Multiple inflation and deflation events at Kenyan volcanoes, East African Rift

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ABSTRACT

The presence or absence of magma exerts a fundamental control on the distribution of strain in continental rift zones, yet the time scales of magma intrusion remain unconstrained. Using more than a decade of measurements from interferometric synthetic aperture radar (InSAR), we detected geodetic activity at four of the eleven central rift volcanoes in the Kenyan sector of the East African Rift. Subsidence of 2–5 cm occurred at Suswa and Menengai over the period 1997–2000, ~9 cm of uplift was recorded at Longonot in 2004–2006, and ~21 cm of uplift occurred at Paka during 2006–2007. The deformation is episodic, and no deformation was observed at these volcanoes during other time periods. Preceding the inflation at Paka, we observed transient uplift and subsidence of a second, nearby source, likely associated with flow through a complex plumbing system. The best-fitting source models for each episode include inflation or deflation of a horizontal penny-shaped crack at a depth of 2–5 km. The episodic nature of the activity, its lack of correlation with seasons, and the preferred source geometry are all consistent with activity in the volatile-rich cap to a crystal-rich magma chamber beneath each of the four volcanoes. The presence of active magmatic systems beneath more than 40% of the volcanoes, and the 2007–2008 explosive eruptions at nearby Oldoinyo Lengai volcano, have implications for models of continental rifting, caldera volcanoes, geothermal resources, and volcanic and seismic hazard in rift zones.

INTRODUCTION

The presence or absence of magma exerts a fundamental control on the distribution of strain in continental rift zones (e.g., White and McKenzie, 1989; Buck 2004). Within the mantle, melt generation extracts incompatible elements, dehydrating and strengthening the mantle. Magma intrusion controls shallow brittle deformation processes by altering the thermal and mechanical structure of the lithosphere (e.g., Buck, 2004). Some of the magma rises efficiently to shallow or surface levels in the form of dikes, and some is trapped within the plate in the form of sills and multiply replenished magma chambers. Hence, knowledge of the distribution and volume of melt intruded or extruded throughout the evolution of continental rifts is fundamental to the development of predictive models of rifting processes. Rift volcanoes attest to the presence of magma reservoirs within the crust, and the magma chemistry provides insights into magma source(s) and storage depth(s). Petrologic studies in the archetypal East African Rift system document the importance of magma chamber recharge, magma mixing, and volatile transport that accompany diking and eruption events (e.g., Espejel-Garcia et al., 2008; Macdonald et al., 2008). Basaltic dike intrusions reheat or recharge existing magma chambers lying near or within the paths of dikes, provoking earthquakes, eruptions, and/or degassing (e.g., Wright et al., 2006; Baer et al., 2008; Keir et al., 2009).

How, when, and where magma rises through the plate within rift zones remain poorly understood. The passage of magma through the crust is commonly marked by low-magnitude earthquakes and is rarely detected on global arrays (e.g., Rubin and Gillard, 1998; Keir et al., 2009). Radar interferometric measurements of surface displacements provide a versatile means to evaluate spatial and temporal scales of magma storage within rift zones. Changing pressures within crustal magma reservoirs caused by magma and/or volatile fluxes produce changes in volcano shape on the scale of centimeters to meters (e.g., Zebker et al., 2000). Interferometric synthetic aperture radar (InSAR) is a satellite-based method used to compare the phase of radar images taken at different times to detect small (<1 cm) surface displacements at high resolution (<90 m). We used InSAR to study volcano geodesy along the Kenyan section of the East African Rift (Fig. 1). Four of ten central rift volcanoes for which a coherent signal could be observed showed signs of inflation or deflation over the period 1997–2008: Paka, Menengai, Longonot, and Suswa. At each volcano, the surface deformation occurred as a discrete pulse, of duration less than a year, within a much longer period of geodetic quiescence.

We interpret the geodetic signals in light of geological and geophysical data as a baseline for future hazard mitigation programs, and to understand the time and length scales for the rise and storage of magma within continental rift zones. Suswa, Longonot, and Menengai volcanoes are located in densely populated areas within 100 km of Nairobi. Suswa and Longonot commenced activity at least ca. 240 ka ago with the eruption of precaldera trachytes. Periodic activity occurred from 240 ka to the present (e.g., a ^{14}C date of <400 yr B.P. for Longonot; Clarke et al., 1990). However, the timing, frequency, and spatial distribution of magma recharge are unconstrained, and there is no in situ geodetic monitoring of the volcanