Controls on the seafloor exposure of detachment fault surfaces

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Abstract :

While oceanic detachment faults have been proposed to account for the accretion of ~40% of new seafloor in the North Atlantic ocean, clear exposures of large-offset, often-corrugated fault surfaces remain scarce and spatially limited. To help resolve this paradox, we examine the conditions under which detachment fault growth may or may not lead to extensive exposure of corrugated fault planes at the seafloor. Using high-resolution bathymetry from four detachment faults at the northern Mid-Atlantic Ridge, we investigate the rafting of hanging wall-derived debris over emerging fault scarps, which can lead to covering shallow-dipping corrugated fault surfaces. We model this process using critical taper theory, and infer low effective friction coefficients (~0.2) on the shallowest portion of detachment faults. A corollary to this result is that detachments emerging from the seafloor at angles <13° are more likely to become blanketed under an apron of hanging wall material. We generalize these findings as a simple model for the progressive exposure and flexural rotation of detachment footwalls, which accounts for the continued action of seafloor-shaping processes. Our model suggests that many moderate-offset, hidden detachment faults may exist along slow mid-ocean ridges, and do not feature an exposed fault surface.

Highlights

► A small fraction of corrugated detachment fault surfaces is eventually exposed at the seafloor. ► Seafloor slopes indicate effective friction of ~0.2 on shallow part of detachments. ► Moderate-offset detachment faults may be largely blanketed by hanging wall material. ► Seafloor-shaping processes profoundly alter the morphology of oceanic core complexes.

Keywords : mid-ocean ridge, detachment faulting, oceanic core complex, critical taper, fault friction

1. Introduction

Bathymetric highs composed of mafic and ultramafic units are a characteristic feature of slowly accreted seafloor. These massifs are often capped by corrugated slip surfaces that represent the rotated footwalls of detachment faults with offsets on par with or greater than the thickness of young oceanic lithosphere (Cann et al., 1997; Tucholke et al., 1998; Parnell-Turner et al., 2018). These faults are generally found on ridge sections characterized by greater-than-average seismicity rates, lava geochemistry indicative of deeper fractionation, and hydrothermal activity (deMartin et al., 2007; McCaig et al., 2007; Escartín et al., 2008b; Blackman et al., 2011; Wilson et al., 2013; Olive and Escartín, 2016). Such observations led Escartín et al. (2008b) to postulate that detachment faulting enables a distinct mode of asymmetric seafloor spreading, favored wherever the magma supply of a mid-ocean ridge is subdued (Buck et al., 2005; Tucholke et al., 2008; Olive et al., 2010).

Significant portions of seafloor in the North Atlantic ocean are presently forming through asymmetric spreading (Escartín et al., 2008b; Cann et al., 2015). However, seafloor exposures of corrugated fault surfaces, a telltale sign of detachment fault growth (Cann et al., 1997), are often

60 spatially confined (≤ 10 km along-axis; Fig. 1) and only make up a small fraction of the > 40 km-
61 long asymmetric sections of slow-spreading ridges. One explanation may be that detachment faults
62 underlie entire ridge segments but are only exposed in areas where hanging wall rider blocks
63 cannot develop (Smith et al., 2008; Reston and Ranero, 2011). Another is that detachment faults
64 have a limited along-axis extent and connect with shorter-offset faults through complex relay
65 structures (Smith et al., 2008; Tian and Choi, 2017). This debate warrants an improved
66 understanding of how various seafloor-shaping processes modulate the exposure of pristine slip
67 surfaces during detachment fault growth. These processes include gravitational mass wasting,
68 which can both erode and cover portions of the footwall (Cannat et al., 2013), as well as rafting of
69 hanging wall material onto the footwall. Here we investigate the mechanical and geometrical
70 factors that lead to covering an emerging detachment surface under a hanging wall apron, making
71 large-offset fault surfaces difficult to detect in shipboard bathymetric data. We then assess the
72 relative impact of hanging wall rafting and mass wasting on the shape of oceanic detachment faults.
73

74 **2. Seafloor morphology near oceanic detachment faults**
75 Fig. 1 shows high-resolution (<2 m) bathymetry acquired using autonomous underwater vehicles
76 at four detachment faults along the Northern Mid-Atlantic Ridge: 13º20'N (Escartín and Petersen,
77 2017; Escartín et al., 2017), 16º36'N and South Core Complex (SCC; Smith et al., 2014), and the
78 Trans-Atlantic Geotraverse (TAG) detachment (Petersen et al., 2016). Geological interpretations
79 of bathymetric features and textures, combined with in-situ observations at 13º20'N, suggest a
80 common sequence of morphological domains at these detachments. The footwall cut-off scarp
81 (i.e., the breakaway high marking the initial location of fault emergence) is often texturally rough
82 (e.g., Fig. 1C), which is interpreted as the result of extensive gravitational mass wasting (Escartín
83 et al., 2017). Towards the ridge axis, this chaotic terrain gradually transitions into the corrugated
84 fault surface (Fig. 1A–D). This transition marks the place where angular blocks and talus stripped
85 from the breakaway ridge no longer blanket freshly exposed corrugated fault surfaces. This
86 difference is likely because the initially steep surface of growing detachments eventually rotates
87 to gravitationally stable angles (<30º, Lavier et al., 1999), which are no longer prone to mass
88 wasting (Cannat et al., 2013; Smith et al., 2014; Escartín et al., 2017).
89 The spatial extent of exposed corrugated surfaces varies greatly from one detachment to
90 another. At the 13º20'N and SCC detachments, for example, the corrugated terrain exceeds 10 km^2

91   and abruptly connects with a rougher region termed "apron", axis-ward of the bathymetric moat

92   that marks the fault termination or hanging wall cut-off (break in slope in Fig. 2). At 13º20'N the

93   apron consists of basaltic and diabase blocks in an unlithified matrix, and incorporates some

94   footwall-derived peridotite and gabbro (Escartín et al., 2017). The apron surface has a texture that

95   is distinct from the adjacent volcanic terrain covering the ridge axis, and in many instances is thin

96   enough for the underlying corrugations to be visible beneath (Fig. 1A–D; Fig. 3A). At TAG, the

97   apron spans an area wider than the corrugated surface (Fig. 1A), and is directly adjacent to the

98   chaotic terrain south of 26°09'N. This geometry suggests that the apron has the potential to blanket

99   large extents of the detachment surface when certain geometrical and rheological conditions are

100 met.

101

102   **3. Detachment aprons as extensional Coulomb wedges**

103 To understand how hanging wall material may be dragged onto the emerging fault surface, we

104 model the apron as a cohesionless, critical Coulomb wedge of seafloor slope α with friction angle

105 ϕ_0 (30º, appropriate for mafic lithologies) overlying a detachment fault of dip β and friction angle

106 ϕ_D (Fig. 3A, Davis et al., 1983; Dahlen, 1984; Xiao et al., 1991; Yuan et al., 2015). We specifically

107 use the critical wedge model of Yuan et al. (2015), which accounts for the possibility of fluid

108 overpressure in the detachment. The fundamental assumption of wedge models is that the state of

109 stress in the apron results from a balance between topographic and frictional forces and is on the

110 verge of failure everywhere in critical wedges. The assumption of a cohesionless material is

111 consistent with observations of the 13º20'N detachment suggesting that the apron consists of a

112 mixture of unconsolidated rubble and finer-grained materials (Escartín et al., 2017).

