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LETTERS

Magma-maintained rift segmentation at continental rupture in the 2005 Afar dyking episode

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Seafloor spreading centres show a regular along-axis segmentation thought to be produced by a segmented magma supply in the passively upwelling mantle[1,2]. On the other hand, continental rifts are segmented by large offset normal faults, and many lack magmatism. It is unclear how, when and where the ubiquitous segmented melt zones are emplaced during the continental rupture process. Between 14 September and 4 October 2005, 163 earthquakes (magnitudes greater than 3.9) and a volcanic eruption occurred within the ∼60-km-long Dabbahu magmatic segment of the Afar rift, a nascent seafloor spreading centre in stretched continental lithosphere[3,4]. Here we present a three-dimensional deformation field for the Dabbahu rifting episode derived from satellite radar data, which shows that the entire segment ruptured, making it the largest to have occurred on land in the era of satellite geodesy. Simple elastic modelling shows that the magmatic segment opened by up to 8 m, yet seismic rupture can account for only 8 per cent of the observed deformation. Magma was injected along a dyke between depths of 2 and 9 km, corresponding to a total intrusion volume of $\sim 2.5\,\mathrm{km}^3$. Much of the magma appears to have originated from shallow chambers beneath Dabbahu and Gabho volcanoes at the northern end of the segment, where an explosive fissural eruption occurred on 26 September 2005. Although comparable in magnitude to the ten year (1975–84) Krafla events in Iceland[5], seismic data suggest that most of the Dabbahu dyke intrusion occurred in less than a week. Thus, magma intrusion via dyking, rather than segmented normal faulting, maintains and probably initiated the along-axis segmentation along this sector of the Nubia–Arabia plate boundary.

Rifting of Africa and Arabia during the past ∼30 Myr produced the ∼300-km-wide Afar depression, which comprises the Afar triple junction. The three rift arms formed within a Palaeogene flood basalt province associated with the Afar mantle plume[4,6,7]. The Dabbahu rift event occurred in the northern, or Red Sea, arm of the Afar triple junction (Fig. 1). Since ∼4 Myr ago, faulting and volcanism within the northern Afar depression have localized to ∼60-km-long axial volcanic ranges with aligned chains of basaltic cones, shallow seismicity and fissural flows, punctuated by stratovolcanoes. These volcanically and seismically active 'magmatic segments'—Dabbahu (Boina), Alayta, Tat 'Ale and Erta 'Ale—are similar in size, morphology, structure and spacing to slow-spreading mid-ocean-ridge segments[4]. The highly extended and intruded crust beneath the Afar depression is ∼18–22 km thick, with strong similarities to crust beneath Iceland[6,8]. Global plate reconstructions based on geological and geodetic data suggest an average spreading rate of $\sim 16\,\mathrm{mm\,yr^{-1}}$ (ref. 9).

The current volcano-seismic crisis in the Dabbahu magmatic segment began on 14 September 2005 with an earthquake of body-wave magnitude (M_b) ∼4.7 (Fig. 1; Supplementary Table SM1). Nearly continuous seismic activity, including tremor, was registered at station FURI (Addis Ababa) between 24 and 26 September. Earthquake locations show that before 25 September, most seismicity occurred in the northern half of the segment, with the greatest earthquake density around Dabbahu and Gabho volcanoes (Fig. 1). The majority of earthquakes from 25 to 29 September occurred south of the two volcanoes. On 26 September, a 500-m-long, 60-m-deep, north–south oriented vent and faults opened on the eastern flank of Dabbahu volcano, south of a small volcanic cone known as Da'Ure (Supplementary Figs SM2–SM5). Initial analysis of pumice erupted

