

1 **Field evidence for the lateral emplacement of igneous dykes: Implications for 3D**
2 **mechanical models and the plumbing beneath fissure eruptions.**

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13

14 **Abstract**

15 Seismological and geodetic data from modern volcanic systems strongly suggest that magma is
16 transported significant distance (tens of kilometres) in the subsurface away from central
17 volcanic vents. Geological evidence for lateral emplacement preserved within exposed dykes
18 includes aligned fabrics of vesicles and phenocrysts, striations on wall rocks and the anisotropy
19 of magnetic susceptibility. In this paper, we present geometrical evidence for the lateral
20 emplacement of segmented dykes restricted to a narrow depth range in the crust. Near-total
21 exposure of three dykes on wave cut platforms around Birsay (Orkney, UK) are used to map out
22 floor and roof contacts of neighbouring dyke segments in relay zones. The field evidence
23 suggests emplacement from the WSW towards the ENE. Geometrical evidence for the lateral
24 emplacement of segmented dykes is likely more robust than inferences drawn from flow-
25 related fabrics, due to the prevalence of ubiquitous 'drainback' events (i.e. magmatic flow
26 reversals) observed in modern systems.

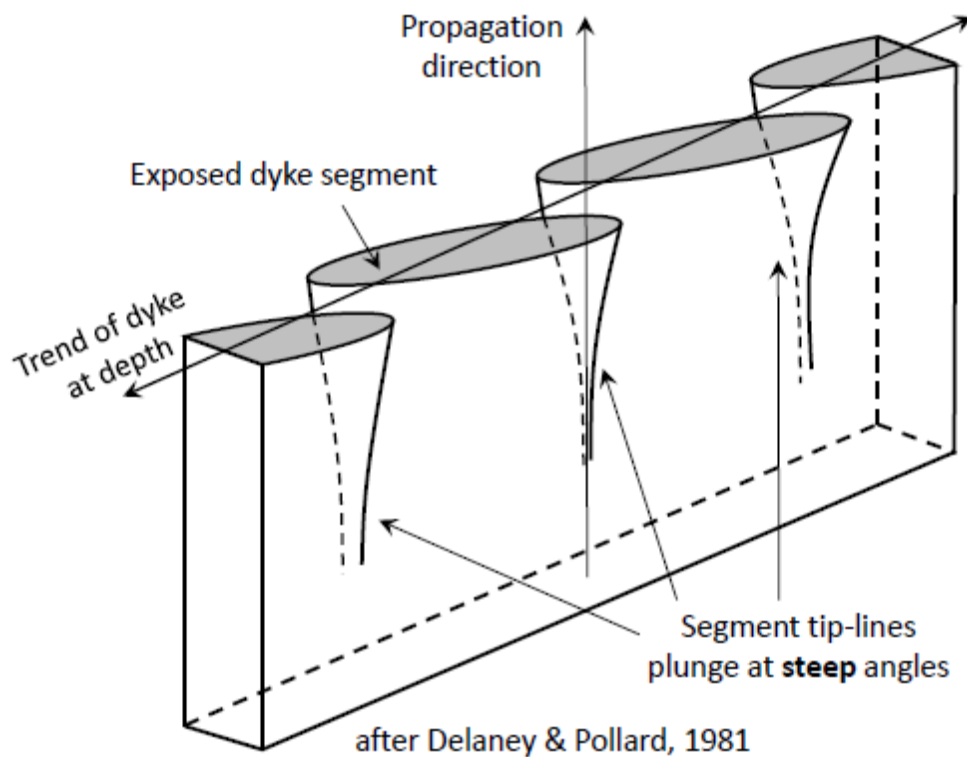
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28 **Introduction**

29 *Background*

30 Igneous dykes are the frozen remnants of magma conduits and preserve evidence of major
31 Earth processes such as magma transport from mantle to crust and the rifting of continents and
32 oceans (Burchardt, 2018). Our understanding of dyke emplacement has been driven by field
33 observations (e.g. Johnson, 1961; Delaney & Pollard, 1981; Gudmundsson, 1983; Ryan, 1988;
34 Agustsdottir et al., 2016), analogue and numerical modelling (e.g. Galland et al., 2006; Kavanagh
35 et al., 2018) and physical theories of fracture mechanics, fluid dynamics and heat flow (e.g.

36 Rubin, 1995; Rivalta et al., 2015; Townsend et al., 2017). Three-dimensional (3D) models of
37 dyke nucleation, propagation and arrest are in their infancy, and our current understanding
38 remains rooted in two-dimensional (2D) models. Melts derived from the mantle must undergo
39 a significant vertical component of movement to be emplaced in the upper crust. However, the
40 specific emplacement direction immediately before the melt solidifies is variable (e.g. Poland
41 et al., 2008). Previous workers have documented significant sub-horizontal components of
42 magma flow and dyke emplacement direction based on some combination of evidence from:
43 flow fabrics in either the solid matrix or the vesicles and amygdales, palaeomagnetic signals
44 from dyke margins, and seismicity (Staudigel et al., 1992; Poland et al., 2008; Townsend et al.,
45 2017). In relation to emplacement directions, the geometrical form of segmented dykes has
46 received relatively little attention. This paper describes three well-exposed segmented dykes
47 in Orkney (UK) and uses their geometrical form in outcrop to infer the likely direction of dyke
48 emplacement.



49

50 **Figure 1.** Schematic diagram of a vertical dyke propagating upwards and divided into *en*
51 *echelon* segments, or 'fringes', at the leading edge (after Delaney & Pollard, 1981). Note that this
52 model implies that the margins of dyke segments at the segment tips are steeply plunging.

53 The dominant paradigm for explaining the geometry of *en echelon* dyke segments has been
54 based on a diagram in Delaney & Pollard (1981; Figure 1). The exposed discrete segments are
55 believed to root down into a continuous dyke at depth. Note that a key corollary of this model
56 is that the segment tip-lines are steeply plunging. This conceptual model is derived from a
57 linear elastic fracture mechanics approach to dyke propagation in tensile cracks (Delaney &
58 Pollard, 1981). Segmentation along the upper edge is due to rotation of the least principal
59 stress during upward (i.e. vertical) propagation. However, seismological, geodetic and outcrop

60 evidence strongly suggests that at least some dykes propagate laterally (Brandsdottir &
61 Einarsson, 1979; Ryan, 1988; Agustsdottir et al., 2016; Townsend et al., 2017). Geophysical
62 evidence from modern volcanic settings, such as Bardabunga-Holuhraun on Iceland and
63 Kilauea on Hawaii, combined with direct observations of temporal and spatial patterns in
64 fissure eruptions, are consistent with significant (i.e. tens of kilometres) sub-horizontal
65 migration of magma away from central vents. The location of the seismicity suggests that the
66 migration pathways are restricted to relatively narrow depth ranges (few kilometres) in the
67 upper crust. A mechanical basis for lateral dyke emplacement at a specific depth has been
68 advanced by Rubin (Rubin & Pollard, 1987; Rubin, 1995) and refined by Townsend et al. (2017).
69 Dyke emplacement will be vertically restricted when the stress intensity factors at the top and
70 bottom tip-lines of the dyke-hosting crack are insufficient to overcome the fracture toughness
71 of the host rock. Moreover, lateral propagation is favoured when the stress intensity factor at
72 the lateral tip-line exceeds the fracture toughness of the host. Likely conditions for lateral
73 propagation are then predicted to occur at the depth of a density contrast in the crust when the
74 magma driving pressure exceeds the dyke normal stress (Rubin, 1995). In modern settings,
75 this is likely to be the interface between the volcanic pile and the underlying basement.

76 *Rationale*

77 In this paper, we present detailed field observations from a suite of three segmented dykes
78 perfectly exposed on the foreshore at Birsay in Orkney (Scotland, UK). We describe the
79 geometry of the dykes in relation to the uniformly dipping sedimentary host rocks, with a
80 particular focus on the relays – or bridges – between adjacent segments. Throughout this
81 paper, we refer to the rock volumes around neighbouring dyke segment pairs as relays, as a
82 direct extension of the concepts and terminology used for faults (Walsh et al., 1999). Even
83 though dykes (and sills) are dominated by extensional (dilatational) strains, and perhaps
84 locally by tensile stresses, we believe the term ‘relay’ accurately captures the core concept of
85 deformation (displacement, strain) being transferred, or more literally ‘passed on’, from one
86 segment to another. The corollary of applying the term relay to dykes is that relays are then
87 seen to constitute a quasi-continuous spectrum of types from those dominated by tensile stress
88 or extensional strain (e.g. dyke, sill or vein relays), through hybrid extension+shear relays, to
89 those dominated by shear strain or stress (e.g. fault relays). Furthermore, this leads to the
90 inference that relays dominated by contractional strain (and/or compressive stress) may also
91 exist, for instance in the case of stylolites or other anti-crack phenomena (Fletcher & Pollard,
92 1981). The terms ‘bridges’ (intact) and ‘broken bridges’ (breached) have been widely used for
93 these dyke relay structures in the past (e.g. Jolly & Sanderson, 1995; Schofield et al., 2012).
94 Nevertheless, we believe ‘relay’ (breached or unbreached) represents a better – more
95 homologous – connection to the underlying kinematics and mechanics of brittle fracture (and
96 filling), and provides scope for a unified understanding of deformation in the rock volumes
97 between neighbouring *en echelon* fractures of any kinematics. We use the term ‘jog’ for a short
98 (typically a few cm) lateral step in a dyke segment where the lateral offset is much less than the
99 dyke thickness – i.e. the segment remains unbroken at the level of exposure.

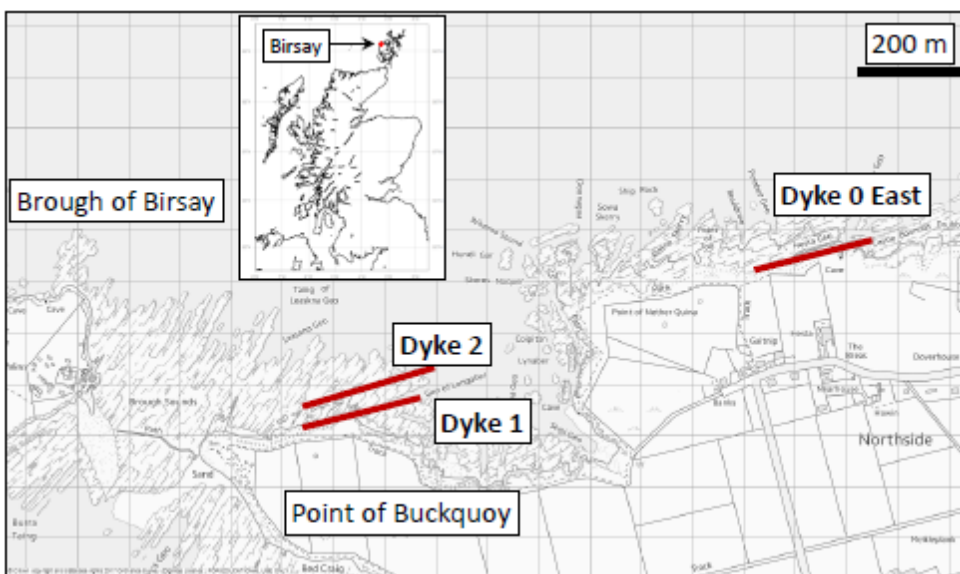
100 Near perfect exposure of thinly-bedded and jointed rocks on the wave cut platforms at Birsay
101 has been exploited using high-resolution photo-mosaics captured by a camera mounted on an

102 Unmanned Aerial Vehicle (UAV, or drone). Using these orthorectified photomosaics as a base,
103 we systematically collected observations and measurements from segment relay zones for all
104 three dykes. These field observations, captured as digital photographs, orientation data and
105 field notebook sketches, form the basis for the interpretations of 3D relay geometry. In the
106 following sections, we describe the location and regional context for the dykes, and their host
107 rocks, and then present a summary of petrological observations. The focus then shifts to the
108 detailed geometries of the dyke segment relays, with observations followed by interpretations
109 of the 3D structure. We then discuss the issues arising from our model for the Birsay dykes, and
110 put this in the context of previous mechanical analyses and data from modern volcanic systems.

