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1 **Igneous Activity in the Bornu Basin, Onshore NE Nigeria; Implications** 2 **for Opening of the South Atlantic**

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8

9

10 **Abstract**

11 The structure of igneous plumbing systems in circum-South Atlantic, intra-continental
12 rift basins, e.g., the West and Central African Rift Systems (WCARS), remains
13 enigmatic due to poor subsurface data coverage and quality. How magmatism in these
14 basins related to the opening of the South Atlantic is thus poorly understood. We
15 integrate 2D and 3D seismic reflection data (c. 27600 km²), data from 23 boreholes,
16 and field observations from the Bornu Basin and Upper Benue Trough, onshore NE
17 Nigeria to examine the timing and development of igneous bodies possibly related to
18 opening of the South Atlantic. We identify numerous sills, which typically have saucer-
19 shaped and en-echelon morphologies, and extrusive volcanic cones. The igneous rocks
20 are alkali basalts and dolerites. Seismic-stratigraphic relationships indicate that
21 emplacement occurred in the Early Cretaceous (Albian-to-Cenomanian; ca. 120 Ma),
22 Late Cretaceous (Santonian-to-early Campanian; ca. 83 Ma), and Cenozoic (Miocene;
23 ca. 22 Ma). Magmatism was broadly coeval with major plate boundary interactions,
24 characterized by major azimuthal changes in fracture zones in the developing South

25 Atlantic Ocean. The broad temporal correlation between intra-continental rift basin
26 magmatism and plate boundary interactions suggests that periods of magma
27 emplacement may have, in some way, been instigated by stress dissipation into intra-
28 continental rift basins.

29

30 **Introduction**

31 The break-up of Gondwana and subsequent opening of the South Atlantic by rifting of
32 the African and South American plates was associated with crustal extension,
33 compression, and strike-slip tectonics in both passive margin and intra-plate rift
34 systems (e.g., Fairhead, 1988; Benkhelil, 1989; Guiraud and Maurin, 1992; Davison,
35 1997; Pérez-Díaz and Eagles, 2014). Intra-continental deformation was accommodated
36 by the development of normal fault arrays and post-rift tectonic inversion. In some
37 cases, intra-continental deformation was also associated with melt generation and
38 magma emplacement, suggesting that igneous activity may relate to and thus provide
39 critical insight into the timing and evolution of plate geodynamic episodes (Sengör and
40 Burke, 1978; Benkhelil, 1989; White and McKenzie, 1989). However, a key barrier to
41 understanding the link between plate margin and intra-plate tectono-magmatic
42 processes is the paucity of age constraints on the timing of igneous activity. Where
43 intra-continental rift basins containing magmatic rocks occur on the African margin of
44 the South Atlantic, the lack of relative timing constraints principally reflects a paucity
45 of outcrops from which to collect igneous rock samples. Furthermore, the typical
46 availability of only sparse, low-quality subsurface data means that it is difficult to
47 accurately establish the structure and age of Gondwana breakup-related rift basins.

48 Numerous tectono-magmatic studies have demonstrated that seismic data and field
49 observations can be used to decode the geometry, distribution, and timing of
50 magmatism in sedimentary basins worldwide, thereby allowing contemporaneous
51 tectonic processes to be established (e.g., Skogseid et al., 1992; Symonds et al., 1998;
52 Planke et al., 2000; Smallwood and Maresh, 2002; Planke et al., 2005; Hansen and
53 Cartwright, 2006a; Jackson et al., 2013; Schofield et al., 2015). In particular, seismic
54 reflection data permit direct imaging of igneous bodies and basin structure, with
55 borehole data and seismic-stratigraphic observations allowing the timing of igneous
56 activity to be constrained (e.g., Smallwood and Maresh, 2002; Trude et al., 2003;
57 Magee et al., 2013c). Here, we use newly available seismic reflection, borehole,
58 biostratigraphic, and petrological data from the Bornu Basin and Upper Benue Trough,
59 onshore NE Nigeria to constrain the regional tectono-magmatic history of this portion
60 of the West and Central African Rift Systems (WCARS) (Fig. 1). We document the
61 geometry and distribution of igneous intrusions and extrusions in the basin and
62 determine the mechanics of magma emplacement. We show that a range of processes,
63 from brittle failure to non-brittle deformation (fluidization) of the host rock, facilitated
64 magma emplacement and controlled the final geometry of intrusions in the Bornu Basin
65 (e.g., Polteau et al., 2008; Jackson et al., 2013; Magee et al., 2013c). For the first time
66 in the Bornu Basin and the WCARS, we apply the concept of seismic-stratigraphy and
67 use biostratigraphic dating to constrain the timing of the three, discrete igneous events
68 in the Early Cretaceous (Albian-to-Cenomanian; ca. 120 Ma), Late Cretaceous
69 (Santonian-to-early Campanian; ca. 83 Ma), and Cenozoic (Miocene; ca. 22 Ma). These
70 age constraints enable us to investigate how intra-continental magmatism is temporally
71 related to regional tectonic events associated with the breakup of Gondwana and
72 opening of South Atlantic Ocean.

74 **Geological setting**

75 The Bornu Basin is an intra-continental, Cretaceous-to-Holocene rift basin located in
76 NE Nigeria (Fig. 1) (Avbovbo et al., 1986). Numerous studies suggest that basin
77 formation involved Early Cretaceous extension, Late Cretaceous shortening, and a
78 period of relative tectonic quiescence in the Cenozoic (Figs 2 and 3) (Avbovbo et al.,
79 1986; Genik, 1992; Fairhead et al., 2013). The oldest rocks in the Bornu Basin consist
80 of Precambrian-to-Lower Paleozoic migmatites and granite, with the oldest
81 sedimentary strata corresponding to the Lower Cretaceous (Albian-to-Cenomanian)
82 lacustrine and terrestrial deposits of the Bima Sandstone (Fig. 2) (Carter et al., 1963;
83 Avbovbo et al., 1986; Guiraud, 1990; Samaila et al., 2006). The Bima Sandstone is
84 overlain by estuarine-to-marine deposits of the Gongila Formation (Cenomanian-to-
85 Turonian), which is itself overlain by the Fika Shale, a marine unit deposited during a
86 major transgression in the Turonian-to-Campanian (Fig. 2) (Carter et al., 1963).
87 Estuarine-to-deltaic clastics of the Gombe Sandstone (Maastrichtian), which is best-
88 developed in the Upper Benue Trough, overlie the Fika Shale (Fig. 2) (Carter et al.,
89 1963). The non-marine Kerri-Kerri Formation (Paleogene) was unconformably
90 deposited onto the Gombe Sandstone in the Upper Benue Trough and the Fika Shale
91 across most of the Bornu Basin; the boundary between these units marks the regional
92 Cenozoic unconformity (Fig. 2) (Carter et al., 1963; Genik, 1992; Obaje et al., 2004a;
93 Obaje et al., 2004b). The youngest rocks in the basin belong to the Quaternary Chad
94 Formation, which largely consist of lacustrine and alluvial sedimentary strata (Fig. 2)
95 (Carter et al., 1963).

96 The structure of the Bornu Basin is defined by an array of basement-involved, NE-SW-
97 striking normal faults that bound a series of horst and graben (e.g., Figs 3 and 4a). These
98 faults are c. 70 km long and dip towards the NW, extending upward into and tipping
99 out within Cretaceous strata (e.g., Fig. 3) (Avbovbo et al., 1986). Basement-detached,
100 strata-bound faults are also developed in the Bornu Basin, being largely confined to the
101 Cretaceous interval and having their upper tips truncated along the regional Cenozoic
102 unconformity. These strata-bound faults strike predominantly NE-SW, although some
103 strike NW-SE. Spatially related to these two fault populations are a series of
104 asymmetric, low-amplitude antiforms and synforms, which have axial planes striking
105 broadly parallel to the basin-bounding faults (Figs 3 and 4a) (Avbovbo et al., 1986).
106 Studies of the neighbouring Doseo and Muglad basins suggest that these folds formed
107 due to Santonian (ca. 83 Ma) inversion tectonics and strike-slip faulting, the latter being
108 expressed in the form of flower structures (Genik, 1992).

109 A number of studies have identified evidence for Cretaceous igneous activity in the
110 Bornu Basin and neighbouring Benue Trough (Avbovbo et al., 1986; Benkhelil et al.,
111 1988; Benkhelil, 1989; Genik, 1992; Alalade and Tyson, 2013). For example, seismic
112 reflection and gravity data presented by Avbovbo et al., (1986) indicate that a series of
113 NW-trending intrusive igneous bodies occur at relatively shallow depths in the Bornu
114 Basin, although the detailed geometry and distribution of these remained poorly
115 constrained due to the poor imaging of the 2D seismic data. In the Upper Benue Trough,
116 two distinct phases of magmatic activity have been identified based on field studies: (i)
117 activity associated with the emplacement of the Mesozoic Burashika Complex (Fig. 1);
118 and (ii) activity associated with the Cenozoic (22-11 Ma) Cameroon Volcanic Line
119 (Carter et al., 1963; Grant et al., 1972b). Extrusive volcanic breccias, tuffs and
120 intrusions are also identified in the Lower Benue Trough in the Asu River Group

121 (Albian) (Benkhelil, 1989). The geometry, distribution and exact timing of
122 emplacement of these igneous bodies, and how the associated magmatic activity may
123 relate to regional tectonic events, remain poorly understood.

124 **Dataset and Methodology**

125 We use 2D and 3D seismic reflection surveys covering a total area of c. 27,600 km²
126 (Fig. 1). The 2D seismic dataset has an irregular line spacing of c. 0.5 to 20 km, with
127 line lengths ranging from c. 13-92 km (Fig. 1). 2D seismic data image down to 6
128 seconds TWT. The vertical resolution of the 2D seismic data within the broad interval
129 of interest is c. 30 m, based on a dominant frequency of 22 Hz ($\pm 10\%$) and a Fika Shale
130 interval velocity of 2414 m/s ($\pm 10\%$) (obtained from the Bulte well; Fig. 4b). The 2D
131 seismic data are minimum phase, with red reflections (peaks) representing a downward
132 increase in acoustic impedance and blue reflection (trough), representing a downward
133 decrease in acoustic impedance. The 3D seismic data are also minimum phase, having
134 a bin spacing of 25 m by 25 m. In the 3D volume, a dominant frequency of 34 Hz
135 ($\pm 10\%$) in the interval of interest and a Fika Shale interval velocity of 2414 m/s ($\pm 10\%$)
136 yield an approximate vertical resolution of c. 20 m.

137 Twenty three wells are available in the study area (Fig. 1), with most containing thin
138 sections of well cuttings, and a suite of logs (e.g. sonic (DT), gamma ray (GR), and
139 density (RHOB)); some contain resistivity logs. The wells are used to constrain basin-
140 fill composition, the age of the deformed and intruded successions, and the composition
141 of the intrusions. Field observations in the neighbouring Upper Benue Trough are used
142 to constrain the sub-seismic geometry of igneous bodies, and aspects of host rock
143 composition and magma-host rock interactions imaged in the Bornu Basin.