113   We describe the state of stress within the wedge using two quantities ψ_D and ψ_0, which

114 denote the angles between the most compressive principal stress (σ_1) and the detachment and apron

115 surface, respectively. These are useful to determine potential slip lines within the apron, which are

116 expected to lie at ($\pm 45°$- $\phi_0/2$) from σ_1 (Fig. 3A). By definition, the critical taper angle for the apron

117 verifies:

118 $$\alpha + \beta = \psi_D - \psi_0 \ . \tag{1}$$

119 If the entire apron is on the verge of Mohr-Coulomb failure, then only certain values of α, ψ_D and

120 ψ_0 are admissible for a given β. These values verify the following set of implicit equations:

121 $$\frac{\sin\alpha'}{\sin\phi_0} - \sin(2\psi_0 + \alpha') = 0 \ , \tag{2}$$

122 and

123 $$\sin(2\psi_D + \phi_D) - \frac{1-\lambda_D}{1-\lambda_0}\frac{\sin\phi_D}{\sin\phi_0} - \frac{\lambda_D - \lambda_0}{1-\lambda_0}\sin\phi_D \cos 2\psi_0 = 0 \ . \tag{3}$$

124 In equation (2), α' is defined as an angle verifying

125 $$\tan\alpha' = \frac{1 - \rho_f/\rho}{1-\lambda_0}\tan\alpha \ , \tag{4}$$

126 where λ_0 and λ_D denote the fluid pressure ratio in the apron and detachment, respectively. The fluid

127 pressure ratio is defined following Yuan et al. (2015) as

128 $$\lambda = -\frac{pf - \rho_f gD}{\sigma_z + \rho_f gD} \ , \tag{5}$$

129 with

130 $$\sigma_z = -\rho gz\, cos\alpha - \rho_f gD \ . \tag{6}$$

131 In equations (5) and (6), p_f is fluid pressure at a point located at a seafloor-normal distance z

132 beneath the apron surface (notation "D2" in Yuan et al., 2015). D is the water depth, and ρ and ρ_f

133 refer to the density of the apron material (2400 kg m^{-3}) and of the fluid percolating within the apron

134 (1000 kg m^{-3}). We assume that seawater easily percolates into the heavily damaged apron (Escartin

135 et al., 2017), and exerts a hydrostatic fluid pressure throughout the wedge, i.e., fluid pressure

136 increases downward in the wedge following a hydrostatic gradient. It can be shown that equation

137 (5) reduces to $\lambda = \rho_f/\rho$ under hydrostatic conditions (see Appendix A. of Yuan et al. 2015). The

138 fluid pressure ratio is thus set equal to 0.42 within the apron for the remainder of our study.

139 Equations (1-3) are formulated in terms of a residual function $F(\alpha, \psi_D, \psi_0) = 0$, and solved

140 with a Newton method for a range of β-values. The associated Jacobian ∇F is estimated using

141 centered finite difference with a step of 10^{-6} rad. Convergence is considered achieved when the

142 norm of the residual falls below 10^{-11}. Our initial guess is $\alpha = \phi_0/2$, $\psi_0 = 20°$, and ψ_D set to either

143 20º or 120º, which are empirically found to promote convergence towards the upper or lower

144 branch of the envelope, respectively. For a given pair of fault friction and fault fluid pressure

145 values –which can be expressed as an effective fault friction μ_{eff} (Fig. 3A)– the slope of the apron

146 and the dip of the detachment must satisfy a set of equilibrium relations, plotted as stability

147 envelopes in Fig. 3B. A MATLAB© script *GetWedgeEnvelope.m* is provided as part of the

148 Supplementary Materials to generate stability envelopes (combinations of α and β) as a function

149   of ϕ_0, ϕ_D, λ_0, and λ_D. This function calls the subroutines *wedge_residual.m* (Residual function) and

150   *wedge_jacobianFD.m* (Jacobian approximation), which are also provided.