111

112 **Geological setting**

113 The dykes at Birsay have been emplaced into Devonian rocks of the Orcadian Basin. This basin
114 extended from Inverness in the south to Shetland in the north, and formed following the
115 collapse of the Caledonian orogen (McClay & Davis, 1987). The basin fill is dominated by cyclic
116 lacustrine deposits towards the basin centre, and alluvial and fluvial deposits towards the
117 margins. The sedimentary sequence at Birsay is dominated by thinly bedded (< 1 metre)
118 sandstones, siltstones and mudstones of Middle Devonian age, assigned to the Stromness Flags
119 Formation, and records lacustrine shoreface facies (Andrews & Hartley, 2015). This
120 sedimentary sequence rests unconformably on metamorphic basement, seen further south
121 around Stromness, correlated with Moine metasedimentary rocks of the mainland (Strachan,
122 2003).



123

124 **Figure 2.** Details of the study area at Birsay, Orkney (UK). Inset map shows the location of
125 Birsay at the NW corner of the Mainland of Orkney, off the north coast of Scotland. Main map
126 shows the locations of the three dykes studied in detail in this paper. Excellent exposures are
127 found in the wave cut platform to the north side of the Point of Buckquoy and at the top of the
128 cliffs beyond the houses at Northside. Dyke thickness exaggerated for clarity. Note that the

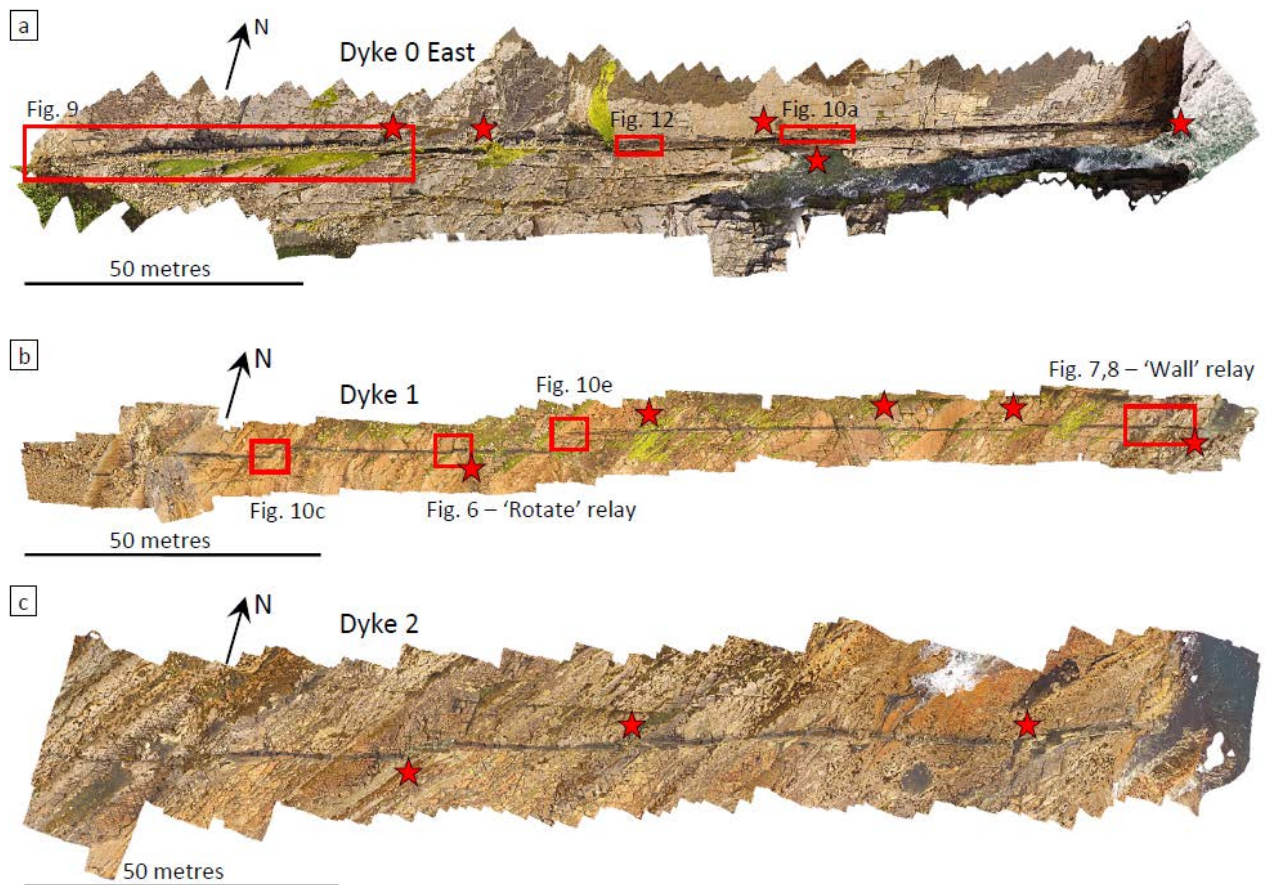
129 segmentation of these dykes is not apparent at this scale. Background Ordnance Survey map
130 from EDINA Digimap.

131 The dykes at Birsay are alkaline lamprophyres and have been assigned to the Permo-
132 Carboniferous camptonite-monchiquite suite by Rock (1983). This suite extends over much of
133 the Scottish Highlands and Islands and comprises dykes and rare vents (plugs). Samples from
134 dykes in Orkney and nearby Caithness on the Scottish mainland have yielded radiometric ages
135 of 245 ± 12 Ma and $249\text{-}268\pm 4$ Ma i.e. late Permian (Brown, 1975; Baxter & Mitchell, 1984).
136 These rocks form part of a widespread Permian alkaline magmatic episode extending across
137 the North Sea to the Oslo Graben (Norway). Dykes from this suite are common in Orkney and
138 Caithness on the Scottish mainland, and typically strike ENE. Their widths vary from a few
139 centimetres to over one metre. Our study at Birsay focuses on three such dykes (Figure 2).

140

141 **Methods**

142 To fully exploit the near total exposure of the dykes and their host rocks at Birsay we surveyed
143 the area with an unmanned aerial vehicle (UAV, or drone) mounted with a 12.4 megapixel
144 camera (DJI™ Phantom 3 Professional). We flew repeated sorties to map the whole wave cut
145 platform and details of selected dykes at altitudes between 5 and 15 m above mean sea level.
146 Digital photographs from these flights were then merged and orthorectified into high-
147 resolution map view mosaics using Agisoft™ Photoscan software. Ten ground control points
148 located with a GPS were used to improve geospatial referencing of the processed image
149 mosaics. The final mosaic has a resolution of about 1 cm per pixel. Sections of the final mosaic
150 were printed on A3 paper and used as detailed basemaps for the collection of field data, such
151 as the orientations of dyke margins, joints and bedding and observations of changes in texture
152 or mineralogy. We mapped three segmented dykes in detail with overall lengths of 225, 205
153 and 186 metres (Dykes 0 East, 1 and 2, respectively; Figure 3).



154

155 **Figure 3.** Orthorectified photo mosaics of the three dykes studied in detail. Dyke 0 East has a
 156 total exposed length of 225 metres, Dyke 1 for 205 metres and Dyke 2 for 186 metres. Note the
 157 segmentation of all three dykes, with the majority of segments left stepping, although right-
 158 steps do occur. Traces of bedding planes in the host rocks can be seen striking NE-SW. Red
 159 boxes mark the locations of the relay zones selected for detailed analysis in this paper. Red stars
 160 mark other locations where evidence for segments floors and/or roofs can be seen, although
 161 not documented in detail in this paper.

162 Orientation data were measured with a standard compass clinometer, with an estimated error
 163 of $\pm 1^\circ$ in dip or strike. Scan line data was collected using the method of Mauldon et al. (2001),
 164 using a circular template of known radius (14.5 cm) placed onto quasi-horizontal surfaces at
 165 fixed intervals. Fracture intensity at each point is then estimated as $n/4r$, where n is the number
 166 of fractures intersecting the circular hoop perimeter and r is the radius of the hoop.

167 We took oriented samples from the dykes, including their margins and cores, for thin section
 168 analysis. Thin sections were analysed under a standard optical petrographic microscope and
 169 then in a Zeiss Gemini 300 scanning electron microscope (SEM) at the University of Aberdeen.
 170 We used a combination of backscattered electron (BSE) images and energy dispersive
 171 spectroscopy (EDS) to map the mineral phases and their chemical composition. We used a
 172 voltage of 15 kV and a working distance of about 10 mm.

