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1 Evidence for focused magmatic accretion at segment
2 centers from lateral dike injections captured beneath the
3 Red Sea rift in Afar

4 **Derek Keir^{1,2}, Ian J. Hamling¹, Atalay Ayele³, Eric Calais⁴, Cindy Ebinger⁵, Tim J.**
5 **Wright¹, Eric Jacques⁶, Kassim Mohamed⁷, James O.S. Hammond⁸, Manahloh**
6 **Belachew⁵, Elizabeth Baker², Julie V. Rowland⁹, Elias Lewi³, Laura Bennati⁴**

7 *¹School of Earth and Environment, University of Leeds, Leeds LS2 9JT, UK*

8 *²Department of Earth Sciences, Royal Holloway University of London, Egham TW20*
9 *0EX, UK*

10 *³Institute of Geophysics, Space Science and Astronomy, Addis Ababa University, Addis*
11 *Ababa PO Box 1176, Ethiopia*

12 *⁴Department of Earth and Atmospheric Sciences, Purdue University, West Lafayette,*
13 *Indiana 47907, USA*

14 *⁵Department of Earth and Environmental Sciences, University of Rochester, Rochester,*
15 *New York 14618, USA*

16 *⁶Institut de Physique du Globe de Paris, 4, Place Jussieu, 75252 Paris, France*

17 *⁷Observatoire de Géophysique d'Arta, Arta, Djibouti*

18 *⁸Department of Earth Sciences, University of Bristol, Bristol BS8 1RJ, UK*

19 *⁹School of Geography, Geology and Environmental Science, University of Auckland, New*
20 *Zealand*

21 **ABSTRACT**

22 Continental breakup occurs through repeated episodes of mechanical stretching
23 and dike injection within discrete, narrow rift segments. However, the time and length
24 scales of the dike intrusions, along with the source regions of melt within continental and
25 oceanic rifts, are poorly constrained. We present measurements of spatial and temporal
26 variability in deformation from the currently active 60-km-long Dabbahu segment of the
27 Red Sea rift in Afar, using satellite radar, global positioning system, and seismicity data
28 sets, that capture emplacement of two ~10-km-long, ~1–2-m-wide dike intrusions in June
29 and July 2006. Our observations show that the majority of strain is accommodated by
30 dikes that propagate laterally over ~4–5 h time scales along the rift axis and are sourced
31 from a reservoir in the middle to lower crust, or upper mantle, beneath the center of the
32 rift segment. New intrusions during the ongoing rifting episode in Afar show that the
33 injection of lateral dikes fed from magma reservoirs beneath rift segment centers is a key
34 component in creating and maintaining regular along-axis rift segmentation during the
35 final stages of continental breakup. Our observations also provide evidence that the
36 focused magmatic accretion at segment centers observed in slow-spreading mid-ocean
37 ridges occurs prior to the onset of seafloor spreading.

38 INTRODUCTION

39 Dike intrusion is a ubiquitous process achieving seafloor spreading in oceanic
40 rifts, and accommodating the majority of strain in some continental rift zones (e.g.,
41 Delaney et al., 1998; Buck, 2004). **However**, length and time scales of the extensional
42 process in magmatic rifts are poorly understood because the earthquake and surface
43 deformation induced by magma injection is so infrequently recorded by seismic and
44 geodetic monitoring equipment. We rely, therefore, on rare large dike intrusions to

45 quantify the associated strain patterns and magma sources (e.g., Björnsson et al., 1977;
46 Abdallah et al., 1979; Tolstoy et al., 2006).

47 In September 2005, a 60-km-long nascent seafloor-spreading segment of the Red
48 Sea rift in Afar (Ethiopia) ruptured with intrusion of a dike that marked the beginning of
49 a rifting episode (Wright et al., 2006; Ayele et al., 2007) (Fig. 1). We use a unique
50 combination of seismic, geodetic, and field data sets collected during rapid response
51 monitoring efforts to identify and model new discrete dike intrusions intruding beneath
52 the rift axis in June and July 2006. For the first time, we have captured and quantified the
53 process of bidirectional, lateral dike injection sourced from a magma reservoir beneath
54 the center of a rift segment prior to the onset of seafloor spreading.