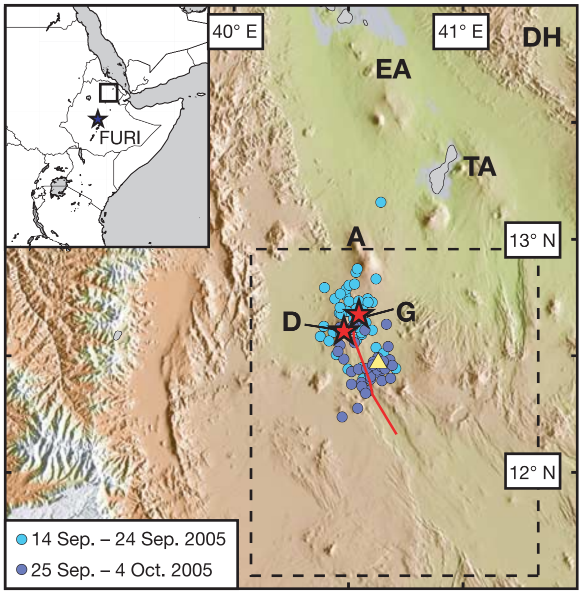

Figure 1 | Coloured and shaded relief map for northern Afar, and study area. Main figure shows the location of the dyke (red line) intruded along the entire Dabbahu magmatic segment, and Gabho (G) and Dabbahu (D) stratovolcanoes (red stars), superimposed on a coloured and shaded relief map derived from the Shuttle Radar Topographic Mission elevation model. Filled circles are earthquake epicentral locations (relative to the event marked by the yellow triangle) determined using the JED method, grouped before and after 24 September 2005. Most events occurred between 20 and 29 September 2005. The ∼60-km-long Dabbahu, Alayta (A), Tat 'Ale (TA) and Erta 'Ale (EA) tectono-magmatic segments are the locus of Quaternary strain[3,4]. To the northeast, the Afar depression is bounded by the northwest–southeast-trending Danakil horst (DH), and to the west, by the western escarpment. Dashed box encloses area shown in Fig. 2. Inset, location of study area with respect to East Africa and seismic station FURI, near Addis Ababa (star).

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from the vent is consistent with a felsic source at a depth of <6 km reheated by injection of basaltic magma.

We use radar data acquired by the European Space Agency's Envisat satellite to form ascending and descending interferograms that record the deformation in the Dabbahu event (Fig. 2a, b; Supplementary Table SM2). In addition we formed range and azimuth offset maps by correlating the radar amplitude images[10] (Fig. 2c–f). Although these data are noisier than interferograms (Supplementary Table SM3), they do not require phase unwrapping and can provide measurements in places where interference fringes break down owing to high deformation gradients. By inverting these four scalar projections of the surface displacement field, where they overlap and are coherent, we have been able to estimate the three-dimensional displacement field of the Dabbahu rifting event[11] (Fig. 3a; Supplementary Methods).

The horizontal component of the deformation field at the surface shows a maximum opening of 6 m perpendicular to the Dabbahu rift segment (Fig. 3a). Along most of the rift, horizontal displacement vectors are fairly symmetrical and perpendicular to the centre of the rift. An approximately 25-km-wide zone centred on the rift was uplifted along most of the 60-km-long rift segment; uplift reached a maximum of ~1.5 m on both rift flanks (Fig. 3a, d). A 2–3-km-wide central zone, flanked by sharp discontinuities on either side, subsided by up to 2 m. At the northern end of the rift, 2–3 m of subsidence occurred around the Dabbahu and Gabho magmatic centres. Horizontal displacement vectors near the two volcanoes at the northern tip of the Dabbahu segment point radially inward.

Both the narrow zone of subsidence within the central rift and the shoulder uplift along the length of the Dabbahu segment are consistent with the displacement field expected for a large-scale vertical dyke intrusion with induced faulting[5,12,13]. The dyke did not reach the surface along most of its length, suggesting that normal faulting occurred ahead of and/or above the laterally propagating dyke, enhancing the graben subsidence caused by the magma emplacement alone[12]. The trends of the inferred normal faults and dyke closely match the orientations of faults previously mapped along the length of the Dabbahu segment[4], and those found in the field (Supplementary Figs SM1–SM3).