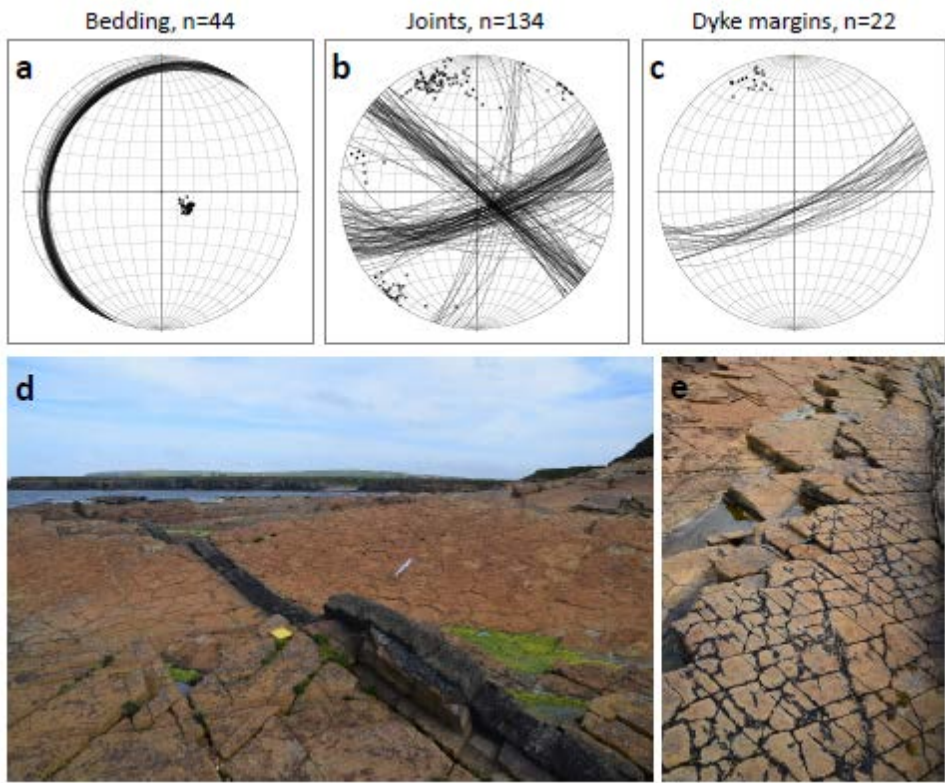
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174 **Observations**

175 *General dyke morphology and structure*

176 The dykes exposed at Birsay trend ENE, varying between 065° to 075°, and dip steeply to the
177 south at 65-80° degrees. All three dykes are composed of multiple segments at the present level
178 of exposure (Figure 3). The dyke comprise *en echelon* arrays of quasi-linear segments rotated
179 a few degrees (< 10°) clockwise of the overall dyke trend. Most segments show no overlap or
180 underlap at the relays. Separations, measured perpendicular to dyke segment strike at the
181 relays, vary from a few centimetres to just over one metre. Dyke segment widths decrease from
182 WSW to ENE in all three dykes. Dyke 0 varies in width from 70 cm to 45 cm. Dyke 1 varies
183 from 45 cm to 25 cm. Dyke 2 varies from 60 cm to 42 cm. Most of the dyke segments are parallel
184 sided for most of their strike length, with only local deviations to oblique margins at jogs.

185 Contacts with the host rock are generally sharp, although more diffuse margins are observed at
186 a few segment tips. The host rocks strike uniformly NNE/SSW and dip at a constant angle to
187 the WNW at around 20 degrees (Figure 4). No significant rotations of bedding were seen
188 adjacent to the dykes, with the exception of small blocks in segment relays (see below). The
189 host rocks are cut by three sets of joints, one of which is parallel to the dyke segment margins
190 (Figure 4). The NNE trending joint set is only weakly developed relative to the other two sets.
191 The dykes have produced baked margins in the sedimentary host rocks, with widths typically
192 less than 100% of the dyke width and approximately symmetrical on both sides. Marked colour
193 changes are apparent in the host rocks, especially in the finer grained siltstones and mudstones,
194 from pale buff-grey to much darker grey. In some cases, these are zoned with a narrow (~1-2
195 cm) very dark grey zone adjacent to the margin, and then a slightly lighter grey zone (~10-20
196 cm wide) outside of this.

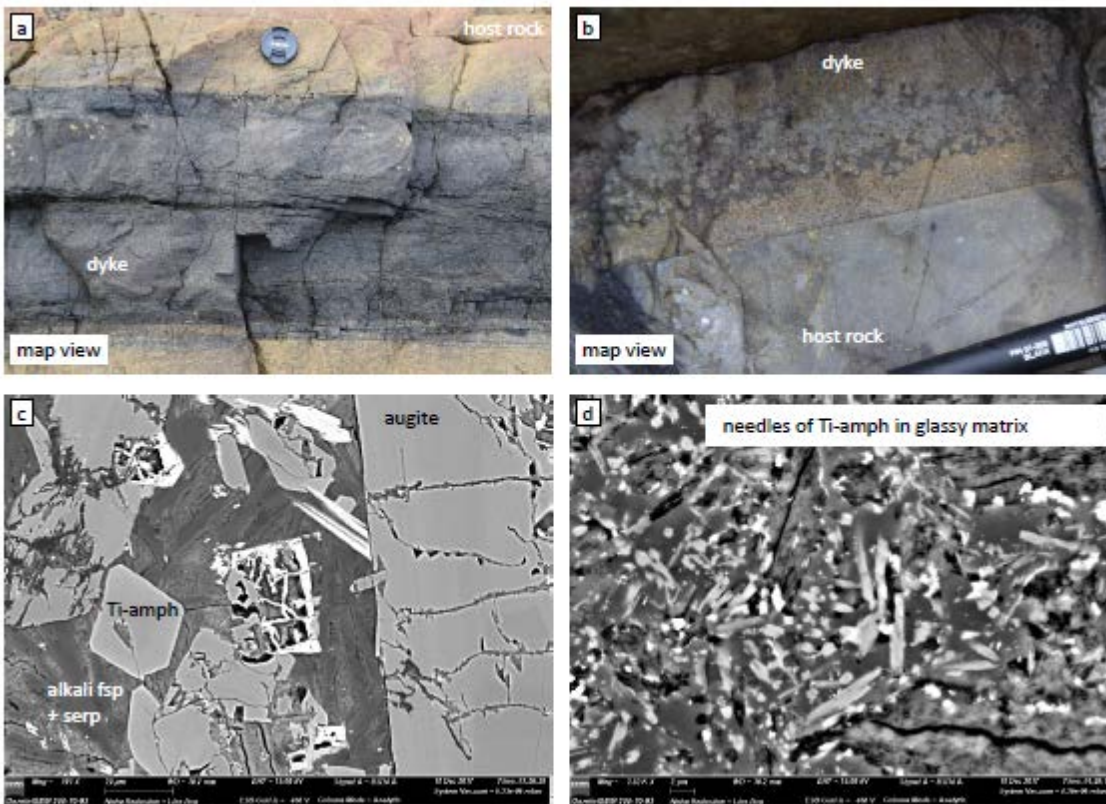


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198 **Figure 4.** Orientation data from Birsay. Stereograms plotted as equal area, lower hemisphere
 199 projections, with great circles and poles. **a)** The orientation of bedding is very uniform over the
 200 whole mapped area, with an average strike of approximately 030 and dipping approximately
 201 20 to the WNW. **b)** Three prominent sets of joints are developed throughout the area, with two
 202 main sets oriented ENE/WSW and NW/SE, and a less well-developed set trending NNE. **c).** Dyke
 203 margins (away from the segment tips) are also very uniform and follow the trend of one of the
 204 joint sets ENE/WSW, dipping steeply (70-80) to the South.

205 *Dyke petrography, mineralogy and textures*

206 In outcrop and hand specimen, the dykes appear mafic. The weathered appearance is a medium
 207 grey, appearing darker grey on fresh surfaces. Groundmass grain size varies from glassy to
 208 medium grained. Many segments display a crude zonation, with chilled margins and a vesicular
 209 central core flanked by non-vesicular zones (Figure 5a). Chilled margins in outcrop can appear
 210 complex with very fine grained or glassy edges passing inwards to zones of mixed lighter and
 211 darker grey aphanitic rock (Figure 5b). Thin sections of samples from all three dykes confirm
 212 the presence of chilled margins and coarser porphyritic cores. The dyke segment cores contain
 213 phenocrysts of zoned augite (up to 5 mm) and Ti-rich amphibole (up to 1 mm) in a fine grained
 214 matrix of alkali feldspar and serpentine (after olivine). Accessory phases include Mn-rich
 215 calcite, dolomite, quartz, Cr spinel and Ni-rich pyrite (Figure 5c). The chilled margins contain
 216 small (~10 µm) needles of Ti-rich amphibole set in a glassy matrix (Figure 5d).



217

218 **Figure 5.** Details of the textures and mineralogies of the dykes at Birsay. **a)** Photograph (map
 219 view, N at the top) showing a typical profile across Dyke 1, with chilled margins and a central
 220 core zone that often appears vesicular in the field (lens cap is 6.5 cm across). Note the

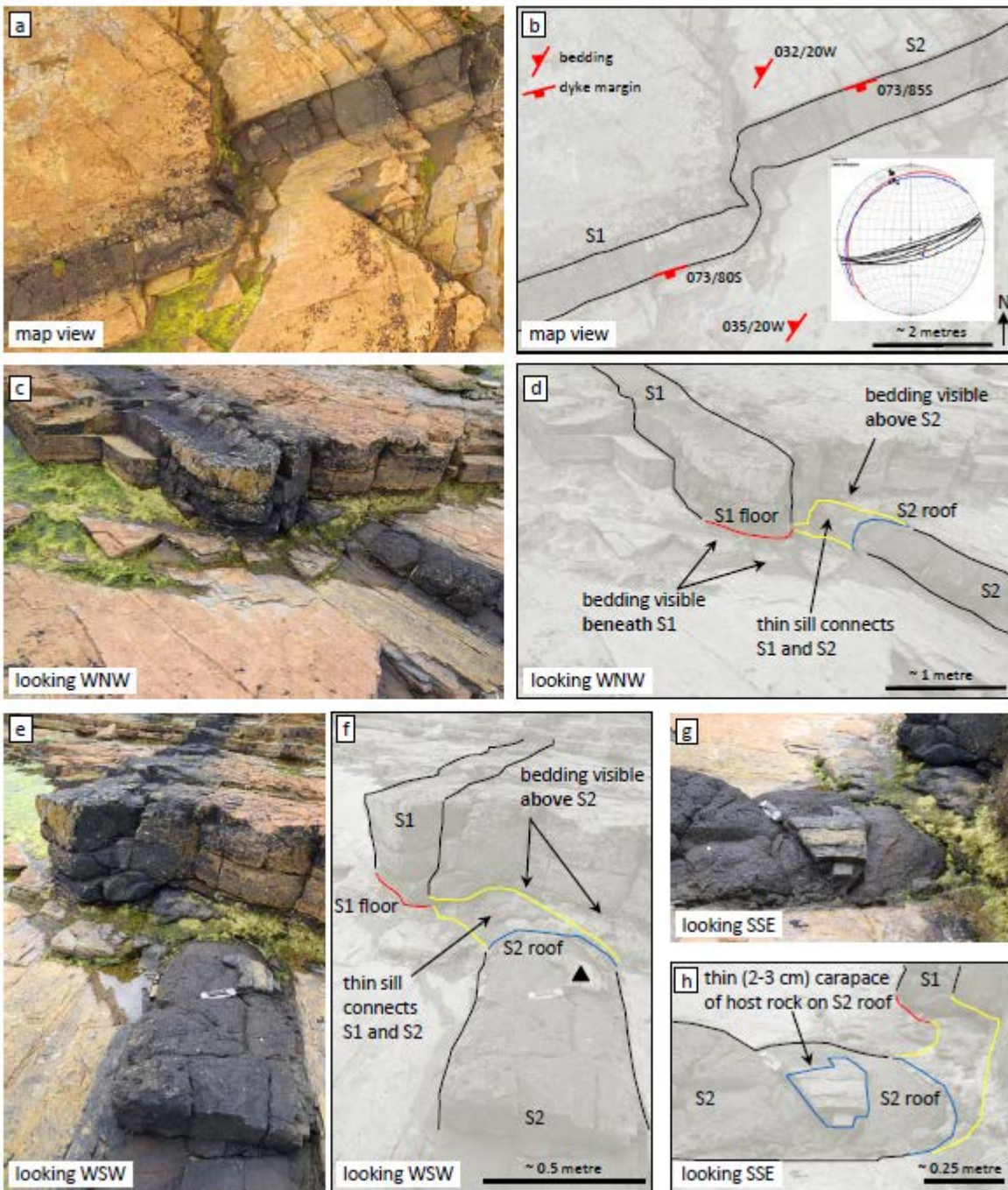
221 discolouration of the host rock in the baked margin. **b)** Photograph (map view, N at the top)
222 showing details of a complex, probably composite, chilled margin within Dyke 1 (pen is 1 cm
223 across). **c)** SEM-BSE image of a thin section from the core of Dyke 1. The groundmass is made
224 up of alkali feldspar and serpentine after olivine (occasional relics preserved). The phenocryst
225 cargo includes Ti-rich amphibole (probably kaersutite) and zoned augite. Other phases include
226 Mn-rich calcite, dolomite, quartz, Ni-rich pyrite and Cr-spinel. **d)** SEM-BSE image of a thin
227 section a chilled margin of Dyke 1 showing needles of Ti-rich amphibole in a glassy matrix.

