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1 Can we relate the surface expression of dike-induced normal  
2 faults to subsurface dike geometry?

3

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5

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10 Many igneous dikes do not reach the surface, instead triggering normal faulting and graben  
11 formation in overlying rock. The surface expression of these dike-induced faults provides  
12 important records of active and ancient diking. For example, surface measurements of graben  
13 half-widths have been used to estimate dike upper tip depths by projecting faults straight  
14 down-dip, whereas extension measured at-surface across dike-induced fault pairs (i.e. their  
15 cumulative heave) is considered a proxy for dike thickness. We use 3D seismic reflection  
16 data to test how the surface expression of two buried, dike-induced faults relates to dike  
17 geometry. The dike-induced faults are non-planar, suggesting fault dips should not be  
18 assumed constant when using graben half-widths to estimate dike depth. Multiple  
19 displacement maxima occur across the dike-induced faults, but rarely at their lower or upper  
20 tips, suggesting they formed through linkage of isolated faults that nucleated *between* the dike  
21 and free surface. Fault heave is greatest where these subsurface displacement maxima occur,  
22 meaning the cumulative heave of the dike-induced fault pair measured at the syn-faulting free  
23 surface underestimates their total extension and poorly reflects dike thickness. Our results  
24 imply that at-surface analyses of dike-induced fault geometry cannot be used to estimate key

25 dike parameters without *a priori* knowledge of fault structure and kinematics, or host rock  
26 lithological variations.

27

## 28 INTRODUCTION

29 Dike intrusion can induce normal faulting of overlying rock (e.g., Pollard et al., 1983; Rubin  
30 and Pollard, 1988; Rubin, 1992; Xu et al., 2016). Dike-induced normal faults form pairs that  
31 dip towards underlying dikes and bound dike-parallel graben (Fig. 1) (e.g., Mastin and  
32 Pollard, 1988; Trippanera et al., 2015a; Trippanera et al., 2015b). Faulting occurs because  
33 dike dilation concentrates tensile stress in two lobes above the dike upper tip and in two  
34 zones at the free surface, within which related shear stresses instigate failure (Fig. 1) (e.g.,  
35 Pollard et al., 1983; Rubin and Pollard, 1988; Rubin, 1992; Gudmundsson, 2003; Koehn et  
36 al., 2019). Because diking drives stress changes promoting faulting, dike emplacement and  
37 shape impact fault growth and geometry (e.g., Trippanera et al., 2015a; Dumont et al., 2017).  
38 Our understanding of these dike and dike-induced fault relationships has been driven by  
39 physical, numerical, and analytical modelling (e.g., Pollard et al., 1983; Mastin and Pollard,  
40 1988; Trippanera et al., 2015b; Hardy, 2016; Bazargan and Gudmundsson, 2019; Koehn et  
41 al., 2019). These models help us invert the surface expression of dike-induced faults to: (i)  
42 track intruding dikes (e.g., Pallister et al., 2010); (ii) estimate dike volumes (e.g., Wilson and  
43 Head, 2002); and (iii) examine how diking controls the morphology of Earth and other  
44 planetary bodies (e.g., Wilson and Head, 2002; Carbotte et al., 2006; Ruch et al., 2016).  
45 However, few outcrops expose the geometry of *both* dikes and overlying dike-induced faults  
46 (e.g., Gudmundsson, 2003; Von Hagke et al., 2019). Without access to the 3D structure of  
47 natural dike and dike-induced fault systems, we cannot test models that underpin how we  
48 invert surface deformation to estimate dike geometry (e.g., thickness and depth).