To estimate the vertical distribution of opening, the volume of intruded magma, the amount of fault slip and the amount of magma sourced from the shallow chambers, we set up a simple elastic model that contains simplified geometries for all of the causative elements. The model has magma chambers beneath Dabbahu and Gabho volcanoes, represented by two point deflation sources[14] at depths of 5 km, as suggested by initial analyses of erupted pumice. The dyke is modelled as a tensile dislocation in an elastic half space extending vertically from the surface to a depth of 10 km, following the centre of the observed subsidence, discretized into a series of rectangular patches, ~2 km long and 1 km wide[15]. Tests where we allowed the dyke to extend deeper showed that no opening was required outside this depth range. The near-surface normal faults are modelled as elastic dislocations dipping at 65° along the boundaries of the subsiding areas. They extend until they intersect the dyke—at 1 km depth in the north, 2 km in the centre and 2.5 km at the southern end, where the dyke is widest. The faults are discretized into 2-km patches along strike, and only normal slip is allowed.

Having fixed the model geometry, we carried out a simple least-squares inversion to determine the amount of dyke opening, fault slip and volume changes at the magma chambers that best fit the radar data, which were subsampled and weighted using the inverse of their full covariance matrices[16]. To prevent oscillatory solutions, the inversion was regularized with a positivity constraint and by requiring the spatial distribution to be smooth, the weight of the laplacian smoothing term being chosen as the best compromise between solution roughness and misfit. Uncertainties in our parameters were determined by Monte Carlo simulation of correlated noise[17].

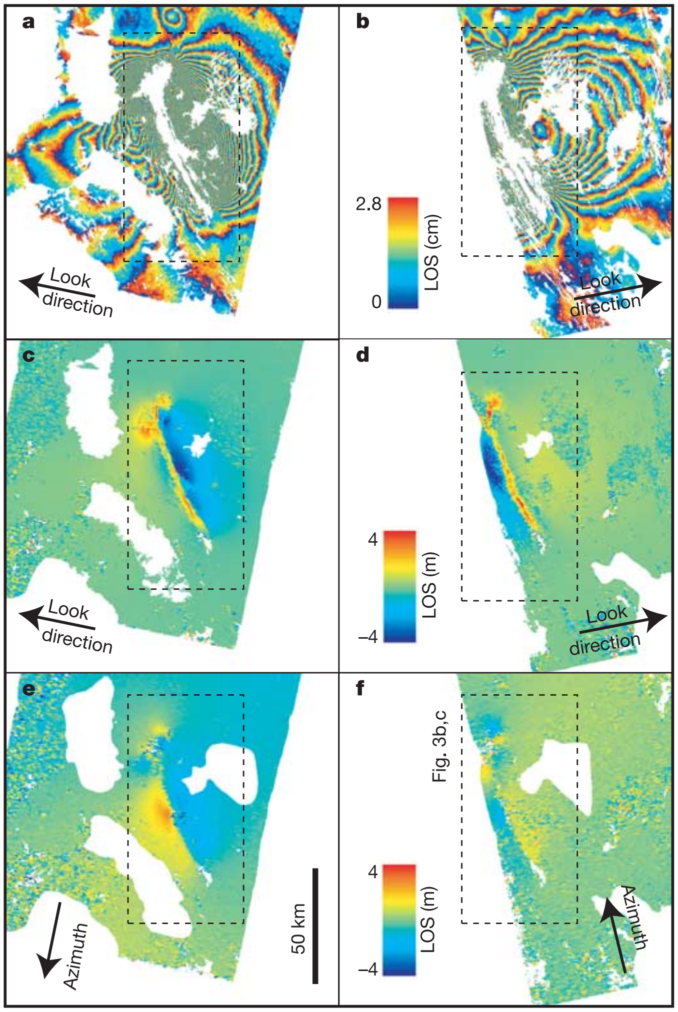

Figure 2 | Satellite radar data spanning the 2005 Dabbahu rifting event produced using data from ESA's Envisat satellite. Left column (**a**, **c**, **e**) from descending track 49 using images acquired on 6 May and 28 October 2005, IS2 beam mode; right column (**b**, **d**, **f**) from ascending track 29 images on 28 July 2005 and 26 October 2005. **a**, **b**, Wrapped interferograms; **c**, **d**, range change (unwrapped interferogram where available, range offsets elsewhere); **e**, **f**, azimuth offsets. LOS, satellite line of sight. Dashed boxes enclose area shown in Fig. 3. All SAR data copyright ESA.