228 *Details of segment tips and relays between segments*

229 In the following detailed descriptions of the segment relays, a local labelling convention is used
230 for the segments in each relay: S1, S2, ..., Sn. These labels have no significance beyond the
231 particular relay under discussion.

232 'Rotate' relay – Dyke 1

233 In this relay, the two neighbouring segments (S1 and S2) of Dyke 1 are approximately 45 cm
234 across (see Figure 3b for location). The lateral offset between the two segments is about 20 cm
235 (Figure 6a-b). At the easternmost exposed edge of S1, a shallow West dipping floor contact
236 between the dyke above and host siltstone below can be traced for about one metre (Figure 6c-
237 d). At the westernmost exposed edge of S2, a shallow West dipping roof contact between the
238 dyke below and host siltstone above can also be traced for about one metre (Figure 6e-f). Both
239 the floor of S1 and roof of S2 dip gently (10-20 degrees) to the NW (stereogram inset in Figure
240 6b). The floor to S1 appears planar and concordant to bedding, whereas the roof of S2 is
241 concordant but gently domed, like the top of a loaf of bread. A further detail confirms this
242 contact as the roof of segment S2: a small (approximately 15 cm x 20 cm), thin (2-3 cm) patch
243 of baked mudstone and siltstone is preserved as a carapace on top of the dyke segment (Figure
244 6g-h). Segments S1 and S2 are connected by a thin (10-20 cm) sill-like body (Figure 6e-f). The
245 name 'Rotate' relay originated from our initial reconnaissance where we believed that the two
246 dyke segments rotated through a sub-horizontal sill, before we observed the floor and roof
247 contacts.



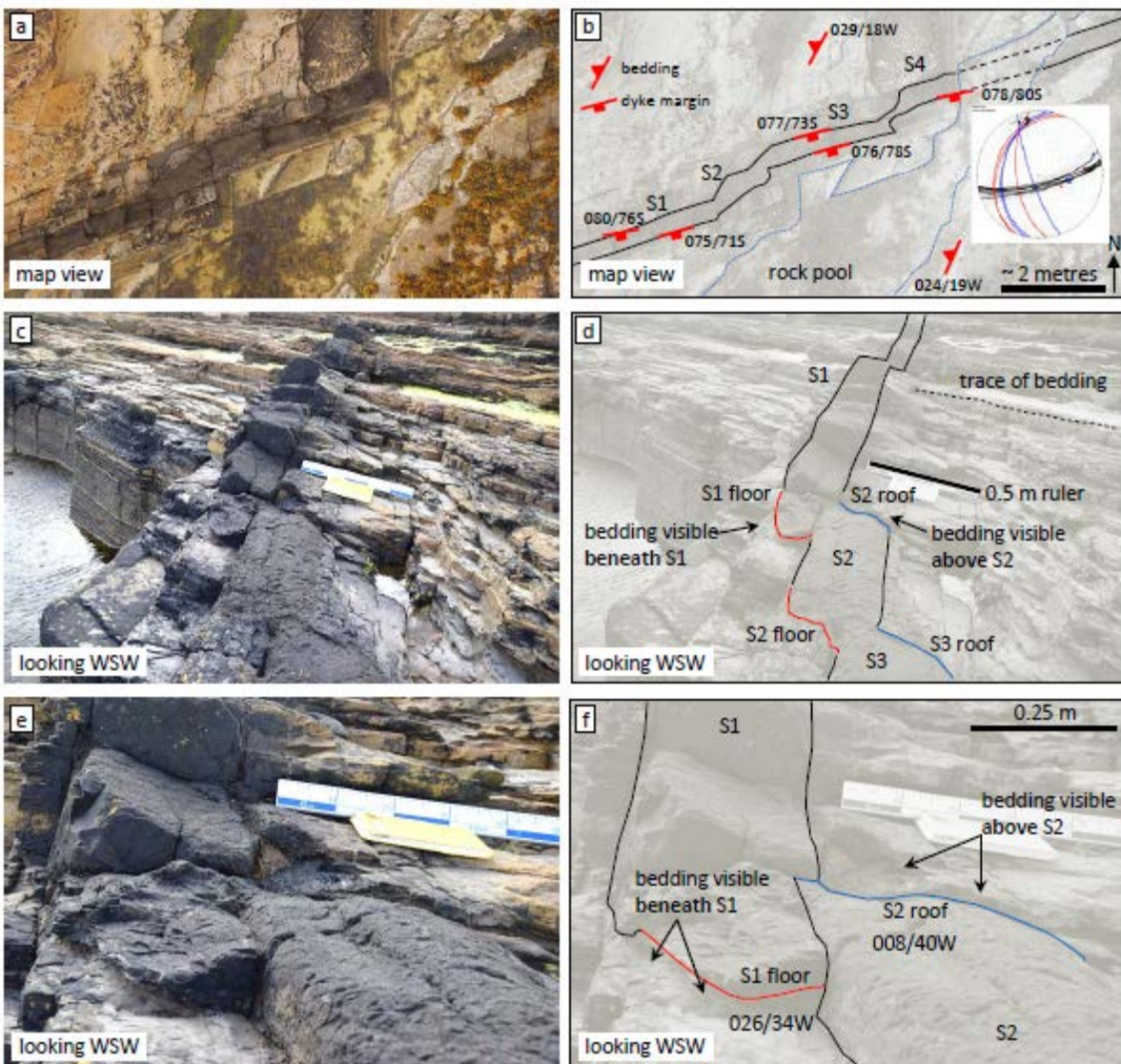
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249 **Figure 6.** Field observations from 'Rotate' Relay on Dyke 1. **a-b)** Photograph and interpretation
 250 in map view of the two segments S1 and S2. The apparent lateral offset is approximately the
 251 width of the dyke, about 45 cm at this locality. The inset stereogram in b) shows the orientations
 252 of the dyke margins (black) and the interpreted floor and roof tip-lines (red and blue,
 253 respectively). **c-d)** Photograph and interpretation of the geometry of this relay zone in oblique
 254 view looking WNW. Bedding in the host rock can clearly be seen *beneath* the easternmost
 255 outcrop of S1, and *above* the westernmost outcrop of S2. These contacts are interpreted as the
 256 local floor (red) and roof (blue) of these segments. The measured orientations of these contacts
 257 are shown in the stereogram in b). A thin (few cm across) sill-like body is seen to connect S1 to
 258 S2. **e-f)** Photograph and interpretation of the Rotate relay zone from a different viewpoint
 259 looking WSW to clarify the floor and roof geometries and the connecting sill. Note the gently
 260 domed appearance of the roof of S2, like a loaf of bread (near the penknife).

261 and interpretation of the roof of S2 (looking SSE) with a thin baked-on remnant of the host rock
262 clearly visible on top of the S2 dyke segment.

263 'Wall' relay – Dyke 1

264 This relay zone is actually three relays in close proximity (approx. 7 m along strike), linking
265 four segments S1-S4. Note that at this ENE end of Dyke 1 (see Figure 3b for location) the
266 segments are approximately 30 cm wide (Figure 7a-b). From the perfect 3D exposure, the floor
267 of segment S1 is clearly defined by the shallow dipping contact with bedding lying directly
268 beneath (Figure 7c-d). This floor contact is planar and concordant, and dips at a shallow angle
269 to the WNW (~20°).



270
271 **Figure 7.** Field observations from 'Wall' Relay on Dyke 1. **a-b)** Photograph and interpretation
272 in map view of four segments S1-S4. The inset stereogram in b) shows the orientations of the
273 dyke margins (black) and the interpreted floor and roof tip-lines (red and blue, respectively).
274 **c-d)** Photograph and interpretation of the relationship between S1 and S2, looking WSW.
275 Bedding in the host rock is seen beneath S1 and above S2, these contacts are taken as a floor
276 and a roof respectively. Bedding is again visible beneath the easternmost end of S2, and this

277 contact is also interpreted as a segment floor. **e-f)** Close-up photograph and interpretation of
278 the S1 floor and S2 roof geometry shown in c-d). The measured orientations of these contacts
279 are shown in the stereogram inset in b). Note again the gently domed appearance of the exposed
280 top (roof) of S2, contrasted with the flat, bedding parallel base (floor) of S1.

281 For the next segment S2, the roof is also clearly visible and defined by the presence of bedding
282 in the overlying stratigraphy (Figure 7c-f). The two segments S1 and S2 overlap by a few tens
283 of centimetres and appear fused together. The central segment in this relay zone (S3) is
284 exposed in a steep segment margin-parallel joint surface, and clearly shows the segment floor
285 dipping to the West, with host rock bedding truncated beneath (Figure 8a-b). Viewed along
286 strike from the ENE, the segment floor is confirmed, with bedding passing continuously beneath
287 the exposed width of the segment. The fourth segment in this system (S4) is joined to S3 by a
288 narrow (few cm across) pipe-like body, flanked by host rocks with rotated (steepened) bedding
289 (Figure 8a-b). The roof to segment S4 is also clearly visible with undisturbed and unfractured
290 host rock bedding passing across the top. The roof to S4 dips at shallow angle ($\sim 10^\circ$) to the
291 WSW, and is gently domed in appearance (Figure 8c-d).