144 A range of seismic attributes, including reflection intensity, relative acoustic impedance
145 and instantaneous frequency, were used to locate and map 53 igneous bodies, of which
146 26 occur within the 3D seismic volume (Figs 4b and c). The seismic expression of
147 igneous intrusions is non-unique (Smallwood and Maresh, 2002; Magee et al., 2015).
148 For example, sandstone intrusions (Dixon et al., 1995; Huuse and Mickelson, 2004),
149 high acoustic impedance sedimentary rocks such as coals (Xu et al., 2009; Xu et al.,
150 2010), and diagenetic boundaries such as the opal-ACT transition (Berndt et al., 2004;
151 Zampetti et al., 2005) can all be expressed as high-amplitude reflection anomalies.
152 Thus, we used the following criteria to identify igneous reflections in the seismic data:
153 (i) borehole data that tie high-amplitude reflections to igneous rocks; (ii) high-
154 amplitude reflections cross-cutting sedimentary strata; (iii) high-amplitude reflections
155 that are laterally discontinuous; and (iii) similarities in size and geometry to igneous
156 intrusions described in previous studies (e.g., Hansen and Cartwright, 2006; Magee et
157 al. 2015; Planke et al., 2015).

158 The estimated vertical resolution of the seismic data (c. 30 m in the 2D data and c. 20
159 m in the 3D data) allow us to constrain the minimum thickness of the igneous bodies
160 imaged in the seismic reflection data. Sills thinner than the estimated vertical resolution
161 are expressed as tuned reflection packages, from which the lower and upper intrusive
162 contacts cannot be separately resolved (Smallwood and Maresh, 2002; Magee et al.,
163 2015). Magma flow indicators such as intrusive steps, bridge structures and magma
164 lobes are observed in the mapped sills (Fig. 5) (Schofield et al., 2012a; Schofield et al.,
165 2012b; Magee et al., 2013c; Magee et al., 2014; Schofield et al., 2015). These magma
166 flow indicators also provide important insights into sill emplacement mechanics; e.g.,
167 intrusive steps form in response to brittle fracture propagation, typically at burial depths
168 ≥ 2 km (Pollard et al., 1975; Schofield et al., 2012b), whereas magma fingers form

169 through non-brittle emplacement, commonly in response to host rock fluidization at
170 burial depths ≤ 2 km (Pollard et al., 1975; Rickwood, 1990; Schofield et al., 2010;
171 Schofield et al., 2012a; Schofield et al., 2012b).

172

173 **Results**

174 **Basin structural style**

175 A depth-structure map of the base of the Bima Sandstone indicates that the study area
176 can be divided into two sub-basins; the eastern (ESB) and western (WSB) sub-basins
177 (Fig. 4a). Faults within and bounding the WSB typically dip at 40° - 60° and strike NE-
178 SW, whilst those in the eastern sub-basin dip at 40° - 55° and strike NW-SE (Fig. 4a).
179 Isolated half-graben within the ESB are, however, bound by faults that strike NE-SW.
180 Some of the normal faults, especially those striking NE-SW, display evidence for minor
181 inversion in the form of low-amplitude hanging wall folds, whereas those striking NW-
182 SE are associated with flower structures (Figs 3 and 4a).

183 **Basin stratigraphy**

184 To provide context for the description of the igneous bodies, here we describe the
185 architecture of the main sedimentary packages in the study area and relate their
186 deposition to the tectonic evolution of the basin. The Bima Sandstone thickens across
187 the main basin-bounding faults and is accordingly interpreted as being a syn-rift
188 sequence deposited during the main phase of Early Cretaceous rifting (Fig. 3). The
189 Gongila Formation overlies the Bima Sandstone and its seismic architecture shows
190 better reflection continuity and parallelism (Fig. 3); the Gongila Formation is

191 interpreted to be post-rift sequence as it does not thicken across faults and is largely
192 unfaulted, capping faulted Bima Sandstone (Fig. 3). The Fika Shale conformably
193 overlies the Gongila Formation thinning across and onlapping onto the fault-parallel
194 anticlines developed in the immediate hanging walls of the basin-bounding faults (Fig.
195 3). Based on this seismic-stratigraphic architecture, we interpret that the Fika Shale
196 forms part of the post-rift 'syn-inversion' sequence. The Kerri-Kerri Formation
197 unconformably overlies Fika Shale and its seismic architecture is sub-parallel (Fig. 3).
198 We interpret that the Kerri-Kerri Formation was deposited after the main phase of
199 inversion during a period dominated by simple subsidence, probably driven by post-rift
200 cooling of the crust. Likewise, we interpret that the overlying, broadly tabular Chad
201 Formation is part of the post-inversion sequence (Fig. 3). Well correlations show that
202 these major stratigraphic units contain range of lithological units such as shale,
203 sandstone and claystone (Fig. 6).

204 **Igneous bodies**

205 The occurrence of igneous rocks within the Bornu Basin is confirmed by the recovery
206 of dolerite cuttings from four wells in the study area; these dolerites are primarily
207 composed of plagioclase, clinopyroxene (augite), and Fe-Ti oxides. The thickest sill
208 intersected by a well is c. 150 m thick (Albarka well; Fig. 4b). Igneous bodies are
209 expressed in wireline-logs (Nelson et al., 2009) by low (c. 29 API) gamma ray and high
210 (c. 177 m/ms) sonic values (Fig. 6).

211 The mapped intrusions typically appear as strata-discordant or concordant, laterally
212 discontinuous (maximum length of c. 14 km in this study), high-amplitude anomalies
213 (e.g., Fig. 2). Igneous intrusions are imaged in seismic data and primarily occur in the
214 Cretaceous units, particularly the Fika Shale marine shales, the fluvial Bima Sandstone,

215 and the heterolithic, coastal plain to estuarine deposits of the Gongila Formation (Figs
216 2 and 6). Most intrusions occur below the regionally developed Cenozoic unconformity
217 but, on very rare occasions, some intrusions appear to cross-cut the unconformity and
218 extend upward into the continental sandstone of the Kerri-Kerri Formation by ~75 ms
219 (Fig. 7). We identify three major geometrical styles of igneous bodies within our
220 seismic data: (i) Type-1 saucer-shaped sills; (ii) Type-2 strata-concordant sills; and (iii)
221 Type-3 volcanic cones.

222 **Type-1:** these are saucer-shaped, high-amplitude reflections consisting of a strata-
223 concordant base that passes laterally into a transgressive, inwardly dipping, inclined
224 limb. They are the most common type of intrusion mapped in the study area being
225 developed in the ESB and WSB. They occur across a wide depth range; spanning 500-
226 2000 m. Here, we describe the detailed morphology of one representative saucer-shaped
227 sill (Sill-1, Fig. 8).

228 Sill-1 was emplaced into the Fika Shale (Fig. 8). It covers an area of c. 6 km², has a
229 strata-concordant inner sill that is up to c. 2500 m in diameter, is c. 40-55 m thick, and
230 contains a series of positive ridges on its surface that demarcate steps in the seismic
231 reflection (Fig. 8a). Intrusive step long axes radiate outward from the deepest, central
232 point of the sill. A planar inclined sheet, which transgresses up to c. 200 m of
233 stratigraphy, occurs around the margins inner sill (Fig. 8a and b). The map-view of the
234 Sill-1 illustrates that the sill can be sub-divided into semi-circular lobes that are
235 superimposed onto the overall geometry (Fig. 8a). The inclined limb of the Sill-1
236 appears to terminate against a flower structure, the steeply dipping boundary faults of
237 which encompass the entire circular intrusion (Fig. 8c). A fold that directly overlies the
238 sill is observed, which has a box-like geometry with a flat top and steep limbs that
239 terminate against flower structure faults (Fig. 8c). Strata above and beneath the sill are

240 displaced upwards by c. 100 ms relative to corresponding reflections in the footwall of
241 the flower structure (Fig. 8c).

242 **Type-2:** these sills are expressed as en-echelon geometry, high amplitude reflections
243 (e.g., Figs 9 and 10). They are developed in both the ESB and WSB and occur across a
244 wide depth range (500-2000 m). Type-2 sills are characterized by transgressive internal
245 limbs. Here, we describe the detailed morphology of two representative sills (Sill-2,
246 Fig. 9; Sill-3, Fig. 10).

247 Sill-2 is asymmetric and has a diameter of c. 4000 m (Fig. 9a). It covers c. 11 km² and
248 is c. 65 m thick at its centre, reducing in thickness to c. 30 m at the en-echelon
249 transgressive limb or branching sheet (Fig. 9). Sill-2 is gently dipping and is thus
250 weakly discordant with the encasing Fika Shale host-rock (Figs 9b and c). Sill-2
251 becomes more strata-discordant towards its distal end, where it turns into an inclined
252 sheet that has a relief of c. 220 m (Figs 9a-c). No intrusion-related deformation, such
253 as host rock forced folding or substantial faulting is observed in association with Sill-2
254 (Figs 9b-d). Sill-2 comprises a linked network of sill lobes that merge together to form
255 a single body (Fig. 9a). The point of coalescence between adjacent lobes is marked by
256 a series of intrusive steps and broken-bridges, which appear to radiate out from the
257 deepest central point of the sill (Figs 9a and d).

258 Sill-3 is at least c. 14000 m in length although, due to being imaged in 2D data only, its
259 full areal extent cannot be constrained (Fig. 10). Sill-3 is c. 85 m thick at its centre,
260 reducing in thickness to c. 40 m at the en-echelon inclined limb (Fig. 10). Sill-3 is more
261 strata-discordant towards its distal end, where it turns into an inclined sheet that has a
262 relief of c. 360 m (Fig. 10). It is important to highlight that the inclined sheet here
263 appears planar and non-transgressive, unlike the one observed in Sill-2 (Figs 9 and 10).

264 Furthermore, an overlying open antiform, with amplitude of c. 760 m, overlies Sill-3;
265 the lateral terminations of the fold directly overlie the seismically resolved lateral sill
266 tips (Fig. 10). Overlying Upper Fika Shale on-laps on the fold and both the Fika Shale
267 and Gongila Formation are truncated at their tops by the regional Cenozoic
268 unconformity (Fig. 10).

269 **Type-3:** A single high-amplitude, mound-like feature (i.e. Type-3) is observed on top
270 of the Bima Formation in the WSB (Fig. 11a). This broadly conical structure is c. 3000
271 m in diameter and has a height of c. 380 m (Fig. 11a). Intra-mound reflections downlap
272 the underlying Bima Sandstone and are sub-parallel to mound upper surface (Fig. 11a).

273 Similar conical structures resting upon the Bima Sandstone, which are up to c. 400 m
274 tall and c. 1000 m in diameter, are observed in the field in the neighbouring Upper
275 Benue Trough (e.g., Fig. 11b). Xenoliths of the Bima Sandstone were observed in some
276 of the rocks that comprise the volcanic cones (Fig. 11c). Petrological analyses reveal
277 that these conical structures are composed of fine-grained (<0.5 mm groundmass),
278 porphyritic alkali basaltic rocks that primarily consist of olivine (up to c. 25%),
279 clinopyroxene (up to c. 20%), and plagioclase (up to c. 40%) (e.g., Fig. 11d). Glass is
280 present in some of the samples collected and minor alkali feldspar (c. <10%), nepheline
281 (c. <8%), and Fe-Ti oxides (c. <10%) are also observed. Plagioclase only occurs in the
282 groundmass and forms elongated laths that occasionally display a trachytic texture (e.g.,
283 Fig. 11d). Phenocrysts are dominated by olivine and clinopyroxene, both of which are
284 up to 4 mm in diameter and typically display euhedral to subhedral habits (e.g., Fig.
285 11d).

