Post-rifting relaxation in the Afar region, Ethiopia

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Received 10 August 2009; revised 23 September 2009; accepted 30 September 2009; published 11 November 2009.

[1] Crustal accretion at divergent plate boundaries typically occurs via the periodic intrusion of dikes, but their emplacement and the associated deformation are rarely observed. The few existing observations at subaerial rifts show that these diking events are followed by a decadal-scale period with extension rates faster than the secular divergent plate motion. This transient accelerated deformation has been explained by continued subsurface magma injection or by relaxation, in the viscoelastic mantle, of the stress changes imparted by dike opening. For the first time, GPS measurements were collected within a few months of a rifting event at a major plate boundary, the September 2005, 60 km-long dike intrusion in the Dabbahu segment, Afar, Ethiopia. Extension rates for the first 3 years greatly exceed the plate motion (Nubia-Arabia) secular divergence rate, even at sites located more than 60 km from the rift axis. Here we show that these observations are consistent with stress relaxation in a viscoelastic upper mantle with a viscosity of about 5×10^{18} Pa·s overlain by a 12–14 km-thick elastic crust. The alternative model of continued diking requires continuous opening well below the Moho and is therefore unlikely. Instead, magma injection in Afar since June 2006 has taken the form of smaller discrete diking events, tapping into a mid-crustal melt reservoir under the segment center.
Citation: Nooner, S. L., L. Bennati, E. Calais, W. R. Buck, I. J. Hamling, T. J. Wright, and E. Lewi (2009), Post-rifting relaxation in the Afar region, Ethiopia, *Geophys. Res. Lett.*, *36*, L21308, doi:10.1029/2009GL040502.

1. Introduction

[2] Observations at subaerial spreading centers show that tensile stresses from far-field plate motions accumulate over decades before being released during relatively short-lived "rifting events", whose succession eventually achieves plate separation. These events typically start with a large dike intrusion, sometimes followed by a series of smaller dikes, accompanied by largely aseismic slip on rift-bounding faults [*Ayele et al.*, 2007; *Cattin et al.*, 2005; *Tarantola et al.*, 1979; *Wright et al.*, 2006]. Geodetic observations following the onset of the 1975–1985 Krafla sequence in Iceland and the 1978 Asal-Ghoubbet sequence in Afar showed that these events were followed by extension at a rate faster than secular plate divergence [*Cattin et al.*, 2005; *Hofton and Foulger*, 1996]. This has been interpreted as the result of continued magma injection at shallow crustal depth [*Cattin et al.*, 2005; *Pollitz and Sacks*, 1996] or as a consequence of stress relaxation in the underlying viscoelastic mantle [*Heki et al.*, 1993; *Hofton and Foulger*, 1996]. However, separating these contributions, estimating mantle viscosity and elastic thickness, and quantifying the interaction with long-term stretching has proven difficult in the absence of continuously sampled geodetic measurements spanning and immediately following the main dike intrusions.

[3] A major dike intrusion occurred in late September 2005 at the Dabbahu rift, Afar, Ethiopia [*Ayele et al.*, 2007], a segment of the boundary between the Nubian and Arabian (Danakil) plates (Figure 1). InSAR data are consistent with up to 8 m of dike opening and the emplacement of about 2.5 km^3 of magma [*Wright et al.*, 2006], making this the largest basaltic event observed since the Laki (Iceland) eruption in 1783, and the first to occur in the era of satellite geodesy. Since the initial intrusion, more than 10 smaller dikes (~10 km long), accompanied by migrating seismicity [*Keir et al.*, 2009], have intruded the southern part of the Dabbahu segment [*Hamling et al.*, 2009]. Persistent seismic activity has been concentrated at the northern end of the rift under the Dabbahu volcano and along its northern and central segment [*Ebinger et al.*, 2008]. A rapid geodetic and seismic response initiated a record of crustal deformation beginning about 3.5 months after the onset of diking, allowing an unprecedented opportunity to directly observe post-diking processes not accessible at most spreading centers.

2. GPS Data and Processing

[4] To measure surface deformation, we installed 19 continuously recording GPS (CGPS) stations in the near-field of the rift and in the far-field 30 survey stations observed twice in March 2007 and May 2008 (Figure 1 and auxiliary material).[5] Except at the two sites on the Dabbahu and Gabho volcanoes, displacements at CGPS sites (Figure S1) show a combination of steady motion and discrete offsets, the latter resulting from dike intrusions that continue to occur in the southern part of the Dabbahu rift [*Hamling et al.*, 2009; *Keir et al.*, 2009]. Significant data gaps at several of the CGPS stations prevented us from calculating the offsets directly from the position time series. We therefore removed these offsets using elastic half-space forward models based on the dike opening distributions from previously published estimates from a joint inversion of the InSAR and GPS data [*Hamling et al.*, 2009]. The corrected

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0094-8276/09/2009GL040502$05.00

[5] Auxiliary materials are available in the HTML. doi:10.1029/2009GL040502.

