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1 Asymmetric growth of strike-slip faults controlled by 3D fault
2 structure: insights from the M_W 7.8 2023 Kahramanmaraş
3 (Turkey) earthquake

4

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13

14 **ABSTRACT**

15 The reactivation of deep-seated, throughgoing strike-slip faults produces highly segmented
16 fault zones at shallower levels, yet how displacement is partitioned among segments as the fault
17 grows remains poorly constrained. We address this by examining a ~160 m long section of the
18 East Anatolian Fault surface rupture of the M_W 7.8 2023 Kahramanmaraş strike-slip earthquake.
19 The rupture offsets meter-spaced ridges and furrows in a ploughed field providing a unique
20 opportunity for detailed displacement measurements, which were obtained from an orthophoto and
21 a DEM built for this study. The surface rupture consists of ten primary segments separated by nine
22 restraining stepovers and is associated with a 3D strain field dominated by ~3.5 m of left-lateral
23 offset. Displacement patterns allow us to derive a new model for strike-slip fault growth in which

24 deformation is asymmetric and controlled by the 3D structure of the fault - specifically, by the
25 position of the underlying fault relative to shallow fault segments. Initially, displacement is
26 accommodated by contraction within restraining stepovers. With increasing displacement, fault
27 segments located closer to the trace of the underlying fault consistently accumulate greater
28 displacement. This asymmetry is facilitated by enhanced synthetic rotation within stepovers. With
29 further displacement, the higher-displacement segment bounding a stepover becomes dominant,
30 while the other one is bypassed and layer rotation ceases. These results not only improve fault
31 growth models but could also inform seismic hazard models and impact industrial applications
32 dealing with subsurface faulted reservoirs.

33

34 INTRODUCTION

35 Modelling and experimental studies, along with field observations of earthquake surface
36 ruptures indicate that the reactivation of a deep-seated, throughgoing strike-slip fault typically
37 leads to the development of a highly segmented fault zone at shallower levels (Cloos, 1928; Riedel,
38 1929; Tchalenko, 1970; Tchalenko and Ambraseys, 1970; Wilcox et al., 1973; Bartlett et al., 1981;
39 Naylor et al., 1986; Swanson, 2006; Lin and Nishikawa, 2011; Dooley and Scheurs, 2012; Quigley
40 et al., 2012; Ren et al., 2021; Yuan et al., 2022; Meng et al., 2024; Karabacak et al., 2023).

41 Most descriptions of these segmented faults agree on the following key characteristics
42 about their geometry and growth. At the outset, the fault consists of multiple *en-echelon* segments
43 known as Riedel (R) shears, forming a low angle to the strike of the underlying fault, and sharing
44 its sense of shear (**Fig. 1A**). Serial cross-sectioning (Naylor et al., 1986) and CT scanning (Richard
45 et al., 1995; Ueta et al., 2000; Yang et al., 2017) of analogue models suggest that R shears splay
46 upward from the underlying fault in a helicoidal 3D geometry (**Fig. 1A**). Overlapping R shears

47 bound restraining zones, often referred to as restraining stepovers (**Fig. 1A**; Swanson, 2006;
48 Pennacchioni and Mancktelow, 2013). With accumulating displacement, adjacent R shears link
49 via P shears, also sharing the same sense of offset as the underlying fault but crossing it in the
50 opposite direction of R shears (**Fig. 1B**), giving rise to a braided fault zone. Ultimately,
51 displacement localizes onto a single fault that approximately coincides with the trace of the
52 underlying fault.

53 Although this geometric evolution is well established, how displacement is partitioned
54 among fault segments prior to localization, and the factors that control that partitioning, remain
55 poorly constrained. This reflects the scarcity of natural and experimental examples where strike-
56 slip faults intersect markers suitably oriented and spaced for detailed displacement measurements
57 (see Peacock, 1991, and Pennacchioni and Mancktelow, 2013, for exceptions to this). Filling this
58 knowledge gap is crucial, as it can provide fundamental insights into how faults grow from
59 distributed to localized deformation.

60 We address this by examining a ~160 m long section of the surface rupture of the $M_w7.8$
61 February 6, 2023 Kahramanmaraş earthquake in south-east Turkey (Karabacak et al., 2023;
62 Petersen et al., 2023; Reitman et al., 2023). The rupture is highly segmented and spectacularly
63 offsets at high angle meter-spaced, sub-parallel ridges and furrows in a ploughed field (**Fig. 2A,**
64 **B**), enabling exceptionally detailed displacement measurements.