151   Estimates for apron slope and detachment fault dip were obtained along 89 profiles oriented

152   parallel to the spreading direction, crossing the hanging-wall cutoff (or moat; see Fig. 2 and

153   3A). High-resolution bathymetry was extracted along profiles spaced 100 m apart at the four study

154   locations (Fig. 1). The position of the hanging-wall cutoff and spatial extent of the moat was

155   identified in map-view, based upon the locus of change in bathymetric slope, and then used to

156   define the hanging wall, footwall, and moat sections along each profile (Fig. 2). The mean apron

157   slope was estimated for each profile using the slope of a linear least-squares fit to the bathymetry

158   calculated over a 500 m distance downslope from the hanging wall-side edge of the moat, hence

159   the moat itself is not included in the fit. The mean detachment fault dip was estimated using the

160   slope of a linear fit to the bathymetry calculated 800 m upslope from the footwall-side edge of the

161   moat. Uniform fitting lengths were chosen for consistency and to minimize the effects of local

162   changes in slope, while not allowing profiles to extend onto the chaotic or neovolcanic terrains.

163   The average apron slope across our detachments is 6.2±3.3º (1 standard deviation), and the average

164   detachment dip right beneath the hanging wall cutoff is 13.8±2.5º.

165

166   **4. Low effective friction on the shallow part of oceanic detachment faults**

167

168   We follow a grid search approach to identify the value of μ_{eff} that best explains the observed pair

169   of (α, $\beta > -\alpha$) along 89 corrugation-parallel bathymetric transects at the four detachments shown

170   in Figs. 1 and 2. For each pair (α, β), we construct 100 envelopes spanning values of $0.42 \leq \lambda_D \leq$

171   0.82 and $0 \leq \phi_D \leq 30º$. Each point on these envelopes corresponds to a specific stress orientation,

172   which determines the orientation of possible slip lines (secondary faults) within the apron (Fig.

173   3A). We restrict our analysis to the upper branch of the envelopes, which predicts net extension in

174   the wedge. We retain the envelopes whose upper branch lies at the shortest distance to each (α, β)

175   pair, within an error of 2º (Fig. 3B). This set of best-fitting envelopes correspond to a narrow subset

176   of (λ_D, ϕ_D) space, and consequently to a narrow range of μ_{eff} values. We repeat this operation for

177   an entire grid of (α, β) values, to which we are able to assign a best fitting μ_{eff} with a typical error

178   of ±0.01, plotted in Fig. 4 and as colored dots for each profile in Fig. 1. For convenience, we also

179   provide a polynomial approximation for μ_{eff} as a function of (α, β), in degrees, which is accurate

180   within the above error margin:

181
$$\begin{aligned}
\mu_{eff} = {} & 0.008252 + 0.004973\beta - 0.003603\alpha \\
& + 0.00012\beta^2 + 1.026\times10^{-5}\alpha\beta + 7.116\times10^{-5}\alpha^2 \\
& - 1.853\times10^{-6}\beta^3 + 3.793\times10^{-7}\beta^2\alpha - 3.959\times10^{-6}\beta\alpha^2 \\
& - 2.385\times10^{-6}\alpha^3
\end{aligned}$$
(7)

182   The inversion procedure described above yields a range of μ_{eff} between 0.06 and 0.16, with

183   a mode at 0.14 (Fig. 4). Since the geometry of the detachment surface is concave-down, measuring

184   fault dip at the termination may underestimate the true dip of the detachment beneath the apron

185   region (Fig. 3A). Estimates of the sub-seafloor fault geometry (available only for TAG and

186   13º20'N: deMartin et al., 2007; Parnell-Turner et al., 2017) suggest that detachments may steepen

187   by at most ~10º across the apron (see section 5). Underestimating the average detachment dip

188   beneath the apron by ~5º would lead to underestimating the effective friction by ~0.04. Fig. 4

189   provides a straightforward way to assess the effect of an underestimated detachment dip (e.g., by

190   translating the points towards the right by ~5º).