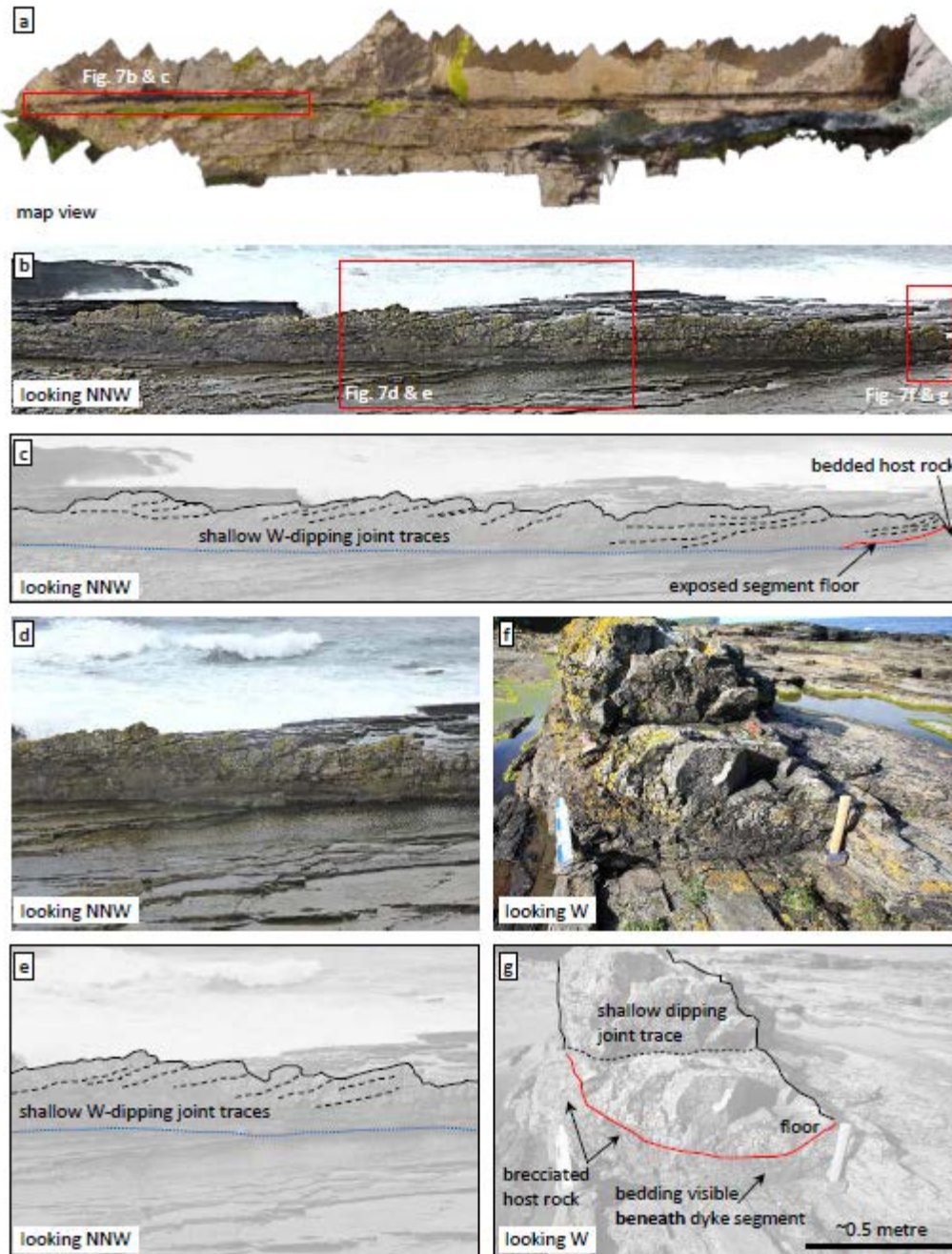
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293 **Figure 8.** Further field observations from ‘The Wall’ Relay on Dyke 1. **a-b)** Photograph and
 294 interpretation of the relationships between S3 and S4 at the eastern end of the relay. Looking
 295 NW onto a nearly vertical section along the southern margin of S3 (‘The Wall’). The floor to S3
 296 can be seen, with bedding in the host rock truncated against the dyke contact. The connection
 297 between S3 and S4 is complex, with rotated steepened bedding. **c-d)** Photograph and
 298 interpretation of S3 and S4 looking WSW. The floor to S3 is clearly visible with host rock
 299 bedding beneath. The roof to S4 is also visible with bedding in the host rock continuous above.
 300 In the background, the floor to S1 is also visible.

301 Dyke 0 East

302 Dyke 0 East provides two other features of interest to this study. This dyke stands proud of the
 303 host rock in a single segment approximately 50-60 metres long at the western end of the
 304 outcrop (Figure 9a-b). Viewed from the South, numerous shallow West dipping joint surfaces
 305 can be traced in the southern margin of the segment. In detail, these joints are often concave

306 upwards (Figure 9c-e). At the eastern exposed end of this segment, the dyke has a quasi-
 307 elliptical cross-section (Figure 9f-g) and is seen to overly bedded host rock. The floor contact
 308 can be traced for about 3 metres across the 'nose' of this segment tip and down along the
 309 segment flank. In addition, further exposed examples of floor and roof contacts are visible in
 310 the segment relays to the East (marked on Figure 3a).



311
 312 **Figure 9.** Field observations from Dyke 0 East. **a)** Orthorectified photomosaic of Dyke 0 East
 313 showing the location of the following images and analysis. **b-c)** Stitched photomosaic and
 314 interpretation looking NNW of the western end of Dyke 0 East. The dyke forms a low (1-2 m
 315 high) wall running along the wave cut platform, and is cut by prominent shallow W-dipping
 316 joints, many with a concave-up geometry. Bedded host rock can be seen beneath the dyke at
 317 the eastern end of this outcrop, interpreted as the segment floor. **d-e)** Close-up photograph and

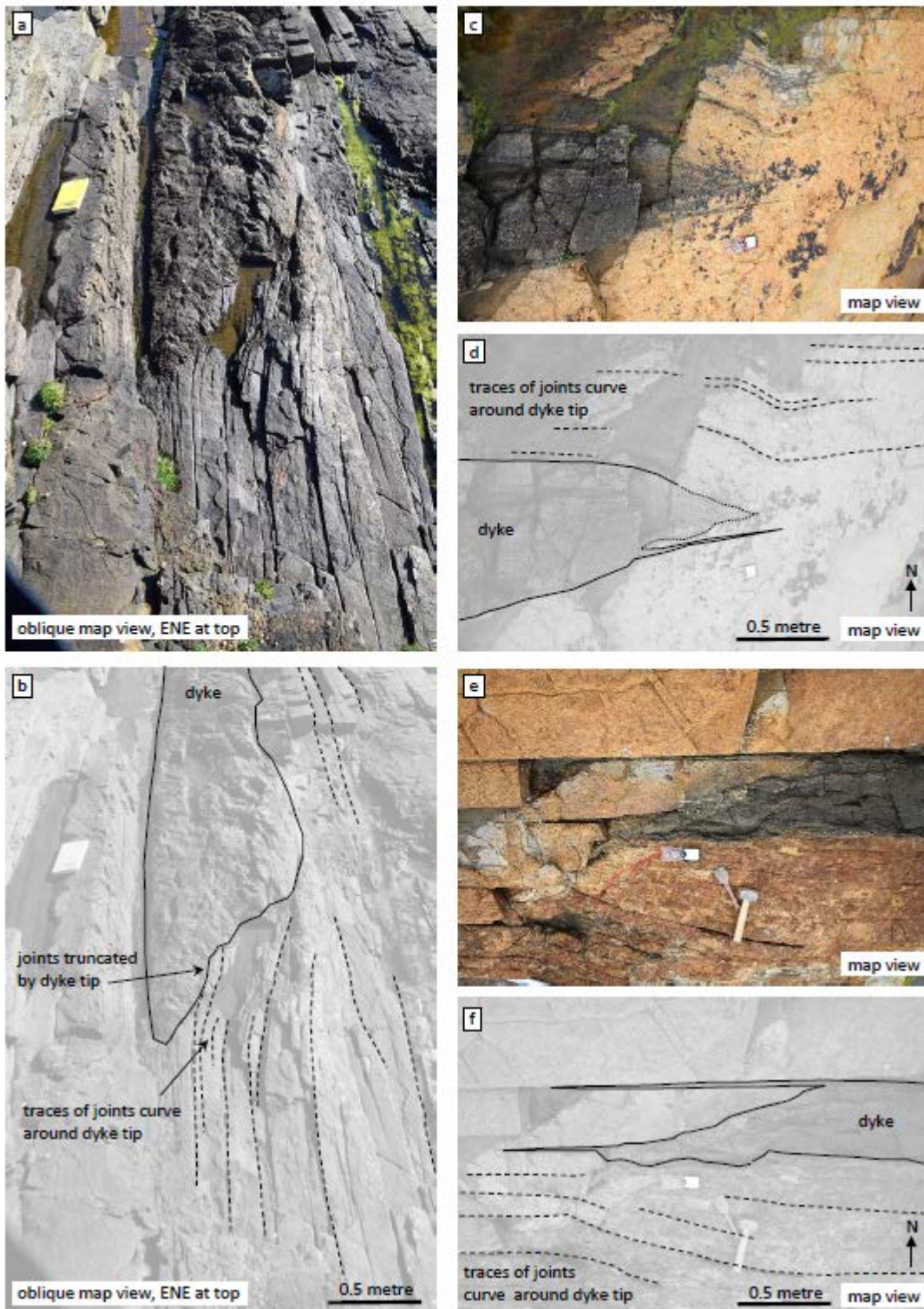
318 interpretation of the shallow W-dipping joints in this segment of Dyke 0 East. **f-g**) Photograph
319 and interpretation of the exposed tip at the eastern end of this segment, looking West. Traces
320 of the shallow W-dipping joints can be seen within the dyke. Bedding is visible in the host rock
321 beneath the exposed dyke tip, with the contact interpreted as the local segment floor (red line).
322 The host rock is also brecciated in places around this tip.

323 Jogs

324 There are many jogs exposed along the three main dykes at Birsay, and they display a common
325 pattern. The host rock in the area immediately along strike of lateral projection of the segments
326 on either side of the jog is intensely brecciated. The breccia clasts range in size from a few mm
327 to a few cm, are invariably angular and rotated. The clasts appear to be derived from the
328 immediate host rock layer for the given level of exposure. In many cases, a locally intense zone
329 of dyke margin parallel joints extends beyond the dyke terminations into the host rock. The
330 baked margins widen around the jog and then return to their normal width alongside the dyke
331 segments extending away from the jog.

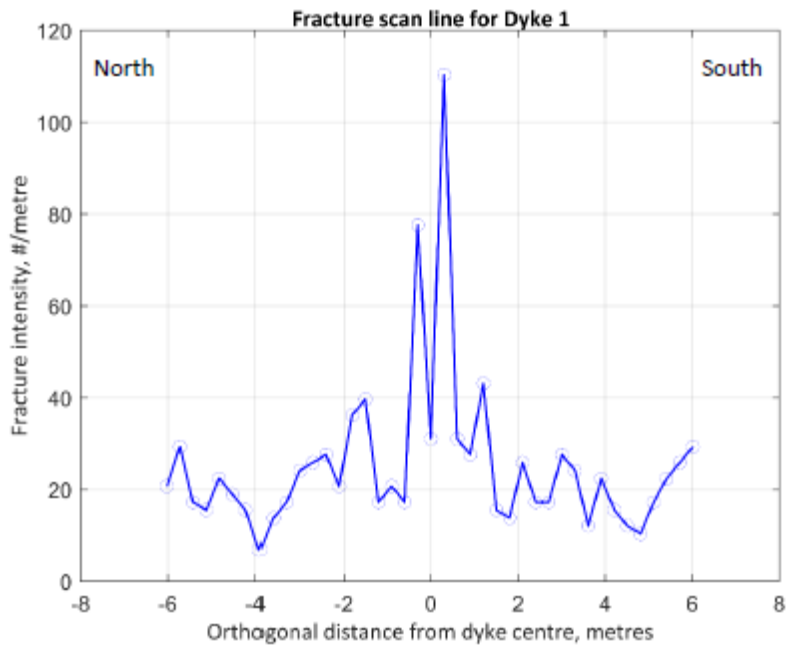
332 Joints

333 Three joint sets are developed in the area, trending ENE, NNE and NW. The NNE set is the least
334 well developed. The ENE set is parallel to the lateral margins of most dyke segments (Figure
335 4b-c). Near the segment relays, joint traces are observed to deflect around the segment tips,
336 and in some cases are truncated by the dyke tip contact (Figure 10a-b). The frequency of ENE
337 trending joints increases near the dyke segment tips and alongside their lateral margins. A
338 scanline across Dyke 1 shows the increase in estimated fracture intensity (number of joints per
339 metre) near the dyke margins. The host rocks have a background fracture intensity of between
340 10-30 m⁻¹, but this rapidly increases within about 0.5 m of the contact to > 100 m⁻¹. In the
341 segment relays, joints are common in front of the segment tips, but less common in the host
342 rocks immediately adjacent to the floor and roof contacts (Figure 6e, 7e, 8c). A handful of the
343 NW trending joints are filled with calcite and these veins are observed to cut across the dyke
344 segments.