65

66 **THE FEBRUARY 6, 2023 KAHRAMANMARAŞ EARTHQUAKE(S)**

67 On February 6, 2023, south-east Turkey and north Syria were struck by two major
68 earthquakes ($M_w7.8$ and $M_w7.6$) occurring ~9 hours apart (Karabacak et al., 2023; Karabulut et
69 al., 2023; Ozkan et al., 2023; Petersen et al., 2023; Reitman et al., 2023; Toker et al., 2023),

70 resulting in over 50000 fatalities. These events involved the reactivation of the East Anatolian left-
71 lateral strike-slip fault system (EAFS), the transform plate boundary between the Anatolian and
72 Arabian plates (Duman and Emre, 2013; **Fig. 2A**). This study focuses on the first, M_w 7.8
73 earthquake which had its epicenter near the primary strand of the EAFS, and developed a surface
74 rupture ~300 km long, with maximum left-lateral displacement of ~7 m (Karabacak et al., 2023;
75 Liu et al., 2023; Meng et al., 2024; Ozkan et al., 2023; Reitman et al., 2023; Toker et al., 2023).
76 The study area locates ~2km SE of the city of Türkoğlu (Turkey), ~20 km west of the epicenter
77 (**Fig. 2A**). There the fault is ~NNE-SSW-striking and aftershock focal mechanisms indicate a
78 component of co-seismic transtension, as opposed to north of Türkoğlu, where the fault strikes
79 NE-SW strike and accommodated more purely strike-slip motion (Petersen et al., 2023).

80

81 **DATA AND METHODS**

82 The surface rupture was analyzed using a Digital Elevation Model (DEM) and an
83 orthophoto built for this study from a ~25-second drone video acquired on February 11, 2023, five
84 days after the earthquake. Together, these datasets allowed us to characterize the 3D (i.e., non-
85 plane) strain field, comprising horizontal and vertical displacement components.

86 The aggregate horizontal component was quantified from the orthophoto as the sum of left-
87 lateral separation of ridges and furrows in the ploughed field across fault segments (hereafter
88 referred to as ‘horizontal displacement’) and synthetic (i.e., anticlockwise) rotation of ridges and
89 furrows within stepovers occurring about a sub-vertical axis. The vertical component (hereafter
90 referred to as ‘vertical displacement’) was measured from the DEM as the vertical separation
91 relative to the undeformed ploughed field, which served as a 0-m elevation reference. The DEM

92 resolution (8.66 cm/pixel) provides a relative accuracy of $\sim 2\text{--}3$ cm, which we take as the
93 uncertainty of our horizontal and vertical displacement measurements.

94 Finally, a best-fit line through the midpoints between the boundaries of the surface rupture
95 was used as a proxy for the surface trace of the underlying fault. An extended description of data
96 and methods is provided in the Supplemental Material.

97

98 **GEOMETRY AND DISPLACEMENT PATTERNS OF THE SURFACE RUPTURE**

99 The surface rupture comprises ten primary fault segments (A–J) separated by nine
100 stepovers (S1–S9; **Fig. 2C**). Most stepovers occur as fault-bound lenses, forming a braided fault
101 configuration. The sigmoidal geometry of bounding segments (**Fig. 2C**) and their orientation
102 relative to the surface trace of the underlying fault (dashed gray line in **Fig. 2C**) suggest they
103 formed through linkage of R shears via P shears (**Fig. 1**). Intersections between adjacent segments
104 are classified as Y-zero and Y nodes (e.g., Manzocchi, 2002), based on whether displacement at
105 that location is null or not; isolated nodes are termed tip points. The positioning of Y-zero nodes
106 and tip points consistently indicates *en-echelon*, right-stepping geometry. Given the left-lateral
107 sense of movement of the fault, all stepovers are restraining.