191   Profiles located away from the center of detachments tend to yield lower μ_{eff} (Fig. 1), which

192   may be due to the termination strike being highly oblique to the spreading direction at these

193   locations owing to the three-dimensional fault morphology. By contrast, profiles oriented normal

194   to the termination (i.e., most compatible with the two dimensional nature of the critical wedge

195   model and often located in the central part of the detachment) commonly yield μ_{eff} values ranging

196   between 0.10 and 0.16, which we consider to be more reliable. Some short-wavelength apparent

197   variability in μ_{eff} directly reflects second-order tectonic features that offset the fault termination

198   and alter slopes (e.g., at SCC, N and S of 16.425ºN, Fig. 1B). Our 2-D analysis is therefore unlikely

199   to resolve frictional heterogeneities on a given detachment, if present.

200   Low values of effective friction are consistent with the common inference that the low

201   strength of detachment faults enables their longevity (Escartín et al., 1997). Our strength estimates

202   are however only representative of the uppermost ~1 km portion of detachments, which may be

203   different from the rest of the fault. A possible manifestation of this difference could be the lack of

204   shallow ($\leq$ 3 km) microseismicity beneath TAG (deMartin et al., 2007) and 13º20'N (Parnell-

205   Turner et al., 2017), as recorded by local ocean bottom seismometers (OBS) arrays. While low

206   effective friction on compressional décollements is typically attributed to elevated fluid pressure

207   (e.g., Dahlen, 1984), such a scenario may be harder to envision in a tensional regime where cracks

208   and pores are likely well connected. If fluid pressure is hydrostatic within the detachment fault

209   zone, as was inferred by Hansen et al. 2013 for the Kane detachment down to depths of ~5 km,

210   then the true friction coefficient of the fault material must lie between ~0.17 and ~0.26 (Fig. 3A).

211   The precipitation of very weak minerals such as talc, with friction coefficients ranging between

212   ~0.05 and 0.23 (Moore and Lockner, 2008; Escartín et al., 2008a) in the fault zone has been

213   invoked as a key contributor to long-term strain localization (Escartín et al., 1997). By contrast,

214   invoking moderately weak clay minerals (with friction coefficients of ~0.4, e.g., Tesei et al., 2012)

215   to explain our estimates of effective friction would however require super-hydrostatic fluid

216   pressure ratios between 0.6 and 0.75. The 13º20'N detachment, however, does not feature extensive

217   weak phases (e.g., serpentinite, talc) and instead shows pervasive silicification (Bonnemains et al.,

218   2017). The low effective friction of detachments may instead have a non-lithological origin.

219   Episodes of seismic slip have been documented in the shallow, microseismically quiet portion of

220   the 13º20'N detachment (Craig and Parnell-Turner, 2017). It is possible that infrequent

221   earthquakes catastrophically reshape apron slopes to balance the low shear stresses that prevail

222   during seismic rupture. The temporally-averaged apron slopes we measure may thus be influenced

223   both by the long-term and the short-term fault strength, although this hypothesis is difficult to

224   evaluate with the available data.

225   The above reasoning relies on the assumption that the apron wedge is critically stable, i.e.,

226   sits on the stability envelope as shown in Fig. 3B. At the 13º20'N detachment, small escarpments

227   are visible in apron topography, potentially indicating secondary faulting (Fig. 3A). Internal wedge

228   deformation alone would be indicative of the unstable wedge regime (outside of the stability

229   envelope, Xiao et al., 1991). When coincident with slip on the detachment, secondary faulting

230   implies a critically-stable apron at 13º20'N. However, slip on other detachments may occur without

231   faulting in the apron. Such systems would plot inside the stability envelope. Since increasing

232   detachment friction shifts the stability boundary towards greater detachment dips (Hayman et al.

233   2003), one can identify the greatest value of detachment friction that allows a wedge of a given (α,

234   β) to remain inside the stability envelope. This value corresponds to the critically-stable

235   configuration. In other words, the effective friction determined with our approach must be thought

236   of as an upper-bound on detachment strength.