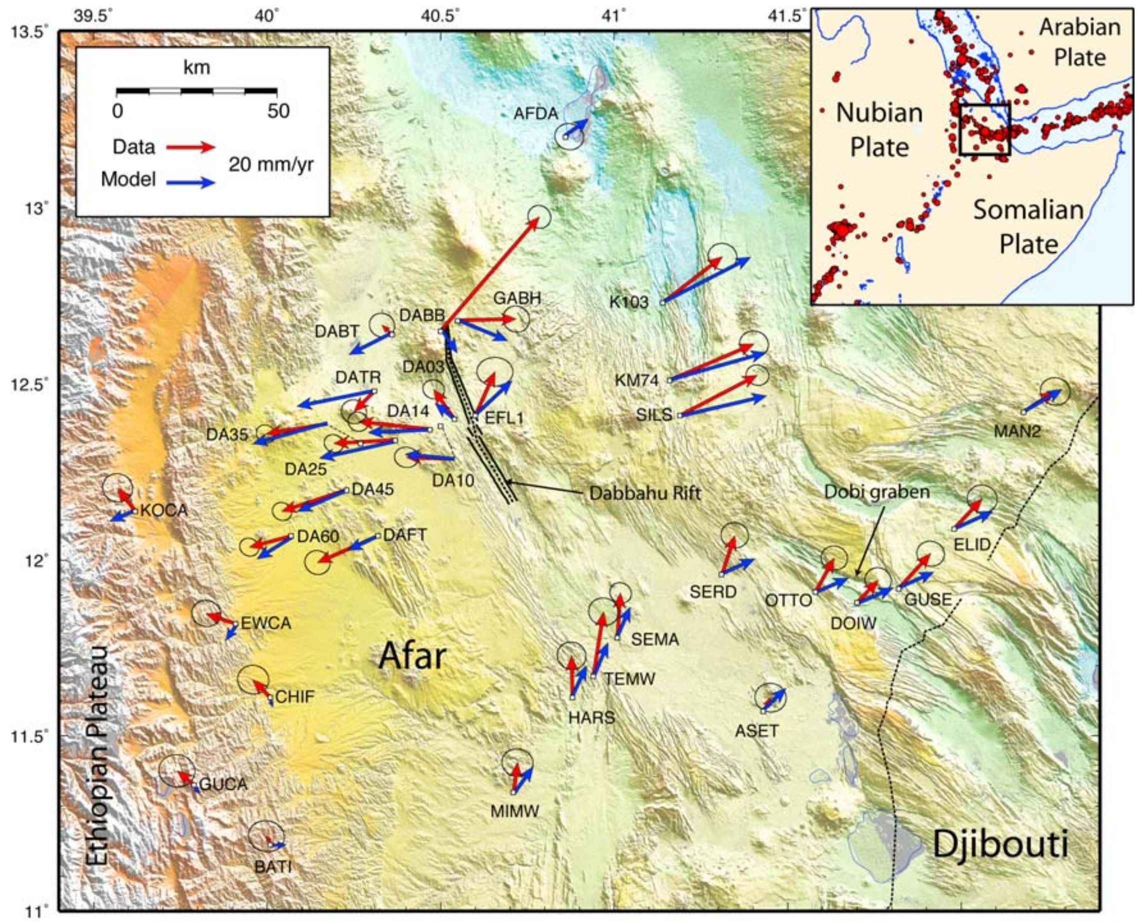

Figure 1. Relief map of northern Afar and study area with GPS and model results. Main figure shows the surface trace of the dike intrusions along the Dabbahu magmatic segment (black dashed line [*Hamling et al.*, 2009; *Wright et al.*, 2006]), along with GPS (red) velocities corrected for discrete dike offsets and best viscoelastic model velocities (blue). GPS velocities are shown with respect to the Nubian plate as defined by *Stamps et al.* [2008] Error ellipses associated with the GPS measurements are 95% confidence. Inset shows the location of the study area within northeastern Africa, with 1973 to present seismicity (red circles) from the NEIC database.

CGPS displacement-time plots are linear (except at the two volcano sites Dabbahu and Gabho; Figure S2), so we computed a velocity at each site, which is expressed with respect to the Nubian plate. This provides us with a consistent set of observables for the modeling, even at sites with observations covering different time spans.