108 The horizontal component of displacement yields an average aggregate value of ~ 3.5 m
109 (**Fig. 2D**), consistent with nearby field (3.3–3.8 m; Karabacak et al., 2023) and seismological
110 (Toker et al., 2023) estimates. Two stepover groups were recognized based on the distribution of
111 horizontal displacement. Stepovers S1, S4, S7, and S9 are bound by segments that exhibit inversely
112 increasing displacements and null-displacement points (Y-zero nodes or tips) on opposite stepover
113 sides (**Fig. 2C**). For example, at S1, segment A increases in displacement SW-ward from its tip
114 point to ~ 3.5 m beyond the stepover, whereas segment B shows a complementary NE-ward

115 increase (**Fig. 2B, C**). Displacement gradients are asymmetric - one segment shows a steeper
116 gradient and larger horizontal displacement at the stepover center (e.g., displacement gradient, and
117 amount of horizontal displacement at the center of S1, are larger for A than for B). Synthetic
118 rotation also increases toward the tip of the higher-gradient segment, as at S9, where segment I has
119 a larger displacement gradient than segment J, and synthetic rotation reaches its maximum
120 magnitude value of ~ 1 towards the tip of segment I (**Fig. 2D**). Conversely, stepovers S2, S3, S5,
121 S6, and S8 are bound by one segment ending in a Y-zero node/tip point and another ending in a Y
122 node on opposite sides (**Fig. 2C**). For instance, at S8, segment H increases in displacement
123 southwestward from its Y-zero node, while segment I increases northeastward but retains ~ 1.7 m
124 displacement at its Y node (**Fig. 2C**). In these cases, maximum values of horizontal displacement
125 and rotation occur near the Y node side of the stepover (**Fig. 2D**).

126 In all stepovers, the bounding segment with the larger horizontal displacement locates
127 closer to the surface trace of the underlying fault (**Fig. 2C**). This relationship is shown in **Fig. 3**,
128 where segment distance from the trace of the underlying fault (D left and D right) and horizontal
129 displacement (HD left and HD right) are plotted for each stepover; all measures were taken at the
130 center of each stepover. In every case, smaller distance to the underlying fault corresponds to larger
131 horizontal displacement, and vice versa (**Fig. 3**).

132 Vertical displacement is highly subordinate to the aggregate horizontal displacement
133 (maximum value of ~ 20 cm is $\sim 5\%$ of the maximum aggregate horizontal displacement, ~ 4 m;
134 **Fig. 2E**) and is localized and restricted to uplift within restraining stepovers, the larger of which
135 (~ 20 cm) occurs within stepover S1 (**Fig. 2E**).

136 A final deformation component consists of open fissures developed along the length of
137 some fault segments due to their 'opening' in a direction nearly perpendicular to the segment

138 strike; examples occur along segment I, segment H to the SSW of stepover S8, and segment F to
139 the SSW of stepover S6 (**Fig. 2B**).

140

141 **DISCUSSION AND IMPLICATIONS**

142 Building on the displacement patterns described above, we further develop the strike-slip
143 fault growth model in **Fig. 1** by incorporating both horizontal and vertical components of
144 displacement. Open fissures are not included, as we interpret them as local features that either
145 accommodate the extensional component of the transtensional co-seismic strain affecting this
146 portion of the EAFS (Petersen et al., 2023) or form due to reduced confinement at the free surface.
147 In both cases, they can be considered deformation components not intrinsic to strike-slip fault
148 growth. Although the linkage between surface segments and the underlying fault cannot be directly
149 imaged here, by analogy with previous studies (e.g., Naylor et al., 1986), we interpret the segments
150 to connect downward to the deeper fault (**Fig. 4**); even if they were physically disconnected, their
151 systematic *en-echelon* arrangement and consistent sense of stepping strongly suggest structural
152 control by the underlying fault; thus, the interpretation presented below would remain valid.

153 In our interpretation, the fault initially comprises R shears that, where overlapping, bound
154 restraining stepovers (**Fig. 1A**). As displacement accumulates, we identify three successive
155 evolutionary stages (**Fig. 4**). At first, displacement gradients toward the tip points of R shears are
156 accommodated through contraction confined within restraining stepovers (**Fig. 4A**). With
157 increased displacement, adjacent R shears link through the development of P shears at Y-zero
158 nodes. The resulting sigmoidal segment located closer to the trace of the underlying fault begins
159 to accrue more displacement than the other, developing a larger displacement gradient towards its
160 Y-zero node (**Fig. 4B**). This produces an asymmetric displacement deficit within the stepover,

161 greatest toward the tip of the higher-displacement segment (**Fig. 4B**) and is compensated by
162 synthetic layer rotation. For ease of description, contraction and layer rotation are here described
163 as successive processes although they may also operate simultaneously. With further displacement,
164 the segment with larger displacement gradient becomes dominant, and its Y-zero node evolves
165 into a Y node. Beyond this point, rotation stops and displacement localizes on the higher-
166 displacement segment, while the adjacent segment bypassed (i.e., ‘dead’; **Fig. 4C**).