237

238

239

240   **5. Implications for the seafloor exposure of detachment fault surfaces**

241   Regardless of the mechanistic interpretation for μ_{eff}, Coulomb wedge theory does predict

242   an effective value for detachment friction that explains apron architecture (including the pattern of

243   secondary faulting: Fig. 3A). A corollary to this model is that a detached piece of apron would not

244   remain affixed to the footwall if the fault emerges from the seafloor with a slope greater than $\tan^{-1}(\mu_{eff}) \sim 6$–$9°$, because the low basal shear stresses would not be able to counteract gravity. Pieces

246   of apron would thus slide back towards the hanging wall instead of blanketing the footwall.

247   Conversely, a detachment fault emerging from the seafloor with a slope <9° should be extensively

248   covered by hanging wall material.

249   The primary challenge in testing this idea is to infer detachment fault dip where it is not

250   exposed. Such estimates are possible at TAG and 13°20'N, which constitute low and high end-

251   members for the extent of the corrugated fault surface, respectively, and have both been

252   instrumented with OBS arrays to illuminate the deeper portions of the fault zone through

253   microseismicity (deMartin et al., 2007; Parnell-Turner et al., 2017). The clouds of extensional

254   microseismicity observed at the roots of TAG and 13°20'N show dips as large as 70° at depths of

255   ~7 km below seafloor. This clearly indicates an overall concave-down geometry of the detachment

256   at depth. High-resolution seismic imaging studies will be needed to improve our knowledge of the

257   near-surface geometry of these detachments. In the meantime, seafloor slopes reveal that a large

258   portion of the apron domain at TAG is underlain by a detachment dipping with angles ≤10° (Fig.

259   2A), which is not the case at 13°20'N, where the fault emerges with slopes of ~15° (Fig. 2D). This

260   simple comparison supports the idea that a gently dipping detachment is prone to extensive

261   blanketing by apron material, and less likely to feature extensive, well exposed corrugated

262   surfaces.

263

264   **6. From covered to exposed detachment surfaces**

265   Seafloor shaping processes are strongly sensitive to slope. Gravitational mass wasting is favored

266   along slopes with an angle of repose steeper than ~20–30° (Cannat et al., 2013). By contrast,

267   blanketing of exposed fault surfaces by hanging wall material is favored for shallow slopes <10°.

268   The emerging slope of a detachment fault is known to change as the footwall undergoes flexural

269   re-adjustment with continued slip (Buck, 1988; Lavier et al., 1999; Morris et al., 2009). Fig. 5

270   illustrates this process using an elastic model for footwall topography with increasing fault offset

271   (Buck, 1988; Schouten et al., 2010; Olive and Behn, 2014). In the early stages of detachment

272   growth, a breakaway ridge forms by slip along a high angle (>30º) fault, which triggers the

273   extensive mass wasting that shapes the chaotic terrain (Fig. 5A). The morphology of young

274   detachments may thus be strongly determined by the competition between the rate of footwall

275   degradation by repeated rockslides, and the fault slip rate. Hence, efficient mass wasting could

276   very well bury short-offset corrugated surfaces under footwall-derived debris.

277   As fault offset increases, flexural rotation decreases the emerging detachment slope until

278   it becomes sub-horizontal (Fig. 5B). This stage favors extensive blanketing of the corrugated fault

279   surface by hanging wall material, as seen today at TAG, a detachment fault with only ~5 km of

280   offset (deMartin et al., 2007). Further extension on the detachment drives footwall doming (Fig.

281   5C), which increases the slope of the emerging footwall (>10º) and shrinks the apron domain,

282   revealing an extensive corrugated surface (e.g., 13º20'N, with 9 km of offset). It should be noted

283   that the emergence angle will to some extent also reflect the amount of volcanic material extruded

284   onto the hanging wall (magmatic accretion in Fig. 5A).