286

287 **Interpretation**

288 **Emplacement mechanics and depth of intrusion**

289 **Type-1:** these reflections correspond to saucer-shaped sills (Fig. 8) (Malthe-Sørensen
290 et al., 2004; Thomson and Hutton, 2004; Hansen and Cartwright, 2006a, b; Polteau et
291 al., 2008; Jackson et al., 2013). The radial disposition of steps, interpreted as intrusive
292 steps, away from the deepest point of the inner sill (e.g. Sill-1, Figs 8a and b) suggest
293 that this intrusion formed through the coalescence of at least five magma segments that
294 propagated radially away from the inner sill centre (Schofield et al., 2012b; Magee et
295 al., 2013c). The overall saucer-shaped geometry of the Type-1 sills implies that they
296 formed at relatively shallow-levels (Malthe-Sørensen et al., 2004; Hansen and
297 Cartwright, 2006a; Magee et al., 2013a). However, the occurrence of intrusive steps,
298 which are typically associated with brittle emplacement at deeper burial depths,
299 suggests that either the depth of emplacement was not too shallow as to inhibit
300 fracturing and/or that the host rock rheology allowed brittle deformation (Schofield et
301 al., 2012b).

302 The fold above Sill-1 (Fig. 8c) may have formed either: (i) synchronous to magma
303 emplacement as an intrusion-induced forced fold, with the small faults directly above
304 the sill possibly representing outer-arc stretching-related faults (Hansen and Cartwright,
305 2006b; Jackson et al., 2013; Magee et al., 2013a); or (ii) in response to strike-slip
306 faulting before magma emplacement. We dismiss the former interpretation for the
307 principal reason that strata beneath the sill are offset across the strike-slip faults by
308 approximately the same amount as strata above the sill, suggesting that they were
309 deformed in the same strike-slip faulting episode (Fig. 8c). This interpretation implies

310 that the faulting and flower structure-related uplift occurred before the emplacement of
311 Sill-1.

312 **Type-2:** we interpret these intrusive bodies as en-echelon transgressive sills (Figs 9 and
313 10). In a similar manner to the Type-1 sills, the radial disposition of the magma flow
314 indicators away from the deepest centre of Sill-2 suggests magma emplacement from a
315 point source (Fig. 9a). The superimposed sheets, each with an en-echelon structure,
316 (Figs 9b, c, and 10) possibly indicate multiple intrusions of magma sheet formed in one
317 of three ways (Fig. 12): (i) break-out of magma at the base of a pre-existing inclined
318 sheet instigates sill propagation; (ii) inclined sheet development at progressively more
319 proximal locations to the magma source, breaking out at the top of existing sheets due
320 to the waning of magma pressure; or (iii) the emplacement of under-or over-accreted
321 sills, resulting in the formation of a sill with different lateral dimensions and thereby
322 different points of sill-inclined sheet transitions. The Type-2 sills are, therefore,
323 composed of multiple, now merged sheets, which we interpret as magma lobes (e.g.,
324 Fig 9a). We interpret that the network of lobes within Sill-2 likely formed as the result
325 of multiple magma segments intruded along bedding planes at shallow depth, which
326 subsequently inflated vertically and laterally (Polteau et al., 2008; Galerne et al., 2011;
327 Schofield et al., 2012a). We infer that the separation of the merged network of lobes at
328 their distal ends and overall lateral thinning of the sills are related to a decrease in the
329 volume of the magma supply which starved the merging lobes as they propagated
330 (Vignerresse and Clemens, 2000; Magee et al., 2013c).

331 The presence of intrusive steps in the inner sill and inclined sheets suggest a typical
332 brittle magma emplacement mechanism (Fig. 9) (Schofield et al., 2012b). The
333 formation of intrusion-related fractures may be influenced by the presence of pre-
334 existing fault and fracture systems in the host rock. This may explain the irregular and

335 selective formation of the en-echelon transgressive limbs, with limbs preferentially
336 forming in intervals where favourably orientated pre-existing faults occur (Magee et
337 al., 2013c). This interpretation is supported by our observation that transgressive limbs
338 are spatially related to faults. In some instances, however, inclined sheets do not appear
339 to exploit pre-existing faults, but rather coincide with steeply oriented rock-rock
340 interfaces. This is best-demonstrated in the inclined sheet that cross-cuts the Cenozoic
341 unconformity, which could have propagated along compliant, sub-vertically orientated
342 bedding in the Cretaceous succession (Fig. 7).

343 We interpret that Sill-3 was emplaced at palaeo-depth of c. 500 m. This is based on the
344 presence of a supra-sill dome above the sill, interpreted as a forced fold that formed to
345 accommodate magma emplacement, onto which overlying strata of the marine Fika
346 Shale onlap (Fig. 10); i.e. the top of the fold represented the palaeo-surface during
347 intrusion (e.g., Hansen and Cartwright, 2006b; Jackson et al., 2013). The age of the
348 forced fold and, therefore, the timing of sill emplacement can also be constrained to the
349 Santonian-to-early Campanian (ca. 83 Ma) by dating the supra-sill strata that onlap the
350 fold (Trude et al. 2003; Jackson et al., 2013; Magee et al., 2013a; Magee et al. 2014).
351 The precise 3D geometrical and spatial relationship between the sill and fold cannot be
352 constrained using 2D seismic data alone. However, the following observations support
353 our forced fold interpretation (Fig. 10): (i) the broad spatial correspondence between
354 the intrusion and the fold; (ii) thinning of the supra-sill stratigraphy (i.e. Fika Shale)
355 across the fold and; (iii) lack of volcanogenic seismic facies in the fold core, suggesting
356 the structure has a non-volcanic origin (Hansen and Cartwright, 2006b; Thomson,
357 2007; Cukur et al., 2010; Jackson et al., 2013).

358 **Type-3:** we interpret that the high-amplitude cone-shaped structure observed in the
359 WSB as a volcano because it has a similar geometry to the alkali basalt volcanic cones

360 observed in the Upper Benue Trough (Fig. 11). The intra-cone reflections may represent
361 the boundaries between individual lavas, or the boundaries between lavas and
362 pyroclastic deposits (Fig. 11a) (Magee et al., 2013b). We interpret that the volcano was
363 emplaced during the late Albian to Cenomanian, based on the observation that it sits
364 directly on the Bima Sandstone; a similar age relationship is observed in the field in the
365 neighbouring Upper Benue Trough where the alkali basalts also contain xenoliths of
366 Bima Sandstone (Fig. 11c). The interpreted volcano could also be a hydrothermal vent
367 (e.g., Planke et al., 2005).

368 **Timing of igneous activity**

369 Based on the age of strata hosting the intrusions, the age of emplacement of the igneous
370 extrusions, and seismic-stratigraphic relationships in overlying strata, we interpret that
371 three phases of igneous activity occurred in the Bornu Basin. The first phase likely
372 occurred in the Early Cretaceous, based on the late Albian to Cenomanian age of the
373 volcanic cone (Figs 11 and 13). Based on our observations that the Santonian-to-early
374 Campanian Upper Fika Shale onlaps onto and thins across the intrusion related forced
375 folds, we interpreted that the second phase of magmatic activity occurred in the Late
376 Cretaceous (Fig. 10 and 13). It should be noted that, we cannot constrain the ages of
377 some intrusions because of the lack of forced folding above them, however, these
378 intrusions are obviously younger than the host rock (Santonian-to-early Campanian).
379 We infer that the sills appearing to post-date strike-slip faulting belong to the Late
380 Cretaceous phase of igneous activity (e.g., Sill-1, Fig. 9). Field studies in the Lower to
381 Middle Benue Trough have reported volcanoclastic sedimentary rocks and other sub-
382 volcanic intrusions in the Ogoja to Abakaliki area (Benkhelil, 1989). Chemical analysis
383 of these samples reveals microgabbro, dolerite and alkaline syenites compositions, with

384 K-Ar dating suggesting ages of 104-70 Ma (i.e. Early to Late Cretaceous), which is
385 broadly consistent with our inferences from seismic reflection data (Benkhelil, 1989).

386 Based on the truncation of Cenozoic regional unconformity by a solitary intrusion
387 which is c. 1 km from the surface, we suggest that a third, Cenozoic phase of igneous
388 activity may have occurred in the Bornu Basin (Figs 7 and 13). This inferred period of
389 igneous activity, although based on very limited seismic-stratigraphic evidence, is
390 consistent with radiometric ages reported from Cenozoic, principally Miocene (ca. 22-
391 11 Ma) intrusives documented in the neighbouring Upper Benue Trough (Fig. 13)
392 (Grant et al., 1972b).

393

394 **Implications for opening of the South Atlantic Ocean**

395 The integration of subsurface data from the Bornu Basin sub-surface datasets with
396 outcrop observations from the neighbouring Upper Benue Trough provide insights into
397 the geometry, distribution and age of emplacement of igneous bodies in the WCARS.
398 Because we have established the relative age of igneous activity, we can thus
399 investigate how this activity might relate to the plate boundary geodynamics occurring
400 during opening of the South Atlantic (Fig. 13).

401 The earliest phase of igneous activity we identify occurred during the Early Cretaceous,
402 broadly correlating with initial separation of the South American and African plates in
403 the Albian (ca. 100 Ma) (Fig. 13). This phase of activity also coincided with a period
404 of major igneous activity identified in other circum-South Atlantic rift basins, such as
405 the neighbouring Benue Trough in the African plate, and the Campos, St. Helena and
406 Rio Grande Rise areas of the South Atlantic plate (Fig. 13) (Torsvik et al., 2009). There

407 is no change in the azimuth of the Kane Fracture Zone associated with this phase of
408 igneous activity (Fig. 13).

409 During the Santonian-to-early Campanian, the main phase of igneous activity occurred
410 in the Bornu Basin, during which most of the saucer-shaped sills and en-echelon sills
411 were emplaced. Similar magmatic events are documented in the Benue Trough and in
412 several southern Brazilian basins in the form of onshore and offshore alkaline-to-
413 peralkaline magmatism (Fig. 13) (Torsvik et al., 2009). This second phase of igneous
414 activity broadly correlates with the time when Gondwana was completely ruptured and
415 oceanic crust was emplaced (ca. 83.5 Ma) (Fig. 13). Collision of the African and the
416 Eurasian plates resulted in a change of stress regime in the South Atlantic Ocean and
417 surrounding plates; this is preserved by a major change in the azimuth of the Kane
418 Fracture Zone (Fig. 13) (Guiraud and Bosworth, 1997; Fairhead et al., 2013). This
419 particular change in the intra-plate stress regime manifested as intra-plate shortening
420 and tectonic inversion in the Bornu Basin, and the development of regional
421 unconformities in several intra-continental rift basins such as Muglad and Doba basins
422 (Fig. 13) (Fairhead, 1988; Genik, 1992; Guiraud and Bosworth, 1997; Fairhead et al.,
423 2013).

424 The third and final phase of igneous activity, which occurred in the Cenozoic, appears
425 to be coincident with a major phase of oceanic magmatism and another change in the
426 azimuth of the Kane Fracture Zone (Fig. 13). This phase of activity broadly coincides
427 with major intra-continental volcanism, such as that which occurred along the Cameron
428 Volcanic Line (Fig. 13). The oldest of these Cenozoic igneous rocks are the Early
429 Miocene (ca. 22 Ma) volcanics preserved in the Benue Trough (Grant et al., 1972b).