49 We use seismic reflection images of the Exmouth Dyke Swarm, offshore NW  
50 Australia (Magee and Jackson, 2020), to quantify the 3D structure of a natural dike and dike-  
51 induced fault system. We test: (i) whether graben half-width can be used to predict dike upper  
52 tip depths (e.g., Wilson and Head, 2002; Trippanera et al., 2015b; Hjartardóttir et al., 2016);  
53 and (ii) if extension across dike-induced fault pairs measured at the syn-faulting free surface  
54 can be considered a proxy for dike thickness (e.g., Rubin and Pollard, 1988; Rubin, 1992;  
55 Trippanera et al., 2015b). Our data also informs the debate regarding whether dike-induced  
56 faults nucleate: (i) as near-surface vertical fractures (Fig. 1A) (e.g., Trippanera et al., 2015a;  
57 Trippanera et al., 2015b; Al Shehri and Gudmundsson, 2018; Von Hagke et al., 2019); (ii) at  
58 dike tips (Fig. 1B) (e.g., Rubin, 1992; Xu et al., 2016; Koehn et al., 2019); (iii) a combination  
59 of (i) and (ii) (Fig. 1C) (Tentler, 2005; Rowland et al., 2007); or (iv) *between* the dike tip and  
60 surface (Fig. 1D) (Mastin and Pollard, 1988; Koehn et al., 2019). These fault growth models  
61 can be used to predict diagnostic displacement-depth profiles, if we assume displacement is  
62 greatest where faults nucleated (Fig. 1) (e.g., Pollard and Segall, 1987; Trippanera et al.,  
63 2015b). Measuring displacement patterns across dike-induced faults may thus reveal their  
64 kinematics, which could relate to dike thickness changes and emplacement mechanics. By  
65 unravelling how diking translates into faulting, we provide insights into the inversion of dike  
66 geometry from surface-based analyses of dike-induced faults.

67

## 68 **EXMOUTH DYKE SWARM AND STUDY AREA**

69 Dikes manifest in the seismic reflection data as ~NNE-trending, sub-vertical, low-amplitude  
70 zones that disrupt stratigraphic reflections (e.g., Figs 2A and B). These dike-related zones are  
71 >100 m wide (Fig. 2A), but borehole data suggests dike thicknesses may only be 10's of  
72 metres (Magee and Jackson, 2020); i.e. the width of a dikes seismic expression may not  
73 capture its true thickness. The radial geometry of the swarm suggests dikes propagated

74 laterally northwards (Fig. 2A) (Magee and Jackson, 2020). Above and parallel to the dikes  
75 are graben bound by normal faults that converge on the upper tips of underlying dikes (Figs  
76 2B and C). The faults displace a ~1 km of Triassic-to-Jurassic strata (Fig. 2B), which locally  
77 comprises interbedded claystones, siltstones, and sandstones (Ellis, 2011). At their upper tips,  
78 dike-induced faults offset the ~148 Myr Base Cretaceous unconformity (horizon HK; Fig.  
79 2B), which marks the syn-faulting free surface and indicates diking occurred during minor  
80 Tithonian rifting (Magee and Jackson, 2020).

81 We examine an ~18 km long section of a graben bound by faults EF1 and EF2, and  
82 underlain by Dike E, imaged in the time-migrated Chandon 3D seismic reflection survey  
83 (Fig. 2). Both EF1 and EF2 are continuous along-strike and rarely intersect pre-existing  
84 tectonic normal faults (Fig. 2C). Using velocity data from four boreholes and dominant  
85 frequency measurements, extracted from the seismic data, we (Supplementary Files 3-5): (i)  
86 convert the data from depth in time to metres; and (ii) estimate the limits of separability  
87 (~20±4 m) and visibility (~3±1 m), which define the data's spatial resolution. We map 11  
88 seismic horizons (HA–HK; Fig. 2B) and identify their hanging wall and footwall fault cut-  
89 offs along 121 transects spaced 125 m apart and oriented orthogonal to EF1 and EF2  
90 (Supplementary Files 6 and 7). For each cut-off pair we measure fault throw and heave,  
91 which we use to calculate fault dip and displacement (Supplementary Files 6-8). Along 60 of  
92 the transects, spaced 250 m apart, we also measure graben half-width at horizon HF, dike  
93 upper tip depth beneath horizon HF, and the width of Dike E's seismic expression at ~4 km  
94 depth (Supplementary Files 6-8).