[5] Post-diking horizontal velocities are perpendicular to the rift, except in the south and southeast where an additional northward component is visible (Figure 1). In the far field of the Dabbahu rift near the Djibouti border, site velocities are consistent with the 17 mm/yr secular Arabia-Nubia spreading rate and direction [*Vigny et al.*, 2007]. Near-field velocities reach 55 mm/yr, 3 times faster than the secular Arabia-Nubia divergence rate. Sites such as SILS, located 60 km due east of the 2005 dike intrusion, show velocities up to 36 mm/yr, still twice as fast as the secular plate divergence rate.

3. Modeling

[6] We first considered how well the deformation field could be fit by the response of a two-layer viscoelastic earth model to a series of discrete dike events. The finite element software PyLith [*Aagaard et al.*, 2007] was used to compute deformation in a 400 $\times$ 400 $\times$ 100 km region consisting of an elastic plate overlying a viscoelastic plate (Figure S3). We imposed a zero-displacement condition along the western boundary to simulate the GPS Nubia-fixed frame, and applied a velocity boundary condition along the eastern boundary consistent with the secular Nubia-Arabia plate motion rate (1.4 cm/yr east and 1.0 cm/yr north) [*Vigny et al.*, 2007]. The north, south, and top model boundaries were left free and the bottom boundary was held fixed in the vertical direction. Elastic parameters as a function of depth (Table 1) were derived from seismic data [*Jacques et al.*, 1999; *Makris and Ginzburg*, 1987] and a joint seismic-gravity inversion [*Tiberi et al.*, 2005]. In addition to the Arabia-Nubia secular plate motion, model deformation was driven by the viscoelastic relaxation of the stresses imparted by the main 2005 dike intrusion and 9 subsequent, smaller, intrusions. We specified dike geometry and opening distribution for these intrusions using previously published values determined from InSAR and GPS inversions [*Hamling et al.*, 2009; *Wright et al.*, 2006] and calculated three-year deformation time series with time steps of 0.1 years.

Table 1. Physical Properties Used in the Numerical Model

Depth (km)	V_p (m/s)	V_s (m/s)	Density (kg/m^3)	Poisson's Ratio	Young's Modulus (GPa)
0–3	4500	2500	2500	0.277	39.90
3–8	6200	3400	2700	0.285	80.21
8–25	6800	3700	2900	0.290	102.41
25–100	7400	3700	3100	0.333	113.17

[7] The thickness of the elastic layer and the viscosity of the lower layer were varied to find the combination that best fits the GPS observations. In general, variations in elastic thickness affect the wavelength of the deformation field while variations in the viscosity affect the rate of the relaxation. The elastic response from individual dike intrusions was then removed and the resulting horizontal velocities were compared to equivalent observations from GPS data using a χ^2 fit given by

$$\chi^2 = \sum_{i=1}^{N} \frac{(o_i - m_i)^2}{\sigma_i^2}, \quad (1)$$

where o_i is the i^{th} observation, m_i is the i^{th} model prediction and σ_i is the uncertainty in the i^{th} data point (Figure 2). The minimum in χ^2 occurred for a 13.2 km thick elastic layer and a mantle viscosity of 5.2×10^{18} Pa·s, consistent with other studies of post-diking relaxation in Iceland and Asal-Ghoubbet, which report estimated viscosities of $\sim 10^{18}$ Pa·s [*Árnadóttir et al.*, 2005; *Cattin et al.*, 2005; *Foulger et al.*, 1992; *Hofton and Foulger*, 1996].

[8] An alternative model for the observed accelerated deformation after large dike intrusions involves continuous, aseismic, subsurface magma injection [*Cattin et al.*, 2005; *Hofton and Foulger*, 1996; *Pollitz and Sacks*, 1996]. We therefore tested whether the GPS observations could be explained by continued opening of a dike buried in a layered half-space with elastic properties varying as a function of depth as in the viscoelastic model described above. We used the same dike geometry described above for the 2005 event, but allowed opening to occur down to a depth of 50 km and modeled deformation resulting from dilatational dislocations on rectangular patches of dimension $\sim 5 \times 5$ km, computed the associated impulse functions [*Wang et al.*, 2006], and used least-squares to invert the system of linear equations that relate opening on a patch to observed surface displacement at the GPS sites. To avoid implausible and overly rough opening distributions, we applied smoothing and positivity constraints.