Our best fitting model (Fig. 3b, c), which explains 92% of the data variance, suggests that 0.3 km^3 and 0.2 km^3 of contraction occurred in magma chambers beneath Dabbahu and Gabho, respectively. South of Dabbahu, the dyke opened by an average of 3.5 m, reaching a maximum of 8.0 m near the centre of the rift segment. The opening is greatest at 5–6 km depth, with little opening occurring below 9 km or above 2 km. Between the two magma chambers, the area coinciding with the greatest density of earthquakes, the modelled dyke opened by as much as 15 m. The modelled normal faults slipped by an average of 2 m, with as much as 7 m of slip inferred on the west of the rift segment above the area of maximum opening. Many discontinuities are evident in this area in the imagery, confirmed by helicopter-assisted field studies showing a ~2-km-wide zone of open fissures, monoclines and normal faults, with up to 3 m of recent displacement (Supplementary Figs SM2–SM5).

Our analysis suggests that a total of 2.4–2.6 km^3 of magma was intruded along the Dabbahu rift segment during the ~2-week rifting episode in September 2005. This single episode was twice as voluminous as estimates from the 1975–84 Krafla (Iceland) rifting events, when 9 m of opening was achieved through 20 dyking events and 9 eruptions[5].

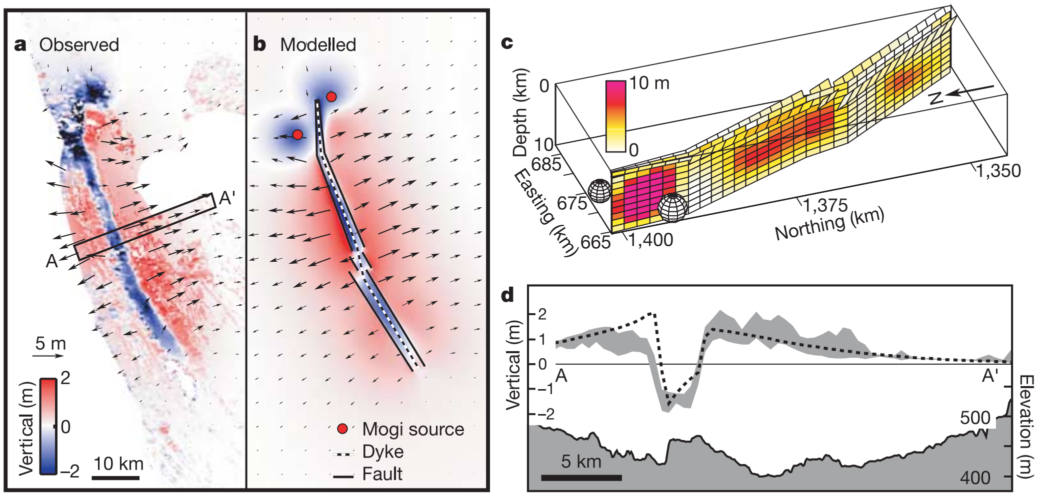

Figure 3 | Observed and modelled three-dimensional deformation field of the 2005 Dabbahu rifting episode. a, Three-dimensional deformation field created from interferograms and range and azimuth offsets (Supplementary Methods). Arrows represent the horizontal component and colours represent the vertical component. **b**, Modelled three-dimensional displacement field. **c**, Model using simplified geometry consisting of two deflating Mogi sources beneath Gabho and Dabbahu volcanoes, shown as spheres, a vertical tensile dislocation with variable opening to represent the dyke and near-surface, dipping, normal faults. Colours indicated the amount of opening (dyke elements) or slip (fault elements). **d**, Profile across the dyke, showing (top) observed and modelled vertical deformation and (bottom) topography in the area outlined by the black rectangle in **a**. Grey band shows estimated 1σ errors for the vertical deformation field, and the black dashed line is from the model.