95

## 96 **GRABEN HALF-WIDTH AND DIKE DEPTH**

97 Graben half-widths ( $HW$ ) measured at the surface are often used to predict dike upper tip  
98 depths ( $D'$ ) by assuming fault dip ( $\alpha$ ) remains constant with depth (i.e.  $D' = HW \tan \alpha$ ) (e.g.,

99 Pollard et al., 1983; Trippanera et al., 2015b; Hjartardóttir et al., 2016). We show  $HW$  along  
100 horizon HF is  $366\pm 18$ – $728\pm 36$  m (Fig. 3A). Using  $HW$  and by projecting both faults straight  
101 down-dip at an angle of  $HF\alpha$  (i.e. the average dip on horizon HF for EF1 and EF2), we  
102 predict  $D'$  is  $343\pm 51$ – $803\pm 121$  m (Fig. 3B). We also measure the depth of Dike E's upper tip  
103 beneath horizon HF ( $D$ ), showing it is  $493\pm 80$ – $896\pm 134$  m (Fig. B).  $HW$  and  $D$  are broadly  
104 positively correlated, with our data showing that  $D$  typically exceeds ( $D':D < 1$ ) but is locally  
105 equal ( $D':D = 0.9$ – $1.1$ ) or less ( $D':D > 1.1$ ) than  $D'$  (Figs 3B and C).

106         The discrepancies between  $D$  and  $D'$  (Figs 3B and C) may relate to the: (i) true  
107 location of Dike E's upper tip being shallower than resolved, such that our measurements  
108 overestimate  $D$ ; and/or (ii) down dip variations in  $\alpha$  (Fig. 3D). Where  $D':D$  is  $< 0.9$ ,  $\alpha$  for EF1  
109 and EF2 broadly decreases below horizon HF and the faults display concave-up (listric)  
110 geometries (Figs 3C and E). Conversely, where  $\alpha$  remains constant with depth or increases  
111 below horizon HF (i.e. faults are convex-up),  $D':D$  is  $> 0.9$  (Figs 3C and E). The variation in  
112  $\alpha$  across EF1 and EF2 may reflect modification of dike-induced stresses by stresses related to  
113 pre-existing tectonic faults (e.g., Fig. 3A), and/or heterogeneity in the mechanical properties  
114 of the layered, sedimentary host rock (e.g., Schöpfer et al., 2006; Bazargan and  
115 Gudmundsson, 2019). Our results imply graben half-width cannot be used to accurately  
116 predict dike upper tip depths without information on subsurface fault structure and host rock  
117 lithological variation (cf. Wilson and Head, 2002; Trippanera et al., 2015b; Hjartardóttir et  
118 al., 2016).

119

## 120 **DIKE-INDUCED FAULT DISPLACEMENTS AND KINEMATICS**

121 Dike-induced fault displacement is intrinsically linked to dike dilation, implying the at-  
122 surface 'cumulative heave' (extension) of dike-induced fault pairs can be related to dike  
123 thickness (e.g., Rubin and Pollard, 1988; Rubin, 1992; Trippanera et al., 2015b). However,

124 fault heave is also dependent on variations in fault dip and displacement. We measure the  
125 cumulative heave of EF1 and EF2 at the syn-faulting free surface (i.e. horizon HK; Magee  
126 and Jackson, 2020), and determine their ‘total extension’; i.e. the sum of maximum heave  
127 values for both faults measured at *any* structural level on each transect (Supplementary File  
128 7). By comparing these measurements to fault dip, displacement distribution, and the width of  
129 Dike E’s expression, we test whether at-surface cumulative heave measurements reflect dike  
130 thickness.

131         We show fault dip and displacement vary across EF1 and EF2, with both faults  
132 displaying zones of elevated displacement (e.g., EF2 segments 1–3) (Figs 3B and 4A).  
133 Displacement maxima measured on each transect ( $\sim 78 \pm 12$  m on EF1;  $\sim 101 \pm 15$  m on EF2)  
134 occur at various structural levels (Fig. 4A); i.e. displacement-depth profiles are more complex  
135 than hypothetical models predict (cf. Figs 1 and 4B). Overall, displacement broadly decreases  
136 northwards (Fig. 4A). The total extension accommodated by the dike-induced faults mimics  
137 the displacement distribution and broadly decreases northwards (Fig. 4C). This northwards  
138 decrease in displacement and total extension coincides with a reduction in the width of Dike  
139 E’s seismic expression (Figs 4A and B). In contrast, the distribution of cumulative heave  
140 across horizon HK does not correlate with variations in the total extension or Dike E width,  
141 showing no clear northwards decrease (Fig. 4B). There is also no correlation between fault  
142 dip, cumulative heave, or total extension (Fig. 4C; Supplementary File 9).