[9] The best-fitting solution of this purely elastic model (Figure 3) requires up to 1.2 m of opening, primarily in the central part of the 2005 dike and concentrated between 20 and 25 km depth with an rms scatter of residuals of 11.5 mm/yr compared to 6.3 mm/yr for the viscoelastic model. The high heat flow, widespread volcanism, and tectonic setting of Afar are consistent with a low viscosity mantle, as found in the viscoelastic model above, and in agreement with independent estimates at other subaerial rift zones [*Árnadóttir et al.*, 2005; *Cattin et al.*, 2005; *Foulger et al.*, 1992; *Hofton and Foulger*, 1996]. This implies sustained dike opening would be occurring in the ductile upper mantle, as the Moho depth is about 17 km in this part of Afar [*Dugda et al.*, 2005; *Hammond et al.*, 2008; *Makris and Ginzburg*, 1987], therefore continuous

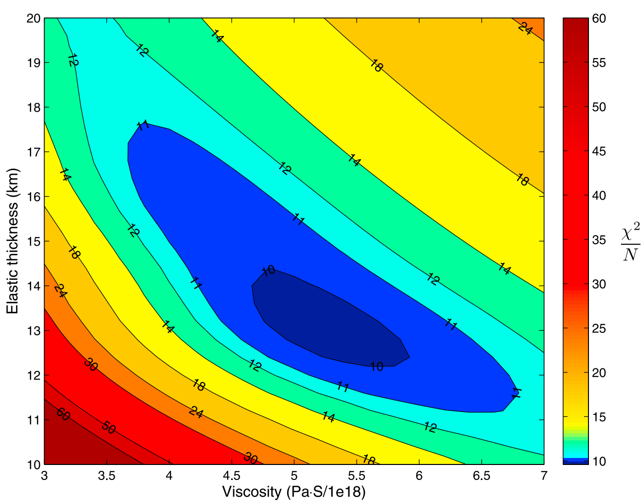

Figure 2. Model fit given by χ^2/N plotted as a function of elastic thickness and viscosity. χ^2/N is a measure of how well the model matches the data within their uncertainties. $\chi^2/N \gg 1$ indicates that that either the model does not adequately describe the observations or that the uncertainties are under-estimated. N is the degrees of freedom (N = 54). Our models do not include sources of inflation/deflation that are suggested by the InSAR data, diminishing the model fit. The best-fit model has an elastic thickness of 13.2 km and a viscosity of 5.2×10^{18} Pa·s.

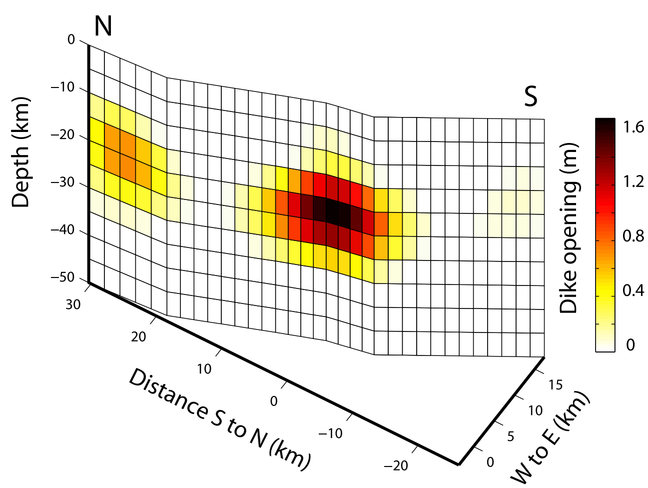

Figure 3. Opening distribution for the best-fit inversion of the postdiking GPS velocities for the continuous diking model. GPS data require continuous opening between 20 and 25 km depth in the central part of the 2005 dike region, below the Moho. This solution would imply sustained dike opening in the ductile upper mantle and is therefore mechanically implausible.

diking alone appears to be a mechanically implausible solution.

4. Discussion

[10] In the Dabbahu rift, earthquakes hypocenters for the 3 months following the main dike intrusion are limited to a narrow region close to the rift axis and lie between 10 km and the surface [*Ebinger et al.*, 2008; *Jacques et al.*, 1999], suggesting a brittle layer thickness of 10 km at the rift, similar to near rift estimates in Iceland [*Árnadóttir et al.*, 2005; *Foulger et al.*, 1992; *Hofton and Foulger*, 1996]. The InSAR and GPS data spanning these diking events strongly constrain the dike opening geometry—something that has not been possible in previous studies of rifting events—allowing us to solve for elastic thickness rather than treating this as a known parameter. Our modeled 13.2 km elastic thickness value for the Dabbahu rift is larger than seismicity at the axis suggests [*Ebinger et al.*, 2008], but is less than direct estimates of Moho depth (17–18 km) in central Afar from seismic data [*Dugda et al.*, 2005; *Hammond et al.*, 2008; *Makris and Ginzburg*, 1987]. It is therefore possible that heat advection from a magma source region and dike intrusions keep the brittle layer thin in a narrow region along the rift axis. This is supported by a recent magnetotelluric profile across the Dabbahu rift which suggests that depth to the top of the partial melt varies from 5 km at the axis to 15 km about 30 km away from the axis [*Desissa et al.*, 2008], and by similar predictions from thermal modeling across the Asal-Ghoubbet rift [*Cattin et al.*, 2005]. This brittle layer may consist of the upper crust only, with viscoelastic relaxation affecting the lower crust, as shown in Iceland after the Krafla dike intrusion [*Hofton and Foulger*, 1996; *Menke and Levin*, 1994].