55 **RIFT SEGMENTS IN AFAR**

56 Rifting between Arabia, Somalia, and Nubia during the past ~30 **m.y.** produced
57 the ~300-km-wide Afar depression at the triple junction between the Red Sea, Gulf of
58 Aden, and East African rifts, formed within the Paleogene flood basalt province
59 associated with the Afar mantle plume (Fig. 1) (e.g., Hofmann et al., 1997; Montelli et
60 al., 2004). Since **ca. 3 Ma**, faulting and volcanism in the subaerial Red Sea rift within
61 Afar have localized to ~15-km-wide, ~60-km-long faulted volcanic ranges with aligned
62 chains of basaltic cones and fissural flows. These rift segments (e.g., Dabbahu segment)
63 are similar in size, morphology, structure, and spacing to the **second-order** non-transform
64 segments of a slow-spreading mid-ocean ridge (Hayward and Ebinger, 1996; Manighetti
65 et al., 1998). Geodetic data **show that** current Nubia-Arabia extensional velocity is ~16
66 mm yr⁻¹ (Vigny et al., 2006), resulting in continued deformation of already highly
67 extended and intruded ~18–22-km-thick crust (Makris and Ginzburg, 1987).

68 During September 2005, $\sim 2.5 \text{ km}^3$ of magma was injected as near vertical dikes
69 into the upper $\sim 10 \text{ km}$ of crust beneath the entire $\sim 60\text{-km}$ -length of the Dabbahu segment,
70 and caused **as much as** $\sim 8 \text{ m}$ of horizontal opening. Magma accommodated $\sim 90\%$ of the
71 total geodetic moment, implying a relatively minor contribution by induced normal
72 faulting near the surface (Wright et al., 2006; Rowland et al., 2007). Simple elastic
73 models of deformation measured using **interferometric synthetic aperture radar (InSAR)**
74 show that deflation of shallow (5 km deep) magma chambers beneath Dabbahu and
75 Gab'ho volcanoes at the northern end of the segment accounts for only $\sim 20\%$ of total
76 dike volume. The volume imbalance between source and dike is explained by either
77 expansion of remaining magma in the chamber from gas exsolving caused by pressure
78 drop, or the presence of an additional source deeper beneath the rift (Wright et al., 2006).
79 However, neither seismicity nor geodetic data from the September 2005 dike can resolve
80 the position of important additional magma sources, or temporal and directional
81 characteristics of dike emplacement. Only in the few months following September 2005
82 **did** a broad $\sim 10 \text{ cm}$ uplift of the Ado' Ale Volcanic Complex **[[SU: AVC spelled out**
83 **herein; no further highlighting]]** near the center of the Dabbahu segment provide some
84 evidence of a middle to lower crustal magma reservoir (Calais et al., 2006; Ebinger et al.,
85 2008).

86 **DEFORMATION BENEATH RIFT SEGMENT CENTER**

87 Seismicity patterns recorded on temporary and permanent stations in Ethiopia and
88 Djibouti provide a continuous record of deformation in Afar (Fig. 1). Details of data sets
89 and methods are supplied in **the GSA Data Repository**¹ and all quoted times are in
90 Greenwich Mean Time (GMT). Between April and August 2006, 182 earthquakes (M_L

91 1.4–4.7) were located in Afar (Fig. 1). The majority of seismicity is along the axis of the
92 Dabbahu segment and occurred within one of two major earthquake swarms on 17–22
93 June and 25–26 July 2006 that ruptured the same 2–3-km-wide zone as in September
94 2005.

95 We use radar data acquired by the European Space Agency’s Envisat satellite to
96 form ascending and descending interferograms that record the surface deformation in
97 Afar, providing a framework for seismicity and continuous global positioning system
98 (cGPS) studies outlined below. Interferograms spanning seismic swarms show intense
99 deformation at the Dabbahu segment center (Fig. 2). Simple elastic modeling of
100 combined InSAR and cGPS data shows that deformation is consistent with tensile
101 dislocation (dike) and minor amount of induced fault slip near the surface (Fig. 2). The
102 first modeled dike is ~10 km long, intrudes 0–10 km depth range, has an opening that
103 varies from near zero at the dike tips to a maximum of 2.2 ± 0.1 m, estimated volume of
104 0.12 ± 0.02 km³, and released 3.7×10^{18} Nm geodetic **moment**. **[[SU: ok, or moment**
105 **magnitude?]]** The second modeled dike is ~9 km long, intrudes 0–5 km depth range, has
106 a maximum opening of 1.1 ± 0.1 m, estimated volume of 0.07 ± 0.02 km³, and released
107 2.2×10^{18} Nm geodetic **moment**. **[[SU: ok, or moment magnitude?]]** Neither dike
108 intrusions are accompanied by subsidence of Dabbahu and Gab’ho volcanoes, nor do
109 elastic models require deflation of a Mogi source beneath the Ado’Ale Volcanic
110 Complex.