430 Factors such as mantle geodynamics (e.g., convection and mantle plumes), changes in
431 the lithospheric thickness, and plate boundary interactions can result in intra-plate
432 magmatism (e.g., Meeuws et al., 2016). Valentine and Perry (2007) argued that regions
433 of basaltic volcanism can be divided into those that are magmatically and tectonically
434 controlled; melt within magma-driven basaltic fields tends to be generated in response
435 to thermal perturbations in the mantle, independent of tectonic processes, whereas
436 tectonically controlled fields rely on and are therefore temporally associated with plate
437 deformation facilitating magma accumulation and ascent. Our findings broadly suggest
438 that the observed intra-plate magmatism along the aborted rifts of the African and
439 possibly South American continents is genetically related to plate boundary
440 geodynamics associated with the opening of the South Atlantic Ocean.

441 **Conclusion**

442 The methodologies employed in our study show how the investigation of magma
443 emplacement mechanics and the 3D geometry of igneous bodies mapped in high
444 resolution seismic reflection data can be used to constrain the timing and tectonic
445 implication of intra-plate magmatism. We particularly examined igneous bodies in the
446 Bornu Basin and Upper Benue Trough, onshore NE Nigeria using seismic reflection,
447 borehole, field, and petrological data. The major igneous geometries identified in this
448 study are: (i) saucer-shaped sills; (ii) strata-concordant sills; and (iii) volcanic cones.
449 These bodies are alkali basalts or dolerites. Seismic-stratigraphic analysis of the
450 igneous bodies and the related host rock deformation suggest emplacement occurred in
451 the Early Cretaceous (Albian-to-Cenomanian; ca. 120 Ma), Late Cretaceous
452 (Santonian-to-early Campanian; ca. 83 Ma), and Cenozoic (Miocene; ca. 22 Ma). The
453 timing of magmatism identified in the study area is consistent with the timing of major
454 plate boundary interactions, some of which are characterized by changes in the azimuth

455 of the oceanic fracture zones. This suggests that periods of melt generation and
456 emplacement in intra-continental rift basins may have recorded plate boundary
457 geodynamics during opening of the South Atlantic Ocean.

458

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466

467 **Figure captions**

468 **Figure 1.** Location of the seismic and borehole datasets used in this study from Bornu
469 Basin and the field area studied in the Upper Benue Trough, onshore NE Nigeria.

470 **Figure 2.** Tectono-stratigraphic chart of the Bornu Basin and interpreted seismic
471 section detailing the seismic-stratigraphy the major stratal units. Within the seismic
472 data, the Gombe Formation is rarely observed due to erosion and formation of the
473 Cenozoic unconformity.

474 **Figure 3. a)** Time-structure map of base Bima Sandstone showing the main fault
475 patterns and styles. **b)** Distribution of igneous bodies at different depth levels in both
476 the WSB and ESB. Note the absence of intrusion at the rift shoulders. **c)** 3D

477 geometries of intrusions, mapped across 3D seismic and closely spaced 2D seismic
478 datasets in the ESB. See the Figure 4b for location.

479 **Figure 4.** Western Sub-basin structural style and major stratigraphic units in the
480 Bornu Basin. The exact locations of fault planes are difficult to constrain, however,
481 the presence of the folded hanging walls suggest reverse reactivation of the
482 extensional normal faults. See Figure 4b for the line location.

483 **Figure 5. a)** Schematic diagram of a sill containing intrusive steps and bridge
484 structures. **b)** Cross-sectional view of intrusive steps and a broken-bridge. **c)** Idealized
485 sketch of magma finger and lobe components within a saucer-shaped sill. Step, bridge,
486 finger, and lobe long axes all demarcate magma flow axes. Modified from Magee et al.,
487 (2016).

488 **Figure 6.** Lithological correlation across some six wells within the study area.

489 **Figure 7.** Seismic profile showing Cretaceous and lowermost Cenozoic successions,
490 separated by the Cenozoic unconformity, cross-cut by an inclined, high-amplitude
491 reflection. See Figure 4b for location.

492 **Figure 8. a)** Time-structure map of Sill-1 illustrating inferred magma flow directions.
493 Contour spacing is 12 ms TWT. See Figure 3c for location. **b)** Arbitrary seismic profile
494 highlighting the discordant nature of Sill-1, which displays intrusive steps. See Figure
495 8a for location. **c)** Sill-1 and a supra-sill fold bounded by strike-slip faults.

496 **Figure 9. a)** Time-structure map of Sill-2, which consists of merged lobes bounded
497 by magma flow indicators. See Figure 3c for location. **b)** Branching sill limb that
498 describe an en-echelon morphology. **c)** Transition between the concordant inner sill

499 and transgressive inclined limbs. **d)** Composite profile illustrating bridge and intrusive
500 step structures. See Figure 9a for seismic line location.

501 **Figure 10.** Uninterpreted seismic section and line drawing showing the en-echelon
502 nature of Sill-3 and the geometry of the overlying forced fold, onto which the Fika
503 Shale onlaps.

504 **Figure 11. a)** Inferred volcanic cone, resting upon the Bima Sandstone, with gently
505 sloping limbs and internal reflections that mirror the external geometry. **b)** Field
506 photograph of a volcanic mound, composed of alkali basalt, on top of the Bima
507 Sandstone within the Upper Benue Trough (Lat. 9°53'17.90"N, Long. 11°10'15.60"E).
508 **c)** Bima Sandstone xenolith within the alkali basalt observed in Figure 4b. **d)** Plane-
509 polarized (left) and cross-polarized (right) light photomicrographs of the alkali basalt
510 observed in Figure 4b. Phenocrysts of clinopyroxene (Cpx) and olivine (Ol) are
511 labelled. See text for details. Other volcanic cones with an alkali basalt composition
512 occur at: (1) Lat. 10°15'57.88"N, Long. 11°27'41.28"E; and (2) Lat. 9°45'26.23"N,
513 Long. 11° 7'50.58"E.

514 **Figure 12.** Schematic cross-section detailing possible mechanics of en-echelon
515 formation.

516 **Figure 13.** Chronology of tectonic evolution, seafloor spreading, sedimentation,
517 magmatism, and azimuthal changes in the Kane Fracture Zone related to the evolution
518 of South Atlantic break-up. Igneous activity highlighted as follows: (1) Karroo and
519 Patagonia; (2) Parana-Etendeka (P-E); (3) early P-E dykes; (4) primary phase of P-E
520 bimodal volcanism; (5) late P-E dykes; (6) P-E alkaline magmatism; (7) widespread
521 duration of alkaline magmatism (onshore, near-shore and oceanic); (8) igneous activity
522 in Benue Trough recorded by dyke intrusion; (9) dyke intrusion in Benue Trough and

523 Brazil; (10) sub-alkaline, mafic magmatism in the Benue Trough, Campos, St Helena,
524 and Rio Grande Rise; (11) pulse of alkaline/peralkaline magmatism; (12) oceanic and
525 hotspot magmatism; and (13) Cenozoic igneous activity in Bornu Basin and other NE
526 parts of Nigeria (Grant et al., 1972a). Timings of igneous activity in the Bornu Basin
527 identified here (i.e. 1, 2, and 3) are compared to azimuthal changes in the Kane Fracture
528 Zone and occurrence of major intra-continental unconformities across South America
529 and Africa (yellow stars). Error bars for our proposed timings of igneous activity are
530 shown and reflect uncertainties in the relative dating of events. Figure adapted from
531 Torsvik et al., (2009) and Fairhead et al., (2013).

532

533 **References**

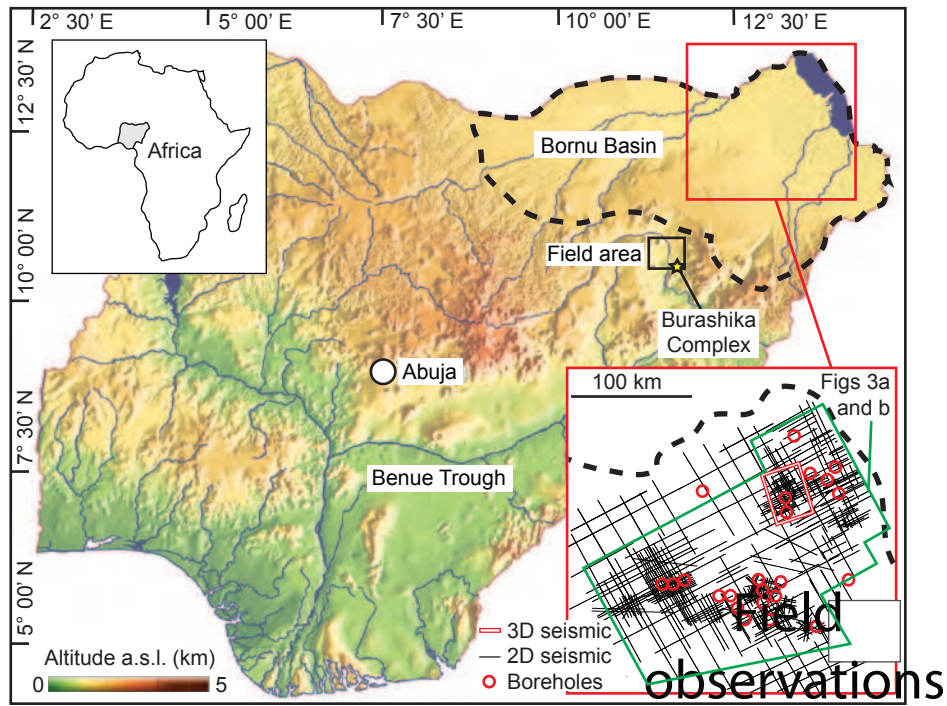
- 534 Alalade, B., and Tyson, R. V., 2013, Influence of igneous intrusions on thermal
535 maturity of Late Cretaceous shales in the Tuma well, Chad Basin, NE Nigeria:
536 *Journal of African Earth Sciences*, v. 77, p. 59-66.
- 537 Avbovbo, A., Ayoola, E., and Osahon, G., 1986, Depositional and structural styles in
538 Chad Basin of northeastern Nigeria: *Am. Assoc. Pet. Geol., Bull.:(United*
539 *States)*, v. 70, no. 12.
- 540 Benkhelil, J., Dainelli, P., Ponsard, J., Popoff, M., and Saugy, L., 1988, The Benue
541 Trough: Wrench fault related basin, on the border of the Equatorial Atlantic,
542 Triassic-Jurassic Rifting—Continental Breakup and the Origin of the Atlantic
543 Ocean and Passive Margins, Volume 22, Elsevier Amsterdam, p. 789-819.
- 544 Benkhelil, J., 1989, The origin and evolution of the Cretaceous Benue Trough
545 (Nigeria): *Journal of African Earth Sciences (and the Middle East)*, v. 8, no. 2,
546 p. 251-282.
- 547 Berndt, C., Bünz, S., Clayton, T., Mienert, J., and Saunders, M., 2004, Seismic
548 character of bottom simulating reflectors: examples from the mid-Norwegian
549 margin: *Marine and Petroleum Geology*, v. 21, no. 6, p. 723-733.
- 550 Carter, J. D., W., B. A., Tait, E. A., and G.P., J., 1963, The geology of parts of
551 Adamawa, Bauchi and Borno provinces in North - eastern Nigeria: *Bulleten*
552 *Geological Survey of Nigeria*, v. 30, p. 1-108.
- 553 Cukur, D., Horozal, S., Kim, D. C., Lee, G. H., Han, H. C., and Kang, M. H., 2010,
554 The distribution and characteristics of the igneous complexes in the northern
555 East China Sea Shelf Basin and their implications for hydrocarbon potential:
556 *Marine Geophysical Researches*, v. 31, no. 4, p. 299-313.
- 557 Davison, I. A. N., 1997, Wide and narrow margins of the Brazilian South Atlantic:
558 *Journal of the Geological Society*, v. 154, no. 3, p. 471-476.