The apparent southward migration of seismicity is consistent with magma depletion from chambers beneath Gabho and Dabbahu volcanoes. However, this simple model suggests that contraction of the magma chambers can only account for 20% of the magma required to fill the dykes. It is possible that magma was intruded into the shallow magma chambers between the date of our last pre-rift radar acquisition (May 2005) and the rifting event (September 2005). Interferograms from November 2003 to April 2004 and April 2004 to May 2005 show no activity at Dabbahu for this entire period, but ~12 cm of uplift at Gabho volcano is observed between April 2004 and May 2005 (Supplementary Fig. SM6), consistent with ~0.01 km^3 magma influx into that chamber. Unless the rate of deformation accelerated dramatically, it seems unlikely that a significant volume of magma was intruded between May and September 2005.

We also note that determining reliable volumes for magma removed from magma chambers using surface geodetic data alone is difficult[18,19]. The results depend strongly on depth, Poisson's ratio (assumed to be 0.25 in these calculations) and the shape of the magma chamber. Furthermore, if the magma remaining in the chamber contains exsolved gases, it will expand when the pressure drops. The volume change of the magma chamber in these circumstances has previously been estimated to be as much as 4–5 times smaller than the volume of magma withdrawn from the chamber[20,21]. We cannot therefore rule out the shallow chambers as being the source for all of the magma intruded into the dyke. Nevertheless, it is possible that additional magma has been sourced directly from deeper magma reservoirs. For example, a combination of magmatic inflation near the crust–mantle boundary and deflation of a shallow magma chamber were required to reproduce patterns in a 6-year series of interferograms in Iceland[22]. If, as in Iceland, the magma is distributed along the length of the rift segment, it would be difficult to extract such a signal from the much larger deformation caused by the shallow dyke intrusion. Further petrological, seismological and geodetic studies will allow us to better constrain the proportions of the two sources.

Seismic moment release during the period 14 September to 4 October 2005 offers additional insights into crustal deformation processes. We estimate the combined seismic moment release to be 6.7×10^{18} N m (Supplementary Methods), more than an order of magnitude smaller than our estimate for the geodetic moment release (~8.0×10^{19} N m). Hence, most of the deformation occurred aseismically. These short-term observations are also borne out by estimates of seismic efficiency over the past 40 years in Afar. Previous studies estimate that half the strain is accommodated aseismically[23], probably by episodic dyke intrusion[24,25]. Structural data suggest that the locations of magma source(s) maintaining the Dabbahu segment have been stable for ~2 Myr (ref. 4).

Geodetic data corroborated with field and seismicity data clearly document deformation along the entire 60 km length of the Dabbahu rift segment, with the injection of a new column of crust up to 8 m wide. Without satellite radar interferometry, it would have been impossible to determine the full spatial extent of this event. Models of the surface deformation indicate that the source of at least 20% of the magma was shallow magma chambers near the northern tip of the segment, with any remainder directly emplaced from sources beneath the crust. The coincidence between the zone of magma intrusion and the previously mapped Dabbahu rift segment indicates that magmatic processes establish and maintain along-axis segmentation during continental rupture. Ongoing petrological, geochemical, seismic and geodetic studies will allow us to further probe the number and depth of magma sources, the temporal and spatial distribution of strain along and across the length of the Dabbahu magmatic segment, and the viscous relaxation[26,27] of the lower crust and mantle beneath the rift.

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Supplementary Information is linked to the online version of the paper at www.nature.com/nature.

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