111 Seismicity and cGPS were used to detect the timing and location of dike
112 intrusions. On 17 June 2006, the National Earthquake Information Center (NEIC)
113 reported five earthquakes of m_b 3.9–4.6 scattered across an ~20-km-wide zone near the

114 Ado' Ale Volcanic Complex (Fig. 2). However, data from nearby stations significantly
115 improve the record of seismicity. During 17–22 June, 73 earthquakes of M_L 2.5–4.7 were
116 located within an ~10-km-long, ~5-km-wide, N-NW–striking cluster on the eastern side
117 of the rift axis where it cuts the northern flank of the Ado' Ale Volcanic Complex,
118 coincident with spatial extent of surface deformation recorded by InSAR (Fig. 2).

119 The first recorded earthquake occurred at 12:39 **[[SU: specify “local” (or**
120 **astronomical) time in parens here?]]** near the southern end of the swarm (Fig. 3).
121 Activity remained low until 13:16, and during the following 4 h a swarm of seismicity
122 progressively migrated northward to a total distance of ~10 km at an average velocity of
123 ~0.5 m/s. However, close inspection of data shows that between 13:16 and 14:33
124 seismicity migrated ~6 km at a velocity of as much as ~1.5 m/s, after which the migration
125 rate decayed. The largest magnitude earthquakes (and resulting majority of total $1.8 \times$
126 10^{17} Nm seismic moment) **[[SU: ok, or moment magnitude?]]** occurred during the ~4-
127 h-long phase of swarm migration. From 17:30 17 June until 22 June, low-magnitude (M_L
128 <3.5) seismicity was scattered throughout the deforming zone. Earthquake depths cannot
129 be reliably constrained from our seismic data recorded on few distant stations. However,
130 depth-constrained rift axis seismicity from higher resolution data shows an ~8-km-thick
131 seismogenic layer (Ebinger et al., 2008).

132 On 17 June 2006, cGPS data from station DA25 located 25 km west of the
133 Dabbahu segment showed 47 mm westward motion (Fig. 2). The spatial coincidence
134 between locus of seismicity and modeled dike (Fig. 2), as well as temporal coincidence
135 between rift opening and migrating seismicity (Fig. 3), suggests that the migrating swarm

136 of larger magnitude seismicity is caused by inflation-induced tension near the tip of a
137 propagating dike (e.g., Rubín and Gillard, 1998; Roman and Cashman, 2006).

138 Few earthquakes were recorded until 25–26 July, when 19 M_L 2–3 earthquakes
139 were detected in an ~15-km-long, N-NW–S-SE–elongate cluster on the eastern side of
140 the rift axis where it cuts the southern flank of the Ado’Ale Volcanic Complex (Fig. 2).
141 Between 20:00 and 21:00 on 25 July, seismicity occurred near the northern end of the
142 swarm, and during the following 6 h it migrated 15 km south at an average velocity of
143 ~0.75 m/s (Fig. 3). However, within the first 1.5 h the swarm initially migrated **as much**
144 **as 6 km** at >1 m/s, after which the rate of migration decayed. Total seismic **moment**
145 **[[SU: ok, or moment magnitude?]]** release is estimated as 1.6×10^{15} Nm.

146 The satellite radar, cGPS, and seismicity data show that two discrete, rift-parallel
147 dike intrusions occurred beneath the center of the Dabbahu segment. Dikes occurring on
148 17 June and 25 July intruded beneath the northern and southern flanks of the Ado’Ale
149 Volcanic Complex, respectively, and propagated laterally in the crust from a single
150 source positioned approximately beneath the center of the **complex**. Both dikes intruded
151 over ~4–5 h time scales, during which the amount and magnitude of seismicity **peaked**.
152 Seismic moment release accounts for only 5% of 3.71×10^{18} Nm geodetic **moment** **[[SU:**
153 **ok, or moment magnitude?]]** released on 17 June, and $<1\%$ of 2.2×10^{18} Nm released
154 on 25 July. Therefore, magma intrusion accounts for the vast majority of deformation
155 during diking.