- 559 Dixon, R. J., Schofield, K., Anderton, R., Reynolds, A. D., Alexander, R. W. S.,
560 Williams, M. C., and Davies, K. G., 1995, Sandstone diapirism and clastic
561 intrusion in the Tertiary submarine fans of the Bruce-Beryl Embayment,
562 Quadrant 9, UKCS: Geological Society, London, Special Publications, v. 94,
563 no. 1, p. 77-94.
- 564 Fairhead, J. D., 1988, Mesozoic plate tectonic reconstructions of the central South
565 Atlantic Ocean: The role of the West and Central African rift system:
566 Tectonophysics, v. 155, no. 1-4, p. 181-191.
- 567 Fairhead, J. D., Green, C. M., Masterton, S. M., and Guiraud, R., 2013, The role that
568 plate tectonics, inferred stress changes and stratigraphic unconformities have
569 on the evolution of the West and Central African Rift System and the Atlantic
570 continental margins: Tectonophysics, v. 594, no. 0, p. 118-127.
- 571 Galerne, C. Y., Galland, O., Neumann, E.-R., and Planke, S., 2011, 3D relationships
572 between sills and their feeders: evidence from the Golden Valley Sill Complex
573 (Karoo Basin) and experimental modelling: Journal of Volcanology and
574 Geothermal Research, v. 202, no. 3-4, p. 189-199.
- 575 Genik, G. J., 1992, Regional framework, structural and petroleum aspects of rift
576 basins in Niger, Chad and the Central African Republic (C.A.R.):
577 Tectonophysics, v. 213, no. 1-2, p. 169-185.
- 578 Grant, N., Rex, D., and Freeth, S., 1972a, Potassium-argon ages and strontium isotope
579 ratio measurements from volcanic rocks in northeastern Nigeria: Contributions
580 to Mineralogy and Petrology, v. 35, no. 4, p. 277-292.
- 581 Grant, N. K., Rex, D. C., and Freeth, S. J., 1972b, Potassium-argon ages and
582 strontium isotope ratio measurements from volcanic rocks in northeastern
583 Nigeria: Contributions to Mineralogy and Petrology, v. 35, no. 4, p. 277-292.
- 584 Guiraud, M., 1990, Tectono-sedimentary framework of the early Cretaceous
585 continental Bima formation (upper Benue Trough, NE Nigeria): Journal of
586 African Earth Sciences (and the Middle East), v. 10, no. 1-2, p. 341-353.
- 587 Guiraud, R., and Maurin, J.-C., 1992, Early Cretaceous rifts of Western and Central
588 Africa: an overview: Tectonophysics, v. 213, no. 1-2, p. 153-168.
- 589 Guiraud, R., and Bosworth, W., 1997, Senonian basin inversion and rejuvenation of
590 rifting in Africa and Arabia: synthesis and implications to plate-scale
591 tectonics: Tectonophysics, v. 282, no. 1-4, p. 39-82.
- 592 Hansen, D. M., and Cartwright, J., 2006a, Saucer-shaped sill with lobate morphology
593 revealed by 3D seismic data: implications for resolving a shallow-level sill
594 emplacement mechanism: Journal of the Geological Society, v. 163, no. 3, p.
595 509-523.
- 596 Hansen, D. M., and Cartwright, J., 2006b, The three-dimensional geometry and
597 growth of forced folds above saucer-shaped igneous sills: Journal of Structural
598 Geology, v. 28, no. 8, p. 1520-1535.
- 599 Huuse, M., and Mickelson, M., 2004, Eocene sandstone intrusions in the Tampen
600 Spur area (Norwegian North Sea Quad 34) imaged by 3D seismic data: Marine
601 and Petroleum Geology, v. 21, no. 2, p. 141-155.
- 602 Jackson, C. A.-L., Schofield, N., and Golenkov, B., 2013, Geometry and controls on
603 the development of igneous sill-related forced folds: A 2-D seismic reflection
604 case study from offshore southern Australia: Geological Society of America
605 Bulletin, v. 125, no. 11-12, p. 1874-1890.
- 606 Magee, C., Briggs, F., and Jackson, C. A.-L., 2013a, Lithological controls on igneous
607 intrusion-induced ground deformation: Journal of the Geological Society, v.
608 170, no. 6, p. 853-856.

- 609 Magee, C., Hunt-Stewart, E., and Jackson, C. A. L., 2013b, Volcano growth
610 mechanisms and the role of sub-volcanic intrusions: Insights from 2D seismic
611 reflection data: *Earth and Planetary Science Letters*, v. 373, no. 0, p. 41-53.
- 612 Magee, C., Jackson, C. A.-L., and Schofield, N., 2013c, The influence of normal fault
613 geometry on igneous sill emplacement and morphology: *Geology*, v. 41, no. 4,
614 p. 407-410.
- 615 Magee, C., Jackson, C. A. L., and Schofield, N., 2014, Diachronous sub-volcanic
616 intrusion along deep-water margins: insights from the Irish Rockall Basin:
617 *Basin Research*, v. 26, no. 1, p. 85-105.
- 618 Magee, C., Maharaj, S. M., Wrona, T., and Jackson, C. A.-L., 2015, Controls on the
619 expression of igneous intrusions in seismic reflection data: *Geosphere*, v. 11,
620 no. 4, p. 1024-1041.
- 621 Magee, C., Muirhead, J. D., Karvelas, A., Jackson, C. A-L., Bastow, I., Holford, S. P.,
622 Schofield, N., Stevenson, C. T. E., McLean, C., McCarthy, W., and Shtukert,
623 O., 2016, Lateral magma flow in sill-complexes: *Geosphere*, v. 12, no. 3, p. 1-
624 33.
- 625 Malthe-Sørenssen, A., Planke, S., Svensen, H., and Jamtveit, B., 2004, Formation of
626 saucer-shaped sills: *Geological Society, London, Special Publications*, v. 234,
627 no. 1, p. 215-227.
- 628 Meeuws, F. J. E., Holford, S. P., Foden, J. D., and Schofield, N., 2016, Distribution,
629 chronology and causes of Cretaceous – Cenozoic magmatism along the
630 magma-poor rifted southern Australian margin: Links between mantle melting
631 and basin formation: *Marine and Petroleum Geology*, v. 73, p. 271-298.
- 632 Nelson, C. E., Jerram, D. A., and Hobbs, R. W., 2009, Flood basalt facies from
633 borehole data: implications for prospectivity and volcanology in volcanic
634 rifted margins: *Petroleum Geoscience*, v. 15, no. 4, p. 313-324.
- 635 Obaje, N. G., Wehner, H., Abubakar, M. B., and Isah, M. T., 2004a, Nasara-I Well,
636 Gongola Basin (Upper Benue Trough, Nigeria): Source-Rock Evaluation:
637 *Journal of Petroleum Geology*, v. 27, no. 2, p. 191-206.
- 638 Obaje, N. G., Wehner, H., Hamza, H., and Scheeder, G., 2004b, New geochemical
639 data from the Nigerian sector of the Chad basin: implications on hydrocarbon
640 prospectivity: *Journal of African Earth Sciences*, v. 38, no. 5, p. 477-487.
- 641 Pérez-Díaz, L., and Eagles, G., 2014, Constraining South Atlantic growth with
642 seafloor spreading data: *Tectonics*, v. 33, no. 9, p. 1848-1873.
- 643 Planke, S., Symonds, P. A., Alvestad, E., and Skogseid, J., 2000, Seismic
644 volcanostratigraphy of large-volume basaltic extrusive complexes on rifted
645 margins: *Journal of Geophysical Research*, v. 105, no. B8, p. 19335-19351.
- 646 Planke, S., Rasmussen, T., Rey, S. S., And Myklebust, R., 2005, Seismic
647 characteristics and distribution of volcanic intrusions and hydrothermal vent
648 complexes in the Vøring and Møre basins: *Geological Society, London,*
649 *Petroleum Geology Conference series*, v. 6, p. 833-844.
- 650 Planke, S., Svensen, H., Myklebust, R., Bannister, S., Manton, B., and Lorenz, L.,
651 2015, *Geophysics and Remote Sensing: Berlin, Heidelberg, Springer Berlin*
652 *Heidelberg*, p. 1-16.
- 653 Pollard, D. D., Muller, O. H., and Dockstader, D. R., 1975, The form and growth of
654 fingered sheet intrusions: *Geological Society of America Bulletin*, v. 86, no. 3,
655 p. 351-363.
- 656 Polteau, S., Mazzini, A., Galland, O., Planke, S., and Malthe-Sørenssen, A., 2008,
657 Saucer-shaped intrusions: Occurrences, emplacement and implications: *Earth*
658 *and Planetary Science Letters*, v. 266, no. 1–2, p. 195-204.

- 659 Rickwood, P., 1990, The anatomy of a dyke and the determination of propagation and
660 magma flow directions: Mafic dykes and emplacement mechanisms, p. 81-
661 100.
- 662 Samaila, N., Abubakar, M., Dike, E., and Obaje, N., 2006, Description of soft-
663 sediment deformation structures in the Cretaceous Bima Sandstone from the
664 Yola Arm, Upper Benue Trough, Northeastern Nigeria: *Journal of African*
665 *Earth Sciences*, v. 44, no. 1, p. 66-74.
- 666 Schofield, N., Stevenson, C., and Reston, T., 2010, Magma fingers and host rock
667 fluidization in the emplacement of sills: *Geology*, v. 38, no. 1, p. 63-66.
- 668 Schofield, N., Heaton, L., Holford, S. P., Archer, S. G., Jackson, C. A.-L., and Jolley,
669 D. W., 2012a, Seismic imaging of 'broken bridges': linking seismic to
670 outcrop-scale investigations of intrusive magma lobes: *Journal of the*
671 *Geological Society*, v. 169, no. 4, p. 421-426.
- 672 Schofield, N. J., Brown, D. J., Magee, C., and Stevenson, C. T., 2012b, Sill
673 morphology and comparison of brittle and non-brittle emplacement
674 mechanisms: *Journal of the Geological Society*, v. 169, no. 2, p. 127-141.
- 675 Schofield, N., Holford, S., Millett, J., Brown, D., Jolley, D., R. Passey, S., Muirhead,
676 D., Grove, C., Magee, C., Murray, J., Hole, M., A.-L. Jackson, C., and
677 Stevenson, C., 2015, Regional magma plumbing and emplacement
678 mechanisms of the Faroe-Shetland Sill Complex: implications for magma
679 transport and petroleum systems within sedimentary basins: *Basin Research*,
680 p. n/a-n/a.
- 681 Sengör, A. M. C., and Burke, K., 1978, Relative timing of rifting and volcanism on
682 Earth and its tectonic implications: *Geophysical Research Letters*, v. 5, no. 6,
683 p. 419-421.
- 684 Skogseid, J., Pedersen, T., Eldholm, O., and Larsen, B. T., 1992, Tectonism and
685 magmatism during NE Atlantic continental break-up: the Vøring Margin:
686 *Geological Society, London, Special Publications*, v. 68, no. 1, p. 305-320.
- 687 Smallwood, J. R., and Maresh, J., 2002, The properties, morphology and distribution
688 of igneous sills: modelling, borehole data and 3D seismic from the Faroe-
689 Shetland area: *Geological Society, London, Special Publications*, v. 197, no. 1,
690 p. 271-306.
- 691 Symonds, P., Planke, S., Frey, O., and Skogseid, J., 1998, Volcanic evolution of the
692 Western Australian continental margin and its implications for basin
693 development: *The sedimentary basins of Western Australia*, v. 2, p. 33-54.
- 694 Thomson, K., and Hutton, D., 2004, Geometry and growth of sill complexes: insights
695 using 3D seismic from the North Rockall Trough: *Bulletin of Volcanology*, v.
696 66, no. 4, p. 364-375.
- 697 Thomson, K., 2007, Determining magma flow in sills, dykes and laccoliths and their
698 implications for sill emplacement mechanisms: *Bulletin of Volcanology*, v. 70,
699 no. 2, p. 183-201.
- 700 Torsvik, T. H., Rousse, S., Labails, C., and Smethurst, M. A., 2009, A new scheme
701 for the opening of the South Atlantic Ocean and the dissection of an Aptian
702 salt basin: *Geophysical Journal International*, v. 177, no. 3, p. 1315-1333.
- 703 Trude, J., Cartwright, J., Davies, R. J., and Smallwood, J., 2003, New technique for
704 dating igneous sills: *Geology*, v. 31, no. 9, p. 813-816.
- 705 Valentine, G. A., and Perry, F. V., 2007, Tectonically controlled, time-predictable
706 basaltic volcanism from a lithospheric mantle source (central Basin and Range
707 Province, USA): *Earth and Planetary Science Letters*, v. 261, no. 1-2, p. 201-
708 216.

- 709 Vigneresse, J. L., and Clemens, J. D., 2000, Granitic magma ascent and emplacement:
710 neither diapirism nor neutral buoyancy: Geological Society, London, Special
711 Publications, v. 174, no. 1, p. 1-19.
- 712 White, R., and McKenzie, D., 1989, Magmatism at rift zones: The generation of
713 volcanic continental margins and flood basalts: Journal of Geophysical
714 Research: Solid Earth, v. 94, no. B6, p. 7685-7729.
- 715 Xu, Y., Huang, W., Chen, T., Cui, R., and Chen, S., 2009, An evaluation of deep thin
716 coal seams and water-bearing/resisting layers in the quaternary system using
717 seismic inversion: Mining Science and Technology (China), v. 19, no. 2, p.
718 161-165.
- 719 Xu, Y., Chen, T., Chen, S., Huang, W., and Wu, G., 2010, Comparison between
720 several seismic inversion methods and their application in mountainous coal
721 fields of western China: Mining Science and Technology (China), v. 20, no. 4,
722 p. 585-590.
- 723 Zampetti, V., Sattler, U., and Braaksma, H., 2005, Well log and seismic character of
724 Liuhua 11-1 Field, South China Sea; relationship between diagenesis and
725 seismic reflections: Sedimentary Geology, v. 175, no. 1-4, p. 217-236.
- 726

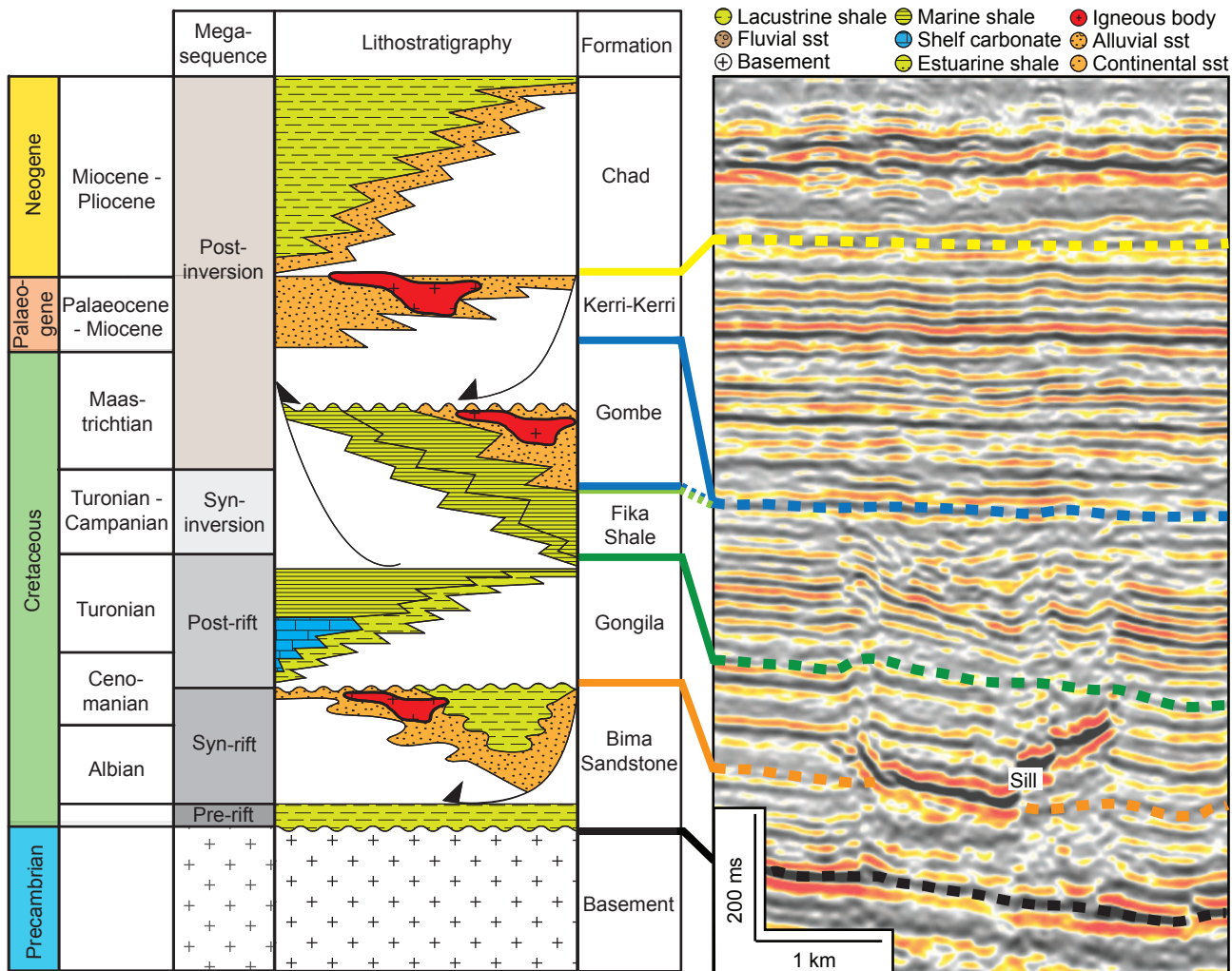


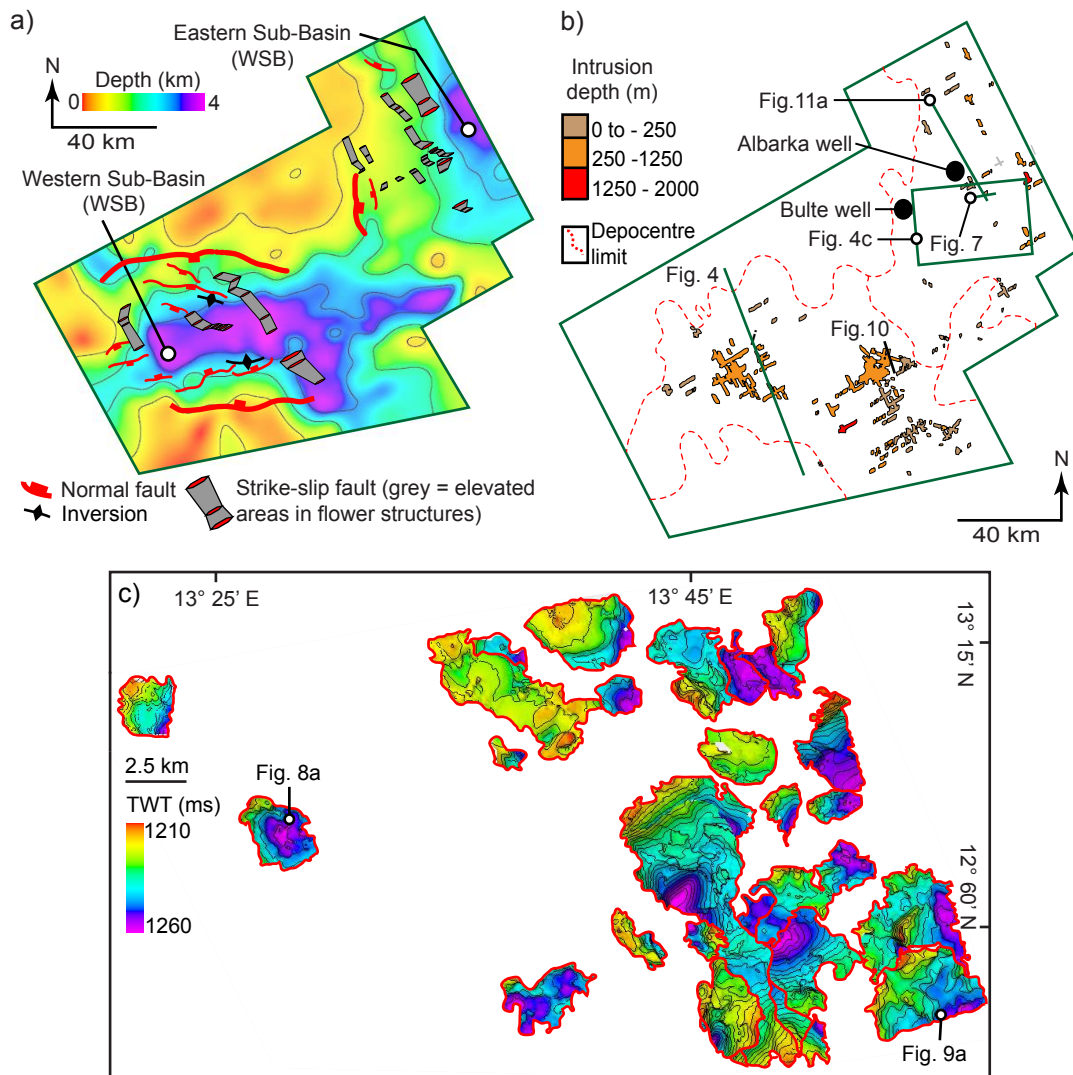
(Upper Benue Trough)