167 This new model demonstrates that strike-slip faults grow asymmetrically and that this
168 asymmetry is fundamentally controlled by the 3D structure of the fault – i.e., the position of the
169 underlying throughgoing fault relative to shallow fault segments. Beyond enhancing fault growth
170 models, these results also improve understanding of surface rupture development in active regions.
171 Surface ruptures represent major geohazards and are widely designated as ‘capable faults’ in
172 regulatory frameworks (e.g., IAEA, 2010). The ability to anticipate where the segment with the
173 largest displacement is most likely to develop at the surface (given knowledge of the position of
174 the pre-existing underlying fault) can help refine seismic-hazard assessment models (e.g., Piccardi
175 et al., 2017; Bonini et al., 2025). These results may also have implications on the management of
176 subsurface faulted reservoirs (e.g., Sun et al., 2023). In particular, given knowledge of the 3D
177 geometry of a strike-slip fault (e.g., from 3D seismic reflection data), these results can help predict
178 how displacement is distributed among fault segments even in the absence of clear displacement
179 markers. This, in turn, can improve the identification of zones where higher strain and block
180 rotation are expected, which may correspond to regions of enhanced fracturing and damage that
181 could facilitate fluid flow.

182

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188 his distinguished career and recent retirement.

189

190 **FIGURE CAPTIONS**

191

192 **Figure 1.** Structure and evolution of strike-slip faults with displacement accrual. **A:** segmented
193 stage with *en-echelon* Riedel (R) shears (after Naylor et al., 1986); **B:** linkage stage where adjacent
194 R shears connect via P shears. Segments splay upward from a throughgoing fault in a helicoidal
195 3D geometry.

196

197 **Figure 2.** Section of the East Anatolian Fault surface rupture produced by the Mw 7.8 2023
198 Kahramanmaraş earthquake, near Türkoğlu (Turkey). The surface rupture offsets at high angle,
199 meter-spaced ridges and furrows in a ploughed field. **A:** Simplified tectonic map (modified after
200 Liu et al., 2023) of the February 6, 2023 Kahramanmaraş earthquake doublet - surface ruptures
201 (red lines) are from Reitman et al., 2023, and focal mechanisms from United States Geological
202 Survey, Earthquakes (USGS, 2023; <https://usgs.gov/programs/earthquake-hazards/earthquakes>).
203 Inset rectangle (Google Maps image) locates the study area in a broader portion of the surface
204 rupture; **B:** Orthophoto of the surface rupture; **C:** map of the rupture. Colored bands correspond to
205 single or grouped ridges and furrows correlated across the surface rupture. Names of segments (A
206 to J) are on the left side of the segment they refer to. S1 to S9 are stepover names. The dashed grey

207 line along the surface rupture strike corresponds to the calculated surface trace of the underlying
208 fault (see also Supplemental Material); **D**: profiles of horizontal displacement (left-lateral
209 displacement, and synthetic rotation expressed as the displacement-equivalent produced by
210 ridges/furrows anticlockwise rotation within stepovers), sub-horizontal grey dashed lines across **C**
211 and **D** indicate the center of each stepover. All markers used for measurements and the data are
212 provided in **Fig. S4**; **E**: DEM of the surface rupture.

213

214 **Figure 3.** Plot showing, for each stepover (S1 to S9): i) the distance of its left (D left) and right (D
215 right) bounding segments from the surface trace of the underlying fault (see **Fig. 2C**); ii) the
216 horizontal displacement on the left (HD left) and the right (HD right) segments. Measures of
217 distance and displacement were taken at the center of each stepover (see **Fig. 2**). In all cases, a
218 shorter distance of a segment from the trace coincides with its larger horizontal displacement, and
219 vice versa.

220

221 **Figure 4.** Asymmetric strike-slip fault growth model illustrated for the stepover of **Fig. 1**. For each
222 stage, a schematic profile of horizontal displacement is provide. **A**: contraction within the stepover;
223 **B**: linkage of R shear via P shears; enhanced displacement on the segment nearer the trace of the
224 underlying fault causes an asymmetric displacement deficit within the stepover compensated by
225 synthetic layer rotation; **C**: the higher-displacement segment becomes dominant while the other is
226 bypassed and rotation ceases.