[11] Although we have included 10 dike intrusions in our modeling, we find that the stress changes due to the main September 2005 event account for about 95% of the relaxation signal measured thus far, while the corresponding magma intrusion accounts for only 75% of the total volume of opening since 2005 [*Hamling et al.*, 2009]. This is probably due to the shallower and shorter lateral extent of opening in the later diking events and, which results in relatively small changes in the stress field within the ductile region.

[12] Our viscoelastic model only considered a Maxwell viscoelastic rheology for the upper mantle, whereas non-linear, stress-dependent rheologies have been inferred elsewhere [*Freed et al.*, 2006]. However, the linear displacement with time seen in both the GPS observations and in the viscoelastic model (Figure S2) indicate that a Maxwell rheology is a good assumption, at least for the early part of the relaxation process (2005–2008). We also did not consider magmatic processes such as the inflation and deflation of magma chambers under the Gabbho and Dabbahu volcanoes [*Pagli et al.*, 2008; *Wright et al.*, 2008] and in the segment center [*Calais et al.*, 2006]. Another broad deflation can be seen in the InSAR ~50 km southeast of the zone of rifting [*Pagli et al.*, 2008; *Wright et al.*, 2008]. Including these sources may improve the overall fit to the GPS data, especially in the vertical component, which neither of our models fit well. Our models do not include lateral variations in the thickness of the brittle layer, which presumably thickens rapidly west of the Dabbahu at the edge of the Ethiopian plateau.

5. Conclusions

[13] GPS measurements following the September 2005, 60 km-long dike intrusion in the Dabbahu rift show extension rates that far exceed the long-term Nubia-Arabia divergence rate. We have shown that the bulk of the observed signal is consistent with a simple model where the stresses imparted by the main intrusion and 9 smaller subsequent ones relax over time in a viscoelastic lower crust and upper mantle below an elastic upper crust. The model best fits the data for an upper mantle viscosity of $\sim 5.2 \times 10^{18}$ Pa·s, which is in agreement with studies of other subaerial rifts. The best fitting elastic thickness of 13–14 km is intermediate between the 17–18 km Moho depth inferred from seismic experiments in Afar and the localized 10 km depth of seismicity at the rift, which suggests rapid thickening of the brittle layer away from the rift. Continued diking models do not adequately explain the far field extension rates across the Dabbahu segment. By comparison with the 1978 Asal-Goubhet event [*Cattin et al.*, 2005], it may take 5 years or more after the main event for extension rates in the Dabbahu rift to significantly slow down. Long-term monitoring of the area is therefore critical to constrain the time-dependence of the deformation and fully understand the processes at work.

[14] **Acknowledgments.** We thank Charles Williams and the Computational Infrastructure for Geodynamics and Sandia National Labs. We are grateful to Laike Asfaw, Atalay Aleye, Araya Asfaw, and Gezahegn Yirgu, who were instrumental in helping organize the rapid response to the Dabbahu crisis, and others involved in the GPS field campaigns, notably John Elliott, Juliet Biggs, Matt Garthwaite, Beth Bartel, Carolina Pagli, and Yelebe Birhanu. We thank the Afar Government for their continued support to this project and for allowing us safe access to the field area. We are grateful to the Ethiopian Mapping Agency for their support, in particular its surveyors Feleke, Negassa, and Worku, whose contribution to the GPS field work is invaluable. Cindy Ebinger also provided valuable support in the field. This work used (outstanding) equipment and engineering services provided by the UNAVCO Facility with support from the National Science Foundation and NASA under NSF Cooperative Agreement EAR-0735156. This work was supported by NSF grants EAR-0635789 and EAR-0613651, and NERC through urgency grant NE/D01039X/2, the Afar Rift Consortium (NE/E007414/1), NE/D008611/1, NE/D01039X/1, and a COMET studentship to IJH, and a Royal Society University Research Fellowship to TJW.

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