285   Our model suggests that moderate-offset detachment faults may be widespread along slow-

286   spreading ridges but remain undetected by shipboard bathymetric surveys, as they are largely

287   blanketed by hanging wall material and do not (yet) expose large corrugated surfaces at the

288   seafloor. Extensive high-resolution bathymetric surveys and a better mechanistic description of

289   seafloor-shaping processes thus constitute crucial next steps to improve our understanding of slow-

290   spreading ridge tectonics.

291

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Figure captions

438

439 **Figure 1.** A–D: Seafloor terrain and slopes at four Mid-Atlantic Ridge detachment faults (locations

440 shown in inset E), from AUV bathymetric data gridded at 2 m resolution and plotted at equal scale.

441 Colored dots mark detachment termination, color-coded by effective friction (see section 4). Red

442 arrows indicate spreading direction, pointing away from the ridge axis. Dashed lines show

443 northernmost and southernmost spreading-parallel profiles bracketing topographic profiles used

444 here, which are evenly spaced at 100 m. RR = rubble ridges, i.e., small fragments of broken-down

445 apron carried by the fault surface.

446

447 **Figure 2.** High-resolution bathymetric profiles oriented parallel to the transport direction (inferred

448 from corrugations), spaced 100 m apart between dashed lines in Fig. 1. Thin red/blue/black

449 sections are hanging wall / footwall / moat sections of each profile, respectively; thick gray lines

450 are linear fits used to obtain estimates for apron slope and detachment fault dip. A: TAG; B:

451 16°36'N OCC; C: South Core Complex; D: 13°20'N OCC.

452

453 **Figure 3.** A: Schematic cross section of the termination of the 13º20'N detachment fault, based on

454 topographic profile XX' from Fig. 1D. Inset shows a zoom on the hanging wall apron, with inferred

455 slip line orientations. Setup of corresponding critical taper model shown below. B: Stability

456 envelopes calculated using extensional taper model. These envelopes all account for slope of

457 13º20'N apron measured along crest profile, and all correspond to an effective friction coefficient

458 of μ_{eff} = 0.15±0.01 on detachment fault.

459

460 **Figure 4.** Contours of best-fitting effective friction on a detachment fault of dip β underlying an

461 apron of slope α, assuming a critical taper model with hydrostatic fluid pressure and an internal

462 friction angle of 30º. Symbols indicate measured slopes along the profiles bracketed in Fig. 1. hc:

463 hanging wall cutoff (termination).

464

465 **Figure 5.** Progressive rollover and exhumation of a detachment fault. Blue curve is rolling hinge

466 model of Buck (1988) for an elastic plate of flexural wavelength L (~1 km at the MAR, Schouten

467 et al., 2010). A: At moderate offsets (e.g., fault heave = 2L), footwall slopes are steep, which leads

468   to mass wasting of the breakaway (fc: footwall cutoff) region, eventually forming the chaotic

469   terrain. B: At intermediate offsets (e.g., fault heave = $3L$) flexural rotation of the footwall leads to

470   very shallow seafloor slopes, promoting a widespread apron zone burying most of the detachment

471   surface. C: Finally, at large offsets (e.g., fault heave = $4L$) late-stage doming occurs close to the

472   fault termination (hc: hanging wall cutoff) where seafloor slopes increase, reducing the extent of

473   the apron and exposing the corrugated detachment surface (wiggly lines).

Figure 1

Figure 2

Figure 3
Click here to download Figure: Figure_3_apron_model.pdf

A

corrugated surface

X

hc

hc

apron

X'

footwall

axis

1 km

1 km

moat

hc

500 m

100 m

X'

α

hc $)+$

σ_1

ψ_0

$\mu_{eff} = (1-\lambda_D)\tan(\Phi_D)$

β

B

extension

critical envelopes with $\lambda_0 = 0.42$,
$\Phi_0 = 30°$, and variable (λ_D, Φ_D)
such that $0.14 \leq \mu_{eff} \leq 0.16$

13°20'N

shortening

apron slope, α (°)

detachment dip, β (°)

Figure 4

Figure 5

Figure 5