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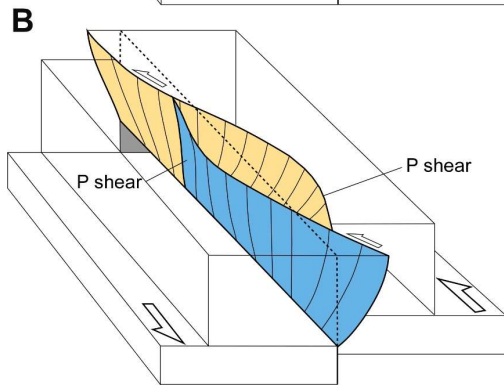
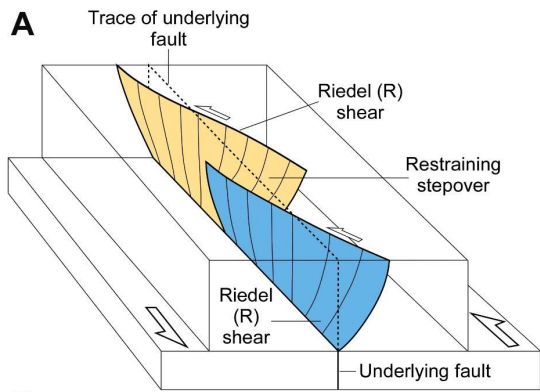
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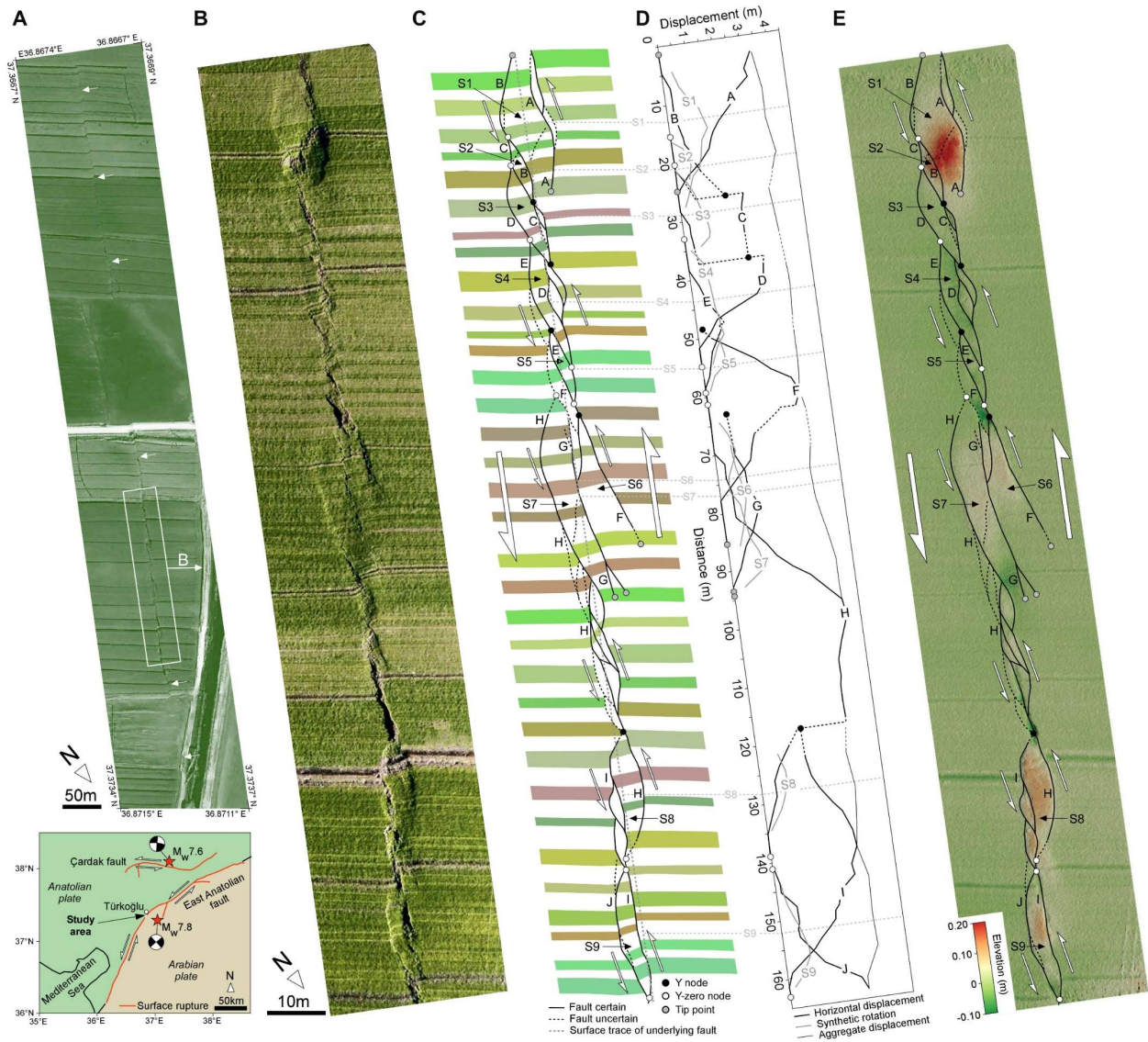