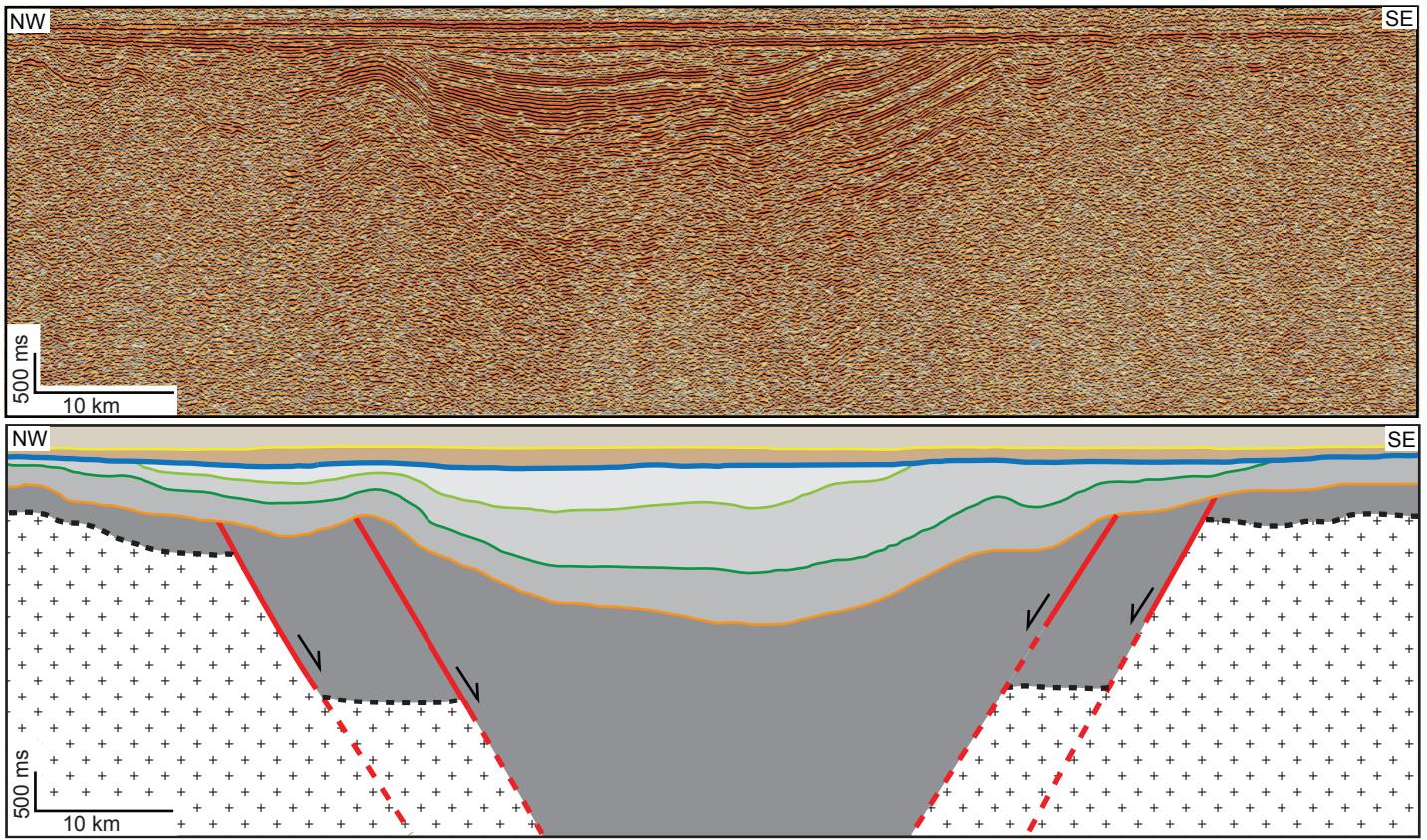
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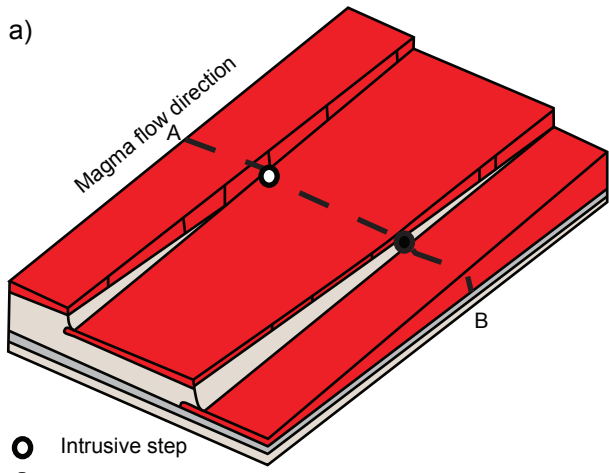
Benue Trough

Figure 2









- Intrusive step
- Broken bridge

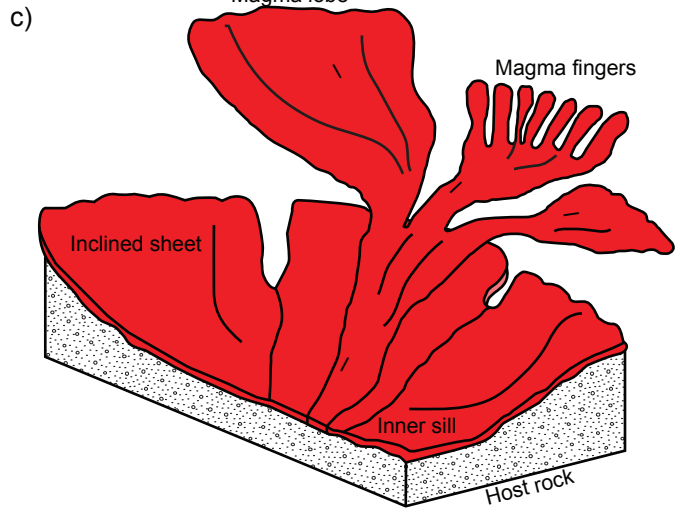
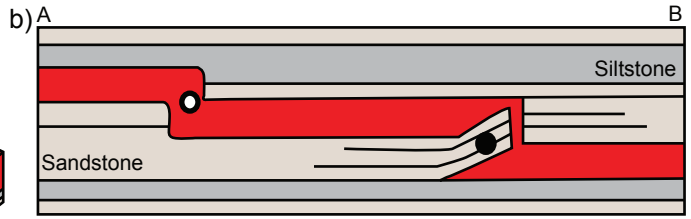
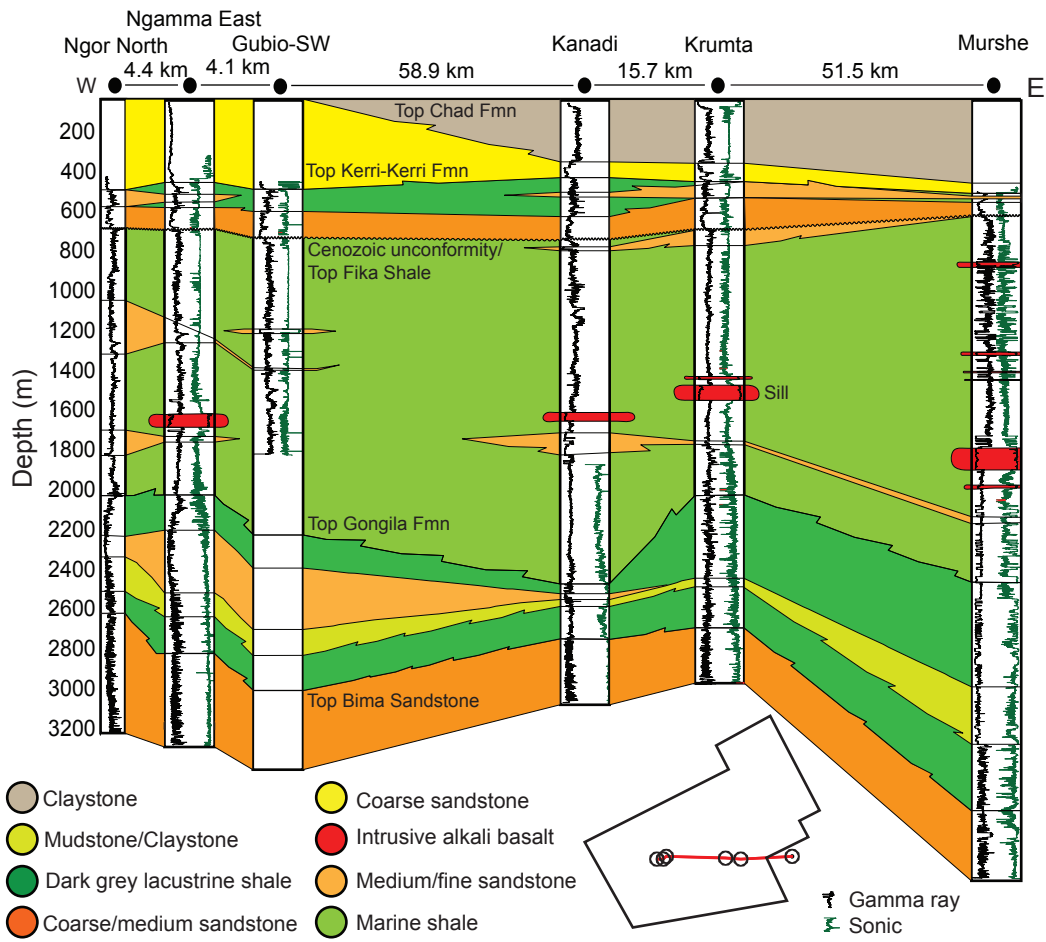
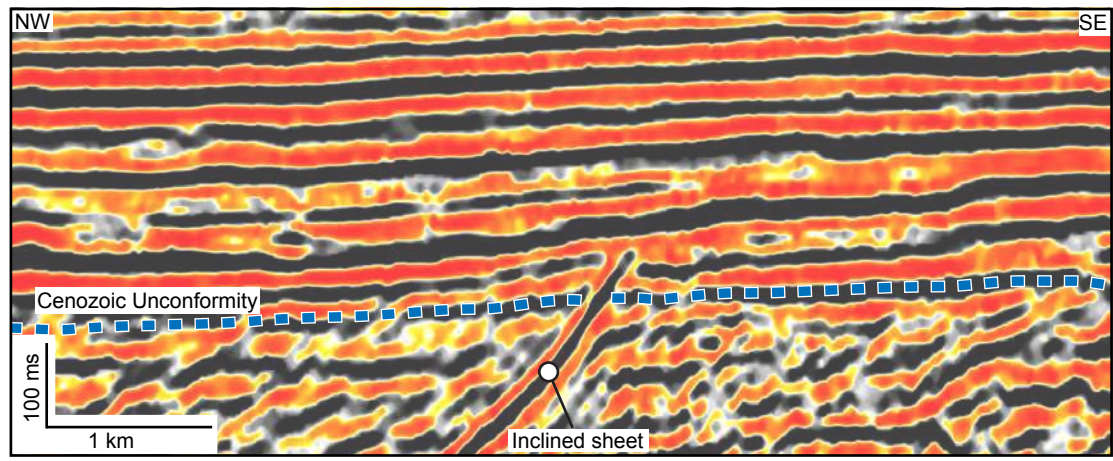
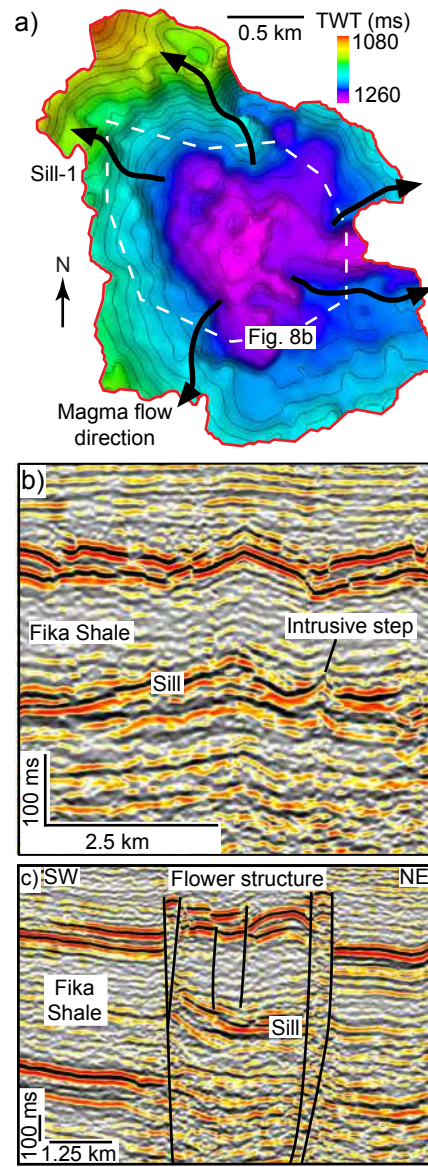
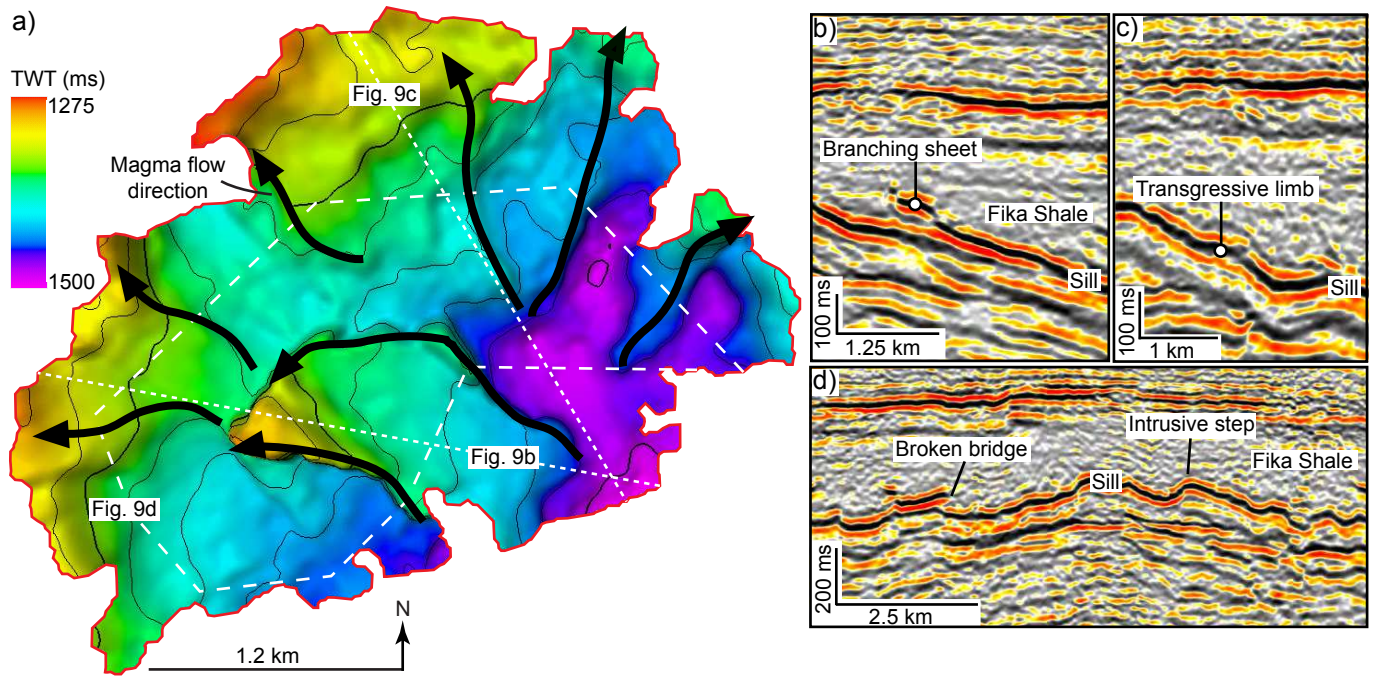