345

346 **Figure 10.** Intense fractures at segment tips. **a-b)** Photograph and interpretation of dyke/host
 347 joint relationships at a segment tip in Dyke 0 East. Oblique view, looking down and along to
 348 ENE. Note the truncations of some host rock joints by the dyke contact, and the deflections of
 349 host rock joint traces away from the generally uniform ENE/WSW trend. **c-f)** Two further
 350 examples from segment tips in Dyke 1, showing the apparent deflection of host rock joint traces
 351 around the dyke tips.

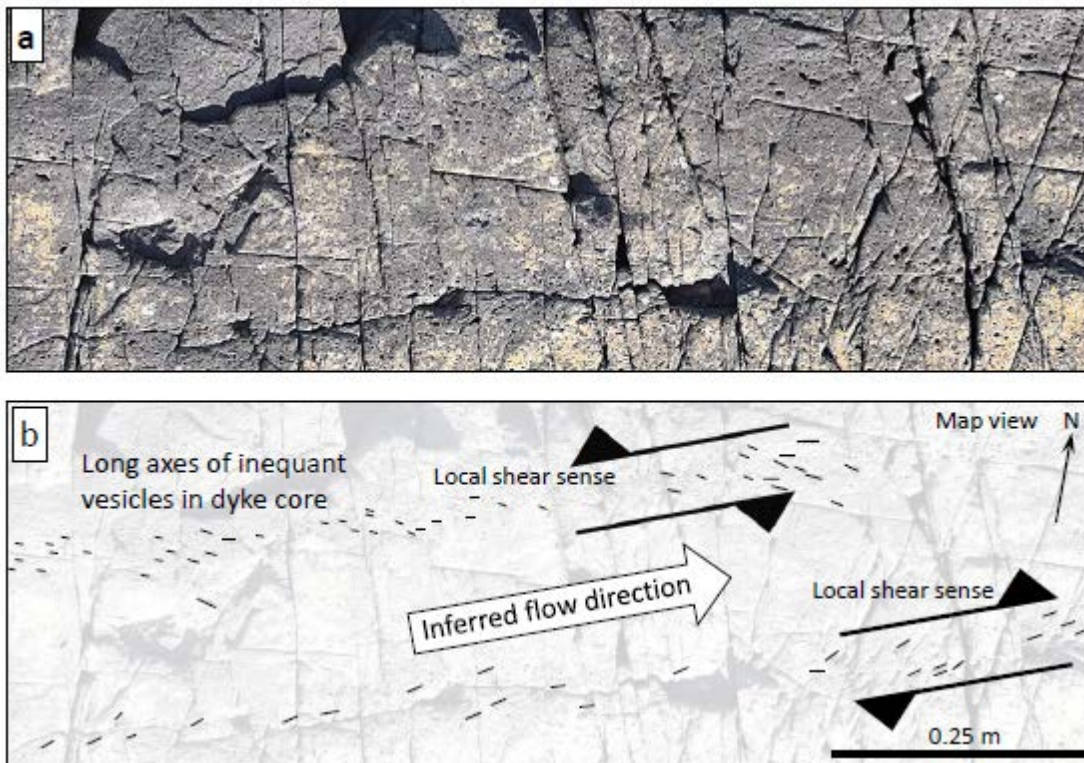


352

353 **Figure 11.** Example of estimated fracture intensities around a dyke segment. Estimated
 354 fracture intensity (number of fractures/metre) has been plotted against orthogonal distance
 355 from the centre of one segment of Dyke 1. At this locality, this segment of Dyke 1 is
 356 approximately 50 cm thick. Away from the dyke, estimated fracture intensity varies from about
 357 10 m⁻¹ to about 30 m⁻¹. Within one dyke width (i.e. 0.5 m), the estimated fracture intensity
 358 jumps to > 100 m⁻¹.

359 Vesicles

360 As noted above, many dyke segments at Birsay contain vesicles, either in the central core or in
 361 paired parallel trains symmetrically disposed either side of the median line. Vesicles range in
 362 size from <1mm to >5 mm (longest dimension). Several of the paired parallel trains display a
 363 systematic asymmetry of vesicle long axes viewed in the horizontal plane (Figure 12). For the
 364 example illustrated from Dyke 0 East, the northern vesicle train has long axes preferentially
 365 oriented ESE, a clockwise rotation of about 20° with respect to the local segment margin. The
 366 southern vesicle train has long axes preferentially oriented ENE, a counter-clockwise rotation
 367 of approximately 10° angle with the local segment margin. Vesicle cross-sections observed in
 368 sub-vertical joint surfaces are elongated, with long axes sub-parallel to the local segment
 369 margin.



370

371 **Figure 12.** Preferred orientations of shaped vesicles in Dyke 0 East. a-b) Photograph and
 372 interpretation of patterns of vesicles observed in the core of one segment of Dyke 0 East (see
 373 Figure 3 for location). Only about 1 metre of the dyke is shown, but this pattern extends for at
 374 least 10 metres on the ground. Two sub-parallel trains of vesicles can be found each about 20
 375 cm in from the dyke margin. Many vesicles are elliptical in this horizontal (map view) cross-
 376 section, with their long axes oriented in opposite trends on either side of the dyke centre line.
 377 The northernmost vesicle train has long axes oriented approximately WNW/ESE whereas the
 378 southernmost train has long axes oriented approximately ENE/WSW. Assuming the vesicles
 379 were originally spherical with circular cross-sections in 2D, this pattern is consistent with a
 380 shear deformation due to eastward flow of the dyke core.

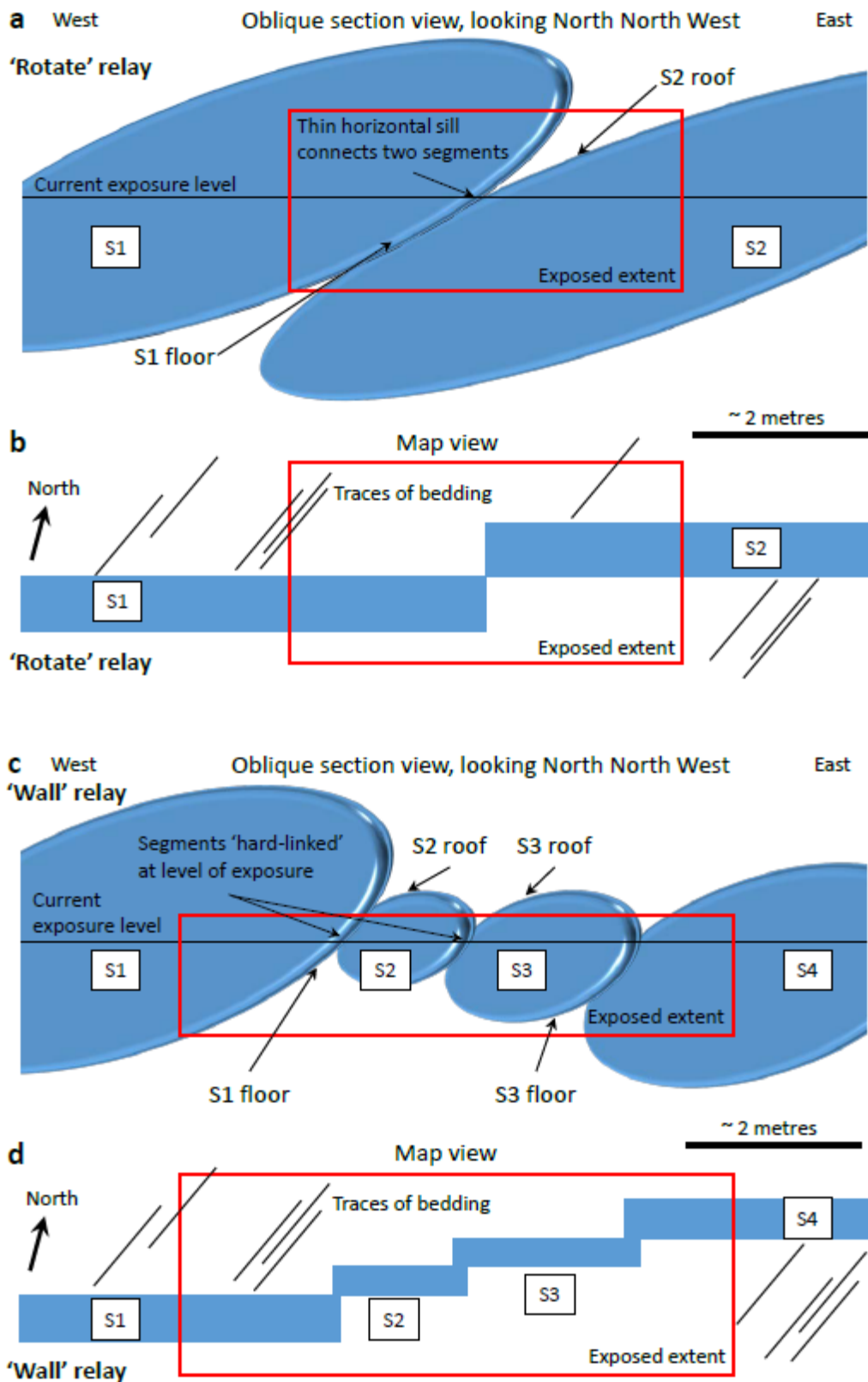
381

382 Interpretations

383 *Dykes (away from relays and jogs)*

384 The mineralogical and textural variations observed in thin section provide clues for the likely
 385 viscosity, temperature and density of the magma that solidified in these dykes. The abundance
 386 of amphibole and the deuteric alteration of olivine to serpentine suggest that the melt was rich
 387 in H₂O. The presence of primary Mn-rich calcite and dolomite suggest the presence of
 388 significant quantities of CO₂. In this preliminary analysis of the composition and physical
 389 properties, we infer that the magma was therefore relatively low temperature (< 1000°C) and
 390 low density (< 2600 kg m⁻³) and therefore low viscosity. Further work is underway to quantify
 391 the modal proportions of the relevant phases and place tighter bounds on the crystallisation
 392 history and the evolution of physical properties.