156 **DISCUSSION**

157 The spatial and temporal characteristics of magma intrusion in the Dabbahu
158 segment share similarities with the 1975–1984 Krafla rifting episode in northern Iceland,

159 during which 9 m of rift opening was achieved through 20 discrete basaltic intrusions and
160 fissural eruptions (Buck et al., 2006). The complex pattern of lateral, bidirectional dike
161 propagation from a single source observed in Krafla is closely mimicked in numerical
162 models assuming that dike propagation is driven by the difference between background
163 stress and magma pressure (Buck et al., 2006). In such a scheme, successive dikes are
164 preferentially drawn from a central chamber toward regions with the lowest minimum
165 compressive stress, reaching the surface once background stress is completely relieved by
166 intrusion. Dikes injected beneath the Dabbahu segment in June and July 2006 did not
167 reach the surface, ruling out direct observations of dike composition. However, the
168 similarity in propagation velocities (1–2 m/s) between dikes in Afar and Krafla
169 (Einarsson and Brandsdóttir, 1980) and observed fissural basaltic eruption during August
170 2007 in the Dabbahu segment strongly point to basaltic dikes (G. Yirgu, **[[SU: need year
171 of commun.; 2007 or 2008?]] personal commun.**).

172 The combination of cGPS and seismicity data from the Dabbahu rift constrains
173 the timing of dike growth. The temporal correlation between rift opening and seismicity
174 coupled with marked reduction in amount and magnitude of seismicity at the cessation of
175 swarm migration indicate that dike widening stopped when the tip of the dike stopped
176 opening (e.g., Roman and Cashman, 2006). However, due to the physical complexities of
177 diking, it is not clear whether the observed progressive decay in velocity of dike
178 propagation is primarily controlled by (1) a drop in magma pressure as the dikes **grow**
179 **along** **[[SU: comma removed after “grow”; correct meaning (or “controlled
180 by...grow, rift gradients...”]? Numbers inserted for clarity]]** rift gradients in tectonic
181 stress, (2) decrease in driving pressure gradient as the dike size increases, or (3)

182 resistance to flow from dike freezing (e.g., Lister and Kerr, 1991; Fialko and Rubin,
183 1998).

184 The combined data sets indicate that the dikes are sourced from the center of the
185 Dabbahu segment, yet the subsidence expected from withdrawal of magma from a
186 chamber is not observed in InSAR or cGPS data. Our geodetic data cannot constrain the
187 depth of the magma source. The absence of subsidence at the surface is likely in part due
188 to magma expansion in the chamber caused by gas exsolving as pressure falls during
189 magma escape, and/or the lower stiffness of tensile fractures compared to a spherical
190 magma chamber (Rivalta and Segall, 2008). However, dikes being fed from a lower or
191 subcrustal source is supported by cGPS and InSAR data in the few months following
192 September 2005 that show a 15-km-wide zone beneath the Ado' Ale Volcanic Complex
193 with 10 cm of uplift, consistent with an inflating Mogi source **[[SU: cite Mogi, 1958, or**
194 **understood (common now)?]]** 10–15 km deep (Calais et al., 2006). In addition,
195 geochemistry of recent basalts is consistent with typical mid-ocean ridge basalts
196 contaminated by gabbroic cumulates near the base of the crust (Barrat et al., 2003),
197 lending further support to the presence of a lower or subcrustal zone of melt
198 accumulation. Our new observations also imply that some of the missing magma **[[SU:**
199 **no quotes]]** supplied to the ~60-km-long September 2005 dike was sourced from the
200 center of the Dabbahu segment, and that total deformation accrued from the intrusion of
201 more than one discrete dike.

202 The inferred dike source is below the along-axis topographic high created by the
203 summit of the Ado' Ale Volcanic Complex. This suggests that the magma plumbing
204 system that focuses magma beneath the center of the Dabbahu segment has maintained

205 positional stability for at least as long as the age of the Ado' Ale Volcanic Complex,
206 estimated as between 0.3 and 1.5 Ma [\[\[SU: absolute age correct here?\]\]](#) (Lahitte et al.,
207 2003). Active dike intrusion in Afar is currently focused solely within the Dabbahu
208 segment, showing that the melt supply beneath the middle of the rift segment that drives
209 deformation is spatially and temporally distinct from adjacent rift segments. This also
210 implies that the magma source beneath each rift segment only contains sufficient partial
211 melt to supply dikes on an episodic basis. In the Ethiopian rift, a system less evolved than
212 the subaerial Red Sea rift, structural and geophysical data show discrete, narrow, ~60-
213 km-long rift segments highly intruded by mafic dikes (Keir et al., 2006). This, coupled
214 with episodic historical fissuring and effusive basaltic eruptions, suggests that episodic
215 magma-assisted rifting, as observed in the Red Sea rift, initiates during the early stages of
216 continental breakup.