143         Assuming the northwards reduction in the width of Dike E’s seismic expression  
144 relates to changes in its true thickness (Magee and Jackson, 2020), the coincident northwards  
145 decrease in total extension (and displacement) may be considered a proxy for dike thickness  
146 (Fig. 4B). Local variations in total extension and displacement superimposed onto this  
147 northwards decrease, which do not relate to changes in fault dip, could reflect processes  
148 controlling dike thickness *during* or *after* emplacement (e.g., thermal wall rock erosion; Fig.

149 4D) (e.g., Delaney and Pollard, 1981; Gudmundsson, 1983; Kavanagh and Sparks, 2011;  
150 Gudmundsson et al., 2012; Rivalta et al., 2015; Vachon and Hieronymus, 2017). An  
151 alternative interpretation is that the zones of elevated displacement and total extension  
152 correspond to fault nucleation sites (e.g., Pollard and Segall, 1987; Trippanera et al., 2015b;  
153 Deng et al., 2017), with the distribution of these zones across EF1 and EF2 suggesting (Figs  
154 4A-C and E): (i) isolated fault segments nucleated and eventually linked (e.g., Willemse et  
155 al., 1996), perhaps due to cyclical phases of dike propagation and stalling (e.g., Woods et al.,  
156 2019); and (ii) segment nucleation primarily occurred between the dike upper tip and  
157 contemporaneous surface (e.g., Mastin and Pollard, 1988; Koehn et al., 2019), with few  
158 nucleating at the dike upper tip (cf. Rubin, 1992; Xu et al., 2016; Koehn et al., 2019) or the  
159 syn-faulting free surface (cf. Trippanera et al., 2015a; Trippanera et al., 2015b; Al Shehri and  
160 Gudmundsson, 2018). Similar to controls on fault dip variation, fault displacement  
161 distribution may have been influenced by the mechanically layered stratigraphy and/or  
162 stresses related to pre-existing tectonic faults (e.g., Schöpfer et al., 2006).

163 Our results show cumulative heave measured at the syn-faulting free surface (i.e.  
164 horizon HK) does not equal or mimic the total extension across EF1 and EF2, nor does it  
165 reflect the broad northwards decrease in the width of Dike E's expression (Fig. 4B), implying  
166 it is not a proxy for dike thickness (cf. Rubin and Pollard, 1988; Rubin, 1992; Trippanera et  
167 al., 2015b). The lack of correlation between fault dip and cumulative heave suggests, instead,  
168 that the latter is likely controlled by the vertical distribution of displacement during fault  
169 linkage and/or dike thickening-related fault slip (Figs 4D and 4E).

170

## 171 **CONCLUSIONS**

172 We use 3D seismic reflection data to image graben-bounding, dike-induced faults that extend  
173 downwards from the syn-faulting free surface to converge on the upper tip of a dike. Our

174 results demonstrate predicted dike upper tip depths, calculated from graben half-width and  
175 assuming faults are planar, consistently underestimates measured dike upper tip depths. This  
176 disparity between predicted and measured dike upper tip depths occurs because fault dip  
177 varies down-dip, which possibly reflects heterogeneity in the mechanical properties of the  
178 sedimentary host rock and/or stresses around pre-existing tectonic faults. We also show  
179 displacement varies across the dike-induced faults, defining zones of elevated displacement.  
180 If these zones of elevated displacement correspond to fault nucleation sites, their distribution  
181 implies most fault segments nucleated *between* the dike upper tip and free surface. Because  
182 the displacement maxima rarely occur at the fault upper tips, our measurements of fault heave  
183 along the syn-faulting surface do not approximate dike thickness. Accurately constraining  
184 dike parameters (e.g., thickness and depth) from the surface expression of dike-induced faults  
185 requires knowledge of fault geometry and kinematics in 3D. Reflection seismology is a  
186 powerful tool for studying how faults grow above dikes, and we anticipate future seismic-  
187 based studies will improve our understanding of how diking translates into surface  
188 deformation.