394 The field evidence from the dyke relays at Birsay shows neighbouring segments with either a
395 clear roof or floor, all dipping at shallow angles (about 20°) towards the West. Using these
396 observed dip angles and the measured (apparent) length of the *en echelon* segments at the
397 present level of erosion, we can estimate the segment height as apparent length x sin(dip of
398 roof or floor). With a maximum segment apparent length of 50 metres, this simple formula
399 yields an upper bound estimate of segment height = $50 \times \sin(20) = 17$ metres. Therefore, these
400 segments are much longer than they are high. The juxtaposition of a segment floor and a
401 segment roof at each relay (Figure 13a, c) implies that either a) the dyke segments are stepping
402 down topographically to the East, or b) that the segments themselves are tilted with their long
403 axes (parallel to segment strike) plunging at shallow angles to the West. The wave cut platform
404 at Birsay is essentially at, or very close to, sea level: there is no significant topographic variation.
405 Therefore, it seems most likely that the segments are tilted at a shallow angle to the West and
406 step down stratigraphically through the NW dipping host rock sequence, while maintaining a
407 broadly constant level within the crust. The observed floor and roof contacts all dip at low
408 angles to the WSW, W or WNW: there are no observations of steeply plunging segment tip-lines
409 as would be expected in the model of Delaney & Pollard (1981) for a vertically propagating
410 dyke with a segmented upper edge. Based on our field observations at Birsay, we consider the
411 individual dyke segments to be broadly ellipsoidal in outline, with their lengths \gg heights \gg
412 widths, and their long axes tilted towards the West (Figure 13). Connectivity between segments
413 is maintained through thin sills and pipes observed at the relays, which are therefore 'hard-
414 linked' in the parlance of fault relay zones (reference). While individual segments vary in size
415 and aspect ratio, the overall pattern is consistent with the segments maintaining a constant
416 structural level within the dipping stratigraphy. The Birsay dykes appear to be segmented from
417 top to bottom i.e. the whole vertical extent of the dyke is segmented, and these segments do not
418 merge downwards into a continuous sheet. The orientation of the dyke segments with respect
419 to the bedding implies that the host rocks were tilted (i.e. folded) prior to dyke emplacement:
420 this is consistent with regional interpretations of sedimentary basin inversion in the
421 Carboniferous (Marshall et al., 1985; Parnell, 1985).



422

423 **Figure 13.** Summary models of field observations from the relays and their interpretations. **a-**
 424 **b)** Schematic idealised section and map view of the 'Rotate' relay, with the segments modelled
 425 as two thin ellipsoidal sheets, oriented with their longest axes inclined to the horizontal, and
 426 steeply dipping to the South. In the section view, S2 is further back (North) than S1. The red box
 427 denotes the region covered by Figure 6. The location of the thin connecting sill (not shown) is
 428 marked. The close juxtaposition of a shallow dipping floor and a roof contact is clearly shown,

429 at the current level of exposure. **c-d**) Schematic idealised section and map view of the 'Wall'
430 relay, with the segments modelled as four thin ellipsoidal sheets, oriented with their longest
431 axes inclined to the horizontal, and steeply dipping to the South. In the section view, segments
432 S2-S4 step back (to the North). The red box denotes the region covered by Figures 7-8. The
433 close juxtaposition of multiple shallow dipping floor and roof contacts is clearly shown, at the
434 current level of exposure.

435 *Joints*

436 The dyke segment margins are seen to be parallel to the ENE trending joints, with some of these
437 joint traces deflected and truncated by dyke contacts at their tips. It is thus tempting to infer
438 that the ENE trending joints pre-date dyke emplacement. However, the scan line data across
439 Dyke 1 (Figure 11) and qualitative observations from the other dykes shows that fracture
440 intensity increases alongside the dyke segment margins. This would suggest a genetic
441 relationship between the dyke emplacement and the formation of at least some of the ENE
442 joints. We speculate that the dykes were emplaced into pre-existing ENE trending joints, and
443 the thermal impact of the dyke promoted margin-parallel hydrofractures in water-saturated
444 sedimentary rocks. Note also that the overall left-stepping geometry of the segments in all three
445 dykes implies a component of right-lateral shear during emplacement. We infer that the
446 minimum horizontal stress was oriented approximately NW/SE during dyke emplacement,
447 promoting oblique extension (transtension) of the pre-existing ENE joint set. It is noteworthy
448 that joint frequency is not high in the host rocks immediately adjacent to the segment floor and
449 roof contacts, a point also made by Gudmundsson (1983) for dykes in Iceland. This has
450 implications for the mode of propagation of each segment within its own plane, and discussed
451 below in relation to mechanical models.

452 The westernmost segment of Dyke 0 East displays clear examples of intra-dyke joints, with
453 numerous shallow West dipping fracture planes, many with a concave-up geometry. We
454 interpret these as internal contacts separating batches of solidified magma emplaced upwards
455 at a shallow angle from the WSW towards the ENE. Less well-developed examples occur
456 throughout segments of Dyke 1 and Dyke 2.

457 *Vesicles*

458 The paired trains of inequant oriented vesicles shown in Figure 12 are interpreted as shear
459 zones, marginal to a flowing central core of magma in this segment moving from the WSW to
460 the ENE. The lack of any significant asymmetry of vesicle long axis orientations in the vertical
461 plane implies this flow was dominantly horizontal at this locality. At other locations in Dykes
462 1 and 2, some apparent 'vesicles' could be weathered out phenocrysts. Nevertheless, their
463 inequant form and systematic asymmetry over paired trains either side of the median line leads
464 to the same conclusion: sub-horizontal magma flow from WSW towards ENE.

465

466 **Discussion**

467 *Dyke segment and relay geometry*

468 Exposures of dyke relay zones at Birsay display shallowest dipping floor and roof contacts of
469 neighbouring dyke segments. None of the observed segment tip contacts is steep (i.e. dipping
470 or plunging $> 45^\circ$, see Figure 1). The observed geometry is therefore inconsistent with the
471 classical model of Delaney & Pollard (1981), with a segmented 'fringe' above a continuous dyke
472 at depth. Previous work on laterally emplaced, depth-restricted silicic dykes described a form
473 of segmentation along the upper edge of a continuous dyke at depth (Poland et al., 2008; their
474 figure 8), but the segment tip-lines are shown as steepening into the continuous deeper sheet.
475 This is also inconsistent with the observations from Birsay. The repeated juxtaposition of
476 consecutive segment floor and roof contacts in the dyke relays at Birsay suggests that each dyke
477 segment, and therefore the dyke as a whole, is depth-restricted – i.e. maintaining a more or less
478 constant depth within the crust. While the dyke segments cut down stratigraphy to the ENE,
479 the host rocks were already tilted at the time of intrusion in the late Permian and the dykes are
480 maintaining the same depth within the upper crust.

481 Connections between the segments have been observed at most of the dyke relays. The
482 geometrical form of these connecting bodies varies from thin (few cm thick) sills to steeper
483 tubular pipes. All segments in a given dyke must have been connected at some point, although
484 some pathways might close as magma pressure wains during drainback events (see below).
485 The dyke relays at Birsay are generally 'hard-linked' in the parlance of fault relays – the
486 segments are visibly joined by connecting bodies of dyke material. Many of these connecting
487 bodies are small in relation to the neighbouring segment size. We speculate that the inferred
488 low viscosity of this alkaline, volatile-rich (H_2O and CO_2) magma may have been critical in
489 facilitating sufficient flow through narrow apertures.

490 The outcrops at Birsay display a wide variety of segment tip geometries, with none of the relays
491 showing identical morphologies (compare Figure 6, 7 and 10). Tip shapes include blunt,
492 pointed or rounded, some with horn-like apophyses or multiple sheet-like fingers. We
493 speculate that this may be due in part to the varied mechanical stratigraphy of the thinly bedded
494 host rock sequence. Most beds are a few tens of centimetres thick and therefore, at the present
495 level of erosion, every segment tip is in a slightly different lithology of different thickness. This
496 lithological variation has consequences for the local fracture toughness that may control tip
497 propagation (e.g. Hoek, 1994). Further work is in progress to quantify these mechanical
498 variations in relation to the range in observed tip geometry.

499 *Magma source and emplacement direction*

500 A range of indicators suggest that the dykes propagated from the WSW towards the ENE,
501 including:

- 502 • segment thicknesses within all three dykes decrease towards the ENE;
- 503 • asymmetry of long axes in paired trains of inequant and oriented vesicles imply that the
504 central cores of dyke segments flowed sub-horizontally and from WSW to ENE;
- 505 • shallow West-dipping, concave up internal joints, interpreted as internal contacts,
506 suggest magma emplacement from slightly deeper in the WSW upwards and along
507 towards the ENE.

508 This suggests a deeper source of magma towards the WSW, i.e. offshore mainland Orkney and
509 buried in the West Orkney Basin. Gravity surveys of the region are consistent with higher
510 density, possibly magmatic, material lying immediately offshore to the WSW of mainland
511 Orkney (Kimbell & Williamson, 2016; their figure 6).

512 *Comparison to modern volcanic systems*

513 Seismological and geodetic data from modern volcanic systems have been used to infer later
514 emplacement of magma for tens of kilometres away from erupting volcanoes. The 2014
515 sequence at Bardabunga-Holuhraun on Iceland has been documented by Agustsdottir et al.
516 (2016), and shows seismic activity extending 48 km away from the source and depth restricted
517 to between 3 and 7 km. The base to these events is sharper than the top, suggesting some kind
518 of depth control on emplacement. Fissure eruptions occurred at intervals along the length of
519 this activity. The seismic events are clearly clustered in space and time (Agustsdottir et al.,
520 2016; their figure 1), and these probably represent discrete segments of the larger dyke.

521 The most recent activity at Kilauea on Hawaii (starting 30th April 2018) also produced
522 spectacular fissure eruptions at the surface in the Lower East Rift Zone, following deflation at
523 the Kilauea vent. The temporal sequence of these eruptions is generally down-rift, but with
524 occasional jumps back towards the Kilauea vent (USGS Hawaiian Volcano Observatory, 2018).
525 The surface fissures are arranged *en echelon* striking ENE, and are generally left-stepping.
526 Compilations of seismological, geodetic and field data from the longer term, combined with
527 mechanical analysis, have generated a detailed model for the sub-surface of Kilauea (Ryan,
528 1988; his plate 1). The intrusions underlying the East Rift Zone are shown with a clear and
529 sharp base. We speculate that the internal structure of this intrusion may resemble the
530 segmented dykes at Birsay, albeit on a much larger scale.

531 Previous activity at Krafla on Iceland in 1977 displayed many similarities to the patterns
532 described above: lateral migration of seismic activity away from a deflating main vent, with the
533 events restricted to a narrow depth range (3-6 km; Brandsdottir & Einarsson, 1979). A
534 potentially significant point to emerge from all of these studies, and made by Delaney & Pollard
535 (1981), is that magma undergoes flow reversals, so-called 'drainback' events, during these
536 periods of activity. For dykes preserved in the geological record this means that flow indicators
537 from fabrics measured in dykes (vesicle or phenocryst orientations, or anisotropy of magnetic
538 susceptibility) may be highly variable, and therefore unreliable in trying to discriminate lateral
539 from vertical emplacement. Analysis of the *geometrical* attributes of the dyke segments and
540 their relationships in dyke relays, as in the current study, provides an alternative strategy.