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375 **Figure 1**

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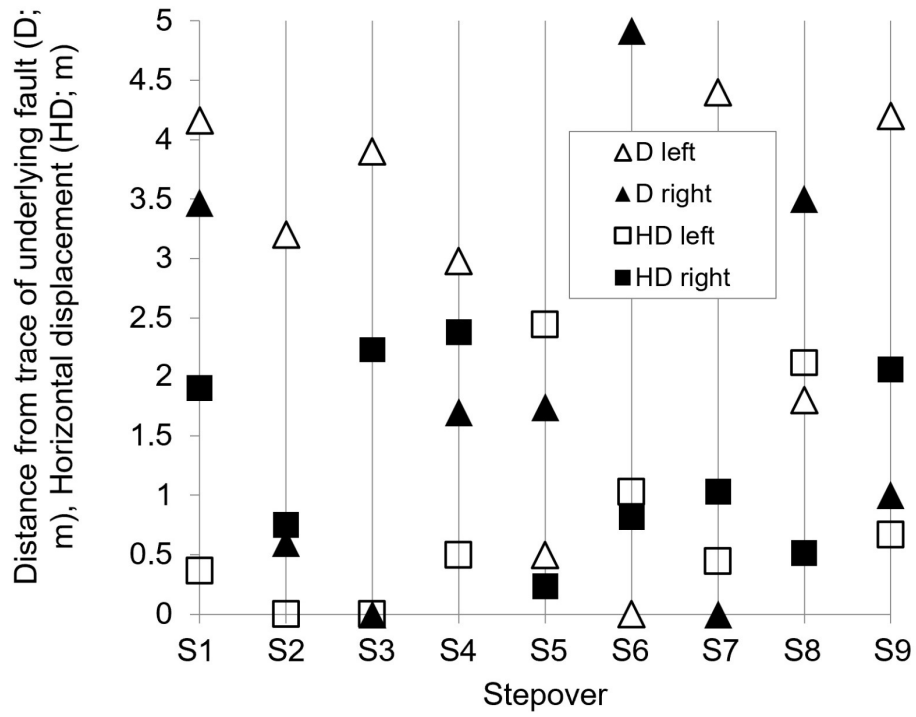


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379 **Figure 2**

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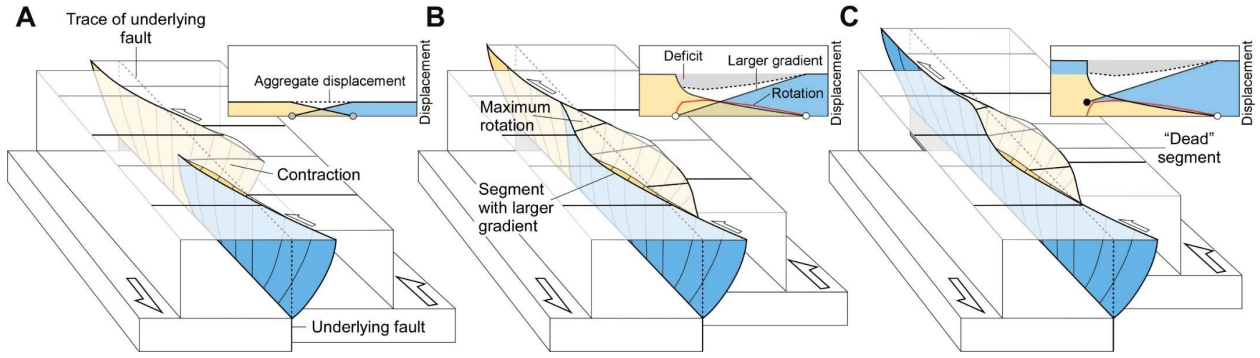


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383 **Figure 3**

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387 **Figure 4**