towards the centre of a segment. Thus as seafloor magmatism increases away from the segment end, there may be a switch from exhumation detachments (OCC formation) to 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 bounded by inward-dipping faults, but underlain by outward-dipping detachment roots. Lenses (open where new) show schematic intrusion into the detachment footwall and subsequent upward transport in the footwall.

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

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 divergence means that the active fault is less distance from the rift axis (dashed line box) and also changes the relative distance between the breakaway and HW cutoff of each detachment. The consequence is that the point where each detachment is cut by the next is close to the rift axis, meaning that each fault initiates at shallow depth (circles). A: reconstruction at the end of movement on the ϖ detachment. Note that the ϖ detachment has yet to be lengthened by intrusion. B: the end of movement on the π detachment: the ϖ detachment system has now been extended to its full length by magmatic activity. C: end of movement on the ζ detachment. D: end of movement on the σ detachment. E: end of movement on the ξ detachment. F: end of movement on the μ detachment. G: the final section, during movement on the current λ detachment.

Figure 9: Tectonic model of ultraslow seafloor spreading, summarising the findings of the paper. Background: mantle is exhumed to form smooth seafloor by slip on successive detachments with alternating polarity: yellow/brown then purple then blue. Block arrows 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 volcanic blocks (foreground); increasing magmatic contribution to divergence accompanies a shallowing of the detachment towards the volcanic centres (e.g. towards the foreground at the right edge). For clarity and to emphasise the geometry of the successive detachments, 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.