541 *Physics of lateral dyke emplacement*

542 A mechanical model for the lateral emplacement of dykes at constant depth in the crust has
543 recently been described by Townsend et al. (2017), building on previous work by Rubin &
544 Pollard (1987) and Rubin (1995). The emplacement at a specific depth depends on a subtle
545 interplay between the magma driving pressure (magma pressure minus the dyke-normal
546 remote stress), the fracture toughness of the host rocks (K_c), the stress intensity factors at the
547 dyke (segment) top, bottom and lateral tips, and the density structure of the crust. Considering

548 the Birsay dyke segments as thin blade-like ellipsoids in 3D, with low heights (< 20 metres) in
549 relation to their lengths (50 metres), vertical gradients in either magma pressure or in dyke-
550 normal horizontal stress are unlikely to be significant. Similarly, variations in K_c are not likely
551 to be significant in these thinly-bedded cyclic sedimentary rocks.

552 Field evidence suggests that the dyke segments were emplaced into pre-existing joints, albeit
553 with some local enhancement of joint frequencies at the segment lateral margins. The current
554 geometry is therefore a function of this original joint pattern. The mechanics of joint formation
555 is likely different from magma-filled crack propagation, especially for these 'dry'
556 (unmineralised) joints. We infer that the driving pressure from magma emplacement did not
557 achieve stress intensity factors at the pre-existing joint tip-lines sufficient to propagate them
558 further, consistent with the evidence that the host rocks immediately adjacent to the floor and
559 roof contacts of the segments are not noticeably fractured. Joints of the ENE trending were
560 passively inflated, and as these were slightly mis-oriented with respect to a minimum
561 horizontal stress (σ_h) aligned NW/SE, magmatic connections along the NNE trending joint set
562 and/or bedding planes were exploited to 'correct' the overall dyke path towards the NE (i.e.
563 perpendicular to σ_h). On a larger crustal scale, the Devonian (lacustrine) host rocks may
564 constitute a relatively low density layer bounded below by higher density 'Caledonised'
565 basement (Strachan, 2003), and above by higher density sand-rich (fluvial) Carboniferous
566 rocks (Marshall et al, 1985; Parnell, 1985). This may explain the relative abundance of Permian
567 dykes in the Devonian of Orkney and Caithness. Further work is underway to quantify the likely
568 viscosity, density and temperature of the alkaline, volatile-rich magma in these dykes to
569 provide better constraints on the mechanics of their emplacement.

570 *Implications for other dyke systems*

571 The observed geometry of the segmented dykes at Birsay has implications for the analysis and
572 interpretation of dykes in other areas. The British Palaeogene Igneous Province (BPIP)
573 contains many basaltic dykes spread over much of northern and western Scotland, many of
574 which are clearly related to discrete central complexes (Emeleus & Bell, 2005). Work is under
575 way to analyse selected dyke segment relay zones to map out the geometry of the tip-lines.
576 Dyke suites are critical markers for geologists working in high-grade gneiss terrains, such as
577 the Lewisian Complex of Scotland. The Scourie dyke suite has been used to separate earlier
578 (Badcallian, Inverian) from later (Laxfordian) structural and metamorphic events in the mid-
579 crust (see Wheeler et al., 2010 for a recent review). Considering these as originally segmented,
580 depth-restricted and laterally emplaced might change some of the structural and tectonic
581 interpretations in these rocks. Igneous systems like the BPIP contain networks of dykes and
582 sills now preserved in offshore sedimentary basins (e.g. Wall et al., 2010; Schofield et al., 2012).
583 Imaging of sub-vertical dykes has long been a problem in seismic reflection data, but insights
584 from our work at Birsay combined with the mechanical models for lateral dyke emplacement
585 (Townsend et al., 2017) suggest that seismic processing to image these intrusions might best
586 be concentrated in the lower density intervals within the stratigraphy.

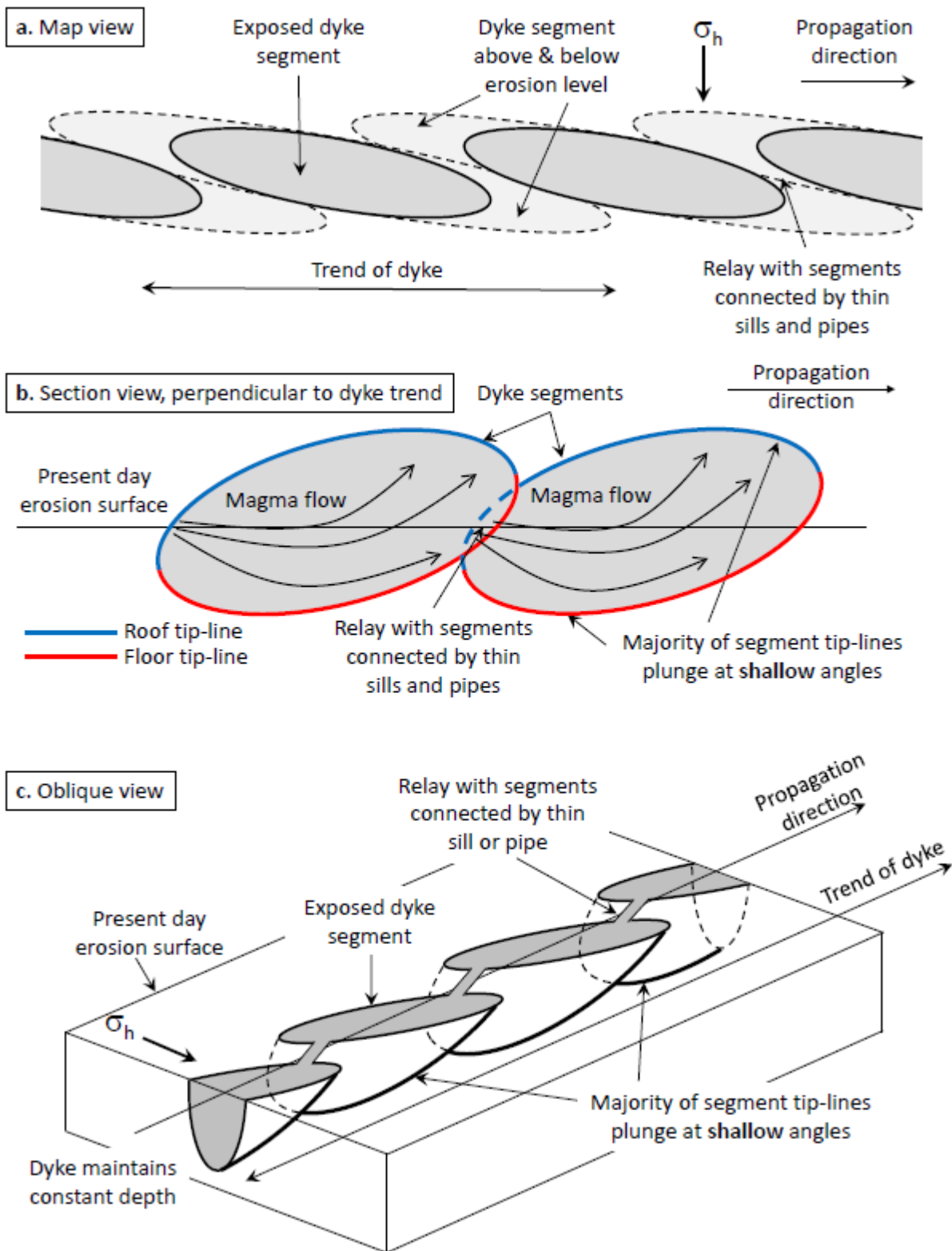
587

588 **Summary**

589 We have presented detailed field evidence for the lateral emplacement of segmented
590 camptonite dykes at Birsay (Orkney, UK). We show that:

- 591 • the exposed segments are juxtaposed in relay zones, with shallow W dipping floor and roof
592 contacts;
- 593 • there is no evidence for these segments merging downwards into a continuous sheet at
594 depth;
- 595 • the dykes are segmented over their whole vertical extent, and can be visualised as oblate
596 ellipsoidal sheets with lengths \gg height \gg width;
- 597 • the segments must be tilted in relation to the present day surface, with their strike-parallel
598 long axes dipping at shallow angles (10-20 degrees) towards the West;
- 599 • the dykes overall therefore maintain a roughly constant structural level within the dipping
600 stratigraphy.

601 At the relays between adjacent dyke segments, the orientations and geometrical relationships
602 of the exposed segment roof and floor contacts strongly suggest that, at least in this region, the
603 dykes were not propagating vertically from below. Instead, the dominant direction of dyke
604 propagation and magma flow was sub-horizontal from WSW to ESE. Thus, the presence of *en*
605 *echelon* dyke segments does not necessarily imply downward connection to a continuous
606 vertically propagating dyke at depth (Delaney & Pollard, 1981). The observed and measured
607 orientations of the segment tip lines – the floors and roofs of the individual segments – are
608 critical in this regard.



609

610 **Figure 14.** Summary diagrams of a new geometrical model for lateral dyke emplacement based
 611 on field evidence at Birsay. **a)** Schematic map view showing discrete *en echelon* dyke segments
 612 (grey) and their inferred extent above and below the current exposure level (light grey).
 613 Connecting sills, dykes and pipes in the relay zones are omitted for clarity, as, based on the
 614 evidence from Birsay, they are much smaller than the segments they connect. σ_h denotes the
 615 inferred orientation of the minimum horizontal stress at dyke emplacement, perpendicular to

616 the overall dyke trend. **b)** Oblique section view showing the dyke segment floor and roof tip-
617 lines (red and blue, respectively), and their close juxtaposition in the exposed relay zone. Note
618 that the majority of the floor and roof tip-lines plunge at shallow angles. The segment long axes
619 are inclined to the horizontal to produce relay zones with the floor of one segment juxtaposed
620 with the roof of the next segment. Schematic flow lines show the inferred direction of magma
621 emplacement. **c)** Schematic oblique 3D view of multiple *en echelon* segments and their relays.
622 Note that the dyke is segmented over the whole vertical extent, and maintains a constant depth.
623 σ_h denotes the inferred orientation of the minimum horizontal stress at dyke emplacement,
624 perpendicular to the overall dyke trend.

625 Our observations provide *prima facie geometrical* evidence for lateral dyke emplacement that
626 complements existing seismological and geodetic data from modern volcanic systems and
627 fabric data (vesicle, phenocryst or palaeomagnetic) from outcrops of older dykes. The lateral
628 emplacement of segmented, depth-restricted dykes has consequences for geological
629 interpretations of seismic reflection data in sedimentary basins and for those trying to unravel
630 complex polyphase structural and metamorphic histories in basement gneiss regions. Careful
631 field observations of segmented dykes in other regions will provide important insights for the
632 next generation of 3D physical models of dyke emplacement.

633

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639

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