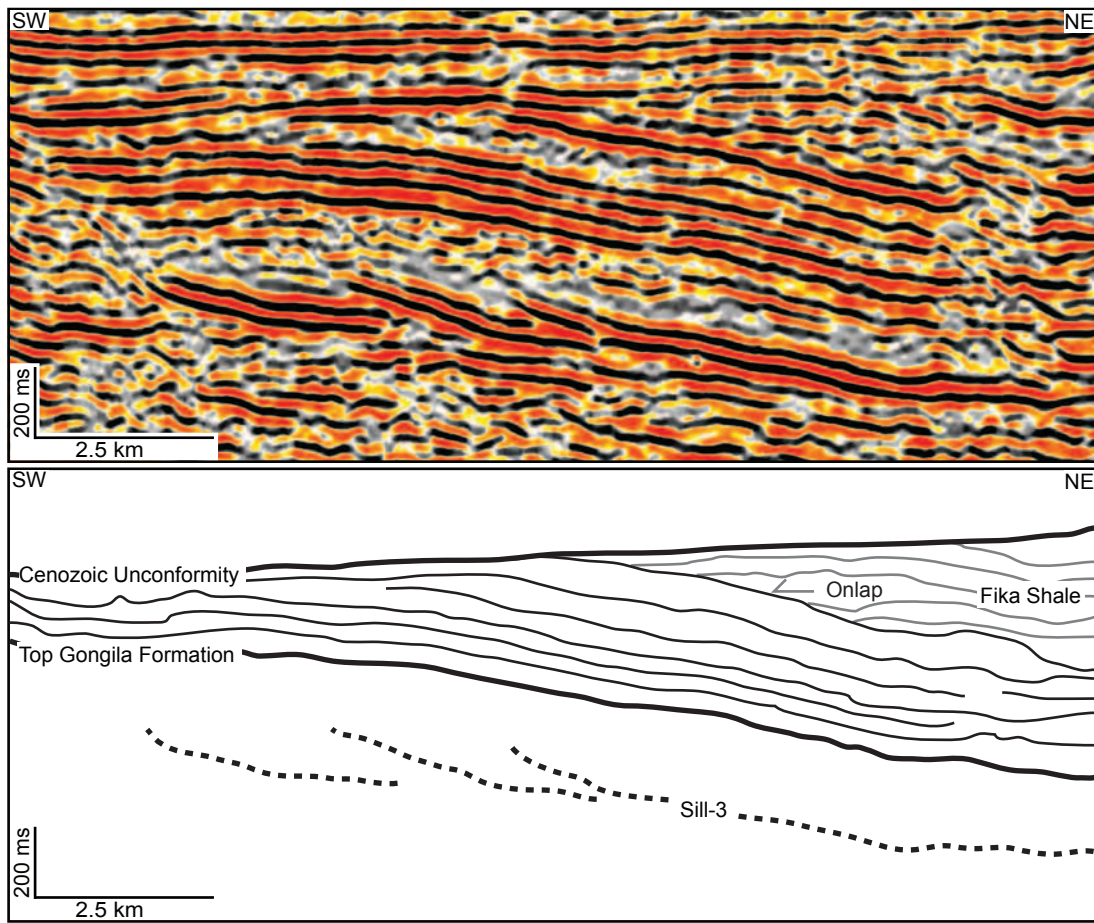
Figure 6

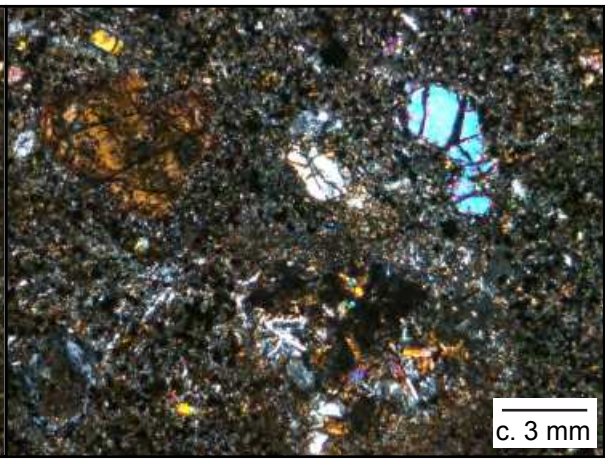
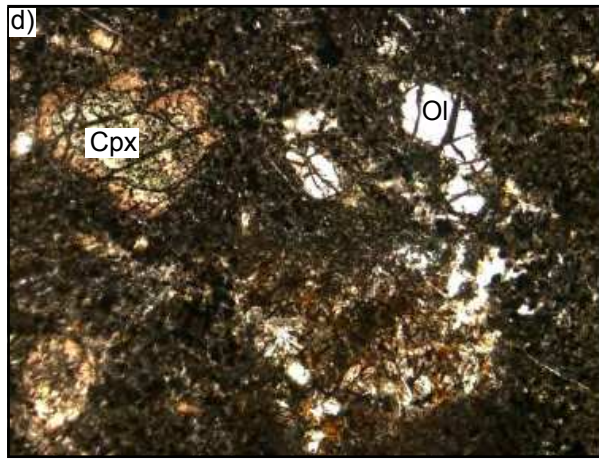
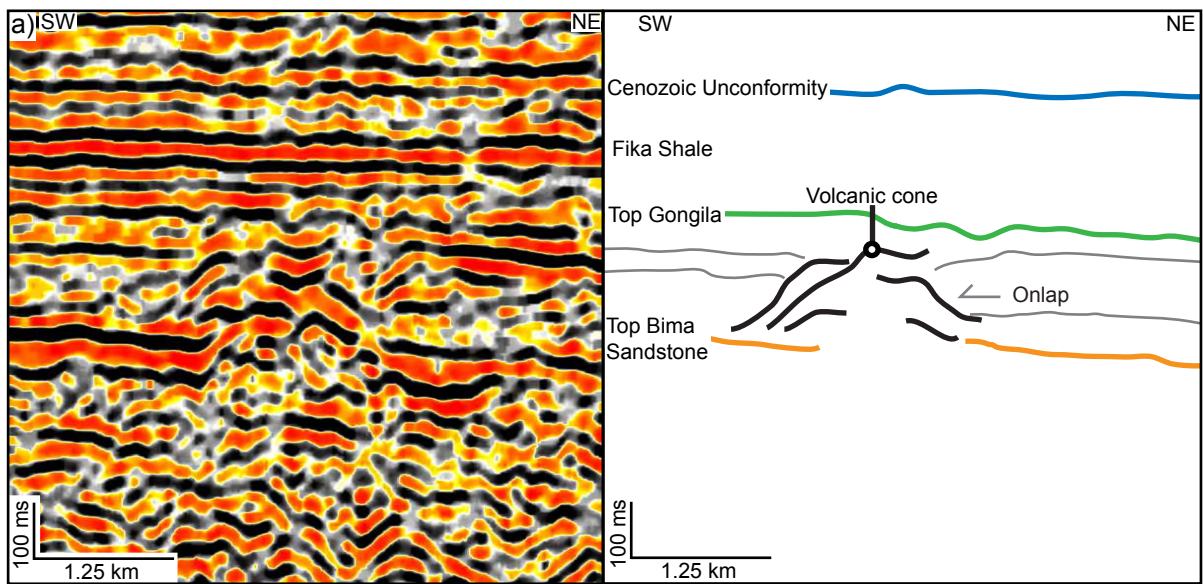












Observed en-echelon sill geometry



Magma sheet progradation (i)



Magma sheet aggradation (ii)



Magma sheet over/under accretion (iii)



Figure 13