189

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194 for constructive comments.

195

## 196 **FIGURE CAPTIONS**

197 **Figure 1:** Half-space schematics showing dike-induced fault growth models (based on  
198 Mastin and Pollard, 1988; Rubin and Pollard, 1988; Tentler, 2005; Trippanera et al., 2015b;

199 Koehn et al., 2019). We predict displacement-depth profiles for each model assuming  
200 displacement is greatest where faults nucleate (e.g., Pollard and Segall, 1987; Deng et al.,  
201 2017). Horizontal stress patterns above an intruding dike, showing concentrated tensile stress  
202 at the surface (i) and above the dike tip (ii), are included (Rubin and Pollard, 1988).

203

204 **Figure 2:** (A) Root-mean squared (RMS) amplitude extraction across a 0.2 km high window  
205 centred at 4 km depth showing dike A–I traces. Four boreholes shown are: 1=Chandon-1;  
206 2=Chandon-2; 3=Chandon-3; 4=Yellowglen-1. Inset: Location map of the Chandon 3D  
207 survey and Exmouth Dyke Swarm. (B) Interpreted depth-converted seismic section; see (C)  
208 for location, Supplementary File 1 for uninterpreted version, and Supplementary File 2 for a  
209 data video. (C) Horizon HF structure map showing dike-induced faults, underlying dike  
210 traces, and tectonic faults.

211

212 **Figure 3:** (A) RMS amplitude map and graph showing variations in graben half-width ( $HW$ )  
213 along-strike at horizon HF. Dip variations of both faults at HF ( $HF\alpha$ ) are highlighted. Error  
214 bars for  $HW$  are  $\pm 5\%$  (see Supplementary File 6 for explanation of error sources). (B) Plot  
215 comparing measured ( $D$ ) and predicted ( $D'$ ) dike upper tip depths below HF. Error envelopes  
216 for  $D$  and  $D'$  are  $\pm 15\%$ . (C) Variation in the ratio of  $D':D$  along the graben related to fault  
217 dip, where: (i)  $D':D < 0.9$  fault dip decreases with depth; (ii)  $D':D = 0.9-1.1$  the fault is  
218 planar; and (iii)  $D':D > 0.9$  fault dip increases with depth. Error envelopes are  $\pm 15\%$ . (D) Dip  
219 map of EF1 and EF2. (E) Fault dips calculated along each measured transect for EF1 and EF2  
220 plotted against their corresponding seismic horizon (i.e. a proxy for depth). The dip profiles  
221 are grouped for  $D':D < 0.9$  and  $D':D > 0.9$ ; inset schematics show how changes in fault dip  
222 beneath horizon HF impact  $D':D$ .

223

224 **Figure 4:** (A) Map of displacement and displacement maxima across EF1 and EF2.  
225 Displacement maxima are plotted against distance, with error bars of  $\pm 15\%$ , and combined to  
226 show cumulative maximum displacement. (B) Depth-displacement profiles for EF1 and EF2;  
227 error bars are  $\pm 15\%$ . See (A) for locations. (C) Along-strike variations in total extension  
228 across EF1 and EF2, compared to cumulative heave at horizon HK and Dike E's seismic  
229 expression width measured from Figure 1A; error bars are  $\pm 15\%$ . Average dip of both faults  
230 at each site are highlighted. (D) Schematic showing how localized zones of high  
231 displacement may form in response to dike thickening. (E) Schematic showing how isolated  
232 fault segments may nucleate in response to dike propagation, then grow and link when the  
233 dike stalls and thickens (e.g., Woods et al., 2019). Lateral separation of fault segments may  
234 reflect magma break-out from the dike nose (Healy et al., 2018).

235

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