217 In Afar, there are clear similarities in the spatial and temporal characteristics of
218 melt supply with patterns observed at slow-spreading mid-ocean ridges, where the regular
219 along-axis segmentation is thought to be produced by a segmented magma supply in
220 passively upwelling mantle that feeds episodic crustal dike injection (e.g., Whitehead et
221 al., 1984). Gravity data, as well as controlled source seismic data from the Mid-Atlantic
222 ridge, show that melt is focused in lower crust beneath the center of rift segments, where
223 cooling and crystallization of associated crustal melt lenses accretes relatively thick crust
224 beneath along-axis bathymetric highs (e.g., Lin et al., 1990; Tolstoy et al., 1993; Singh et
225 al., 2006). These short-lived crustal melt bodies episodically feed lateral propagation of
226 basaltic dikes over tens of kilometers that accrete relatively thinner crust beneath axial
227 grabens toward segment ends (e.g., Smith and Cann, 1999).

228 **CONCLUSION**

229 Our observations of deformation in the Dabbahu segment show that injection of
230 multiple basaltic dikes along the axis of the rift accommodates the majority of strain
231 during episodes of rapid rift opening. Magma is sourced directly to the center of the rift
232 segment from reservoirs in the middle to lower crust or upper mantle and delivered into
233 the upper 10 km during lateral dike injection, inducing seismicity and associated fault
234 growth. Observations show the segmented magma supply responsible for the second-
235 order along-axis segmentation of oceanic rifts develops prior to continental breakup, and
236 it is maintained by episodes of basaltic dike intrusion.

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346 **FIGURE CAPTIONS**

347 Figure 1. Earthquakes during April–August 2006 recorded on temporary broadband
348 seismic stations (triangles) and permanent short period stations (squares). Seismic
349 stations are in named towns and stars denote **continuous global positioning system**
350 **(cGPS)** stations. Major volcanic centers: A—Ado’Ale Volcanic Complex, D—Dabbahu,
351 E—Erta’Ale, F—Fielle, G—Gabho. Dashed white line shows axis of Dabbahu segment;
352 dashed black lines show axes of other subaerial Red Sea rift segments. Top right inset
353 shows location of Afar. **[[SU: what is ATD in lower right of figure?]]**

354

355 Figure 2. A: Seismicity during 20 May–24 June 2006 on topography. B: Seismicity
356 during 20 May–24 June 2006 on descending interferogram. White circles are earthquake
357 locations as recorded by the local network and gray circles are five earthquakes reported
358 by **National Earthquake Information Center** on 17 June. Dashed black line is position of
359 along-axis topographic profiles in Figure 3. Segment-long red line shows position of

360 modeled September 2005 dike. White arrow shows horizontal motion at **continuous**
361 **global positioning system station** DA25. Error ellipse shows 95% confidence interval.
362 Solid red line on interferograms shows position of modeled dike shown in C. C: Elastic
363 model of June 2006 dike opening. **D, E: As in A and B**, except seismicity and descending
364 interferogram span 24 June–29 July 2006. **AVC—Ado’Ale Volcanic Complex** F: Elastic
365 model of July 2006 dike opening. **[[SU: what is Az, Los in B, E?]]**

366

367 Figure 3. A: **East-west** motion at **continuous global positioning system station** (cGPS)
368 DA25 and along-axis position of earthquakes in the Dabbahu segment against time.
369 Earthquakes are colored and scaled by magnitude and error bars are measured errors in
370 arrival times. Two horizontal lines correspond to inferred dike source. Data within dashed
371 rectangles are **zoomed**. **[[SU: or enlarged (for detail)?]]** Along-axis topographic profile
372 displayed in Figure 2 is in right panel. B: **Three** days **east-west** motion at cGPS DA25.
373 Shaded histograms are seismic moment release in 2 h intervals and **show that** rift opening
374 is coincident with peak in seismicity. C: Along-axis position in seismicity, as in A, but
375 over ~1 day, showing migration of seismic swarms away from **Ado’Ale Volcanic**
376 **Complex**. Histograms show seismic moment release binned at hour intervals and plotted
377 on log scale. **GMT—Greenwich Mean Time**.

378 ¹GSA Data Repository item 2009xxx, **[[SU: need item designation and description**
379 **here]]**, is available online at www.geosociety.org/pubs/ft2009.htm, or on request from
380 editing@geosociety.org or Documents Secretary, GSA, P.O. Box 9140, Boulder, CO
381 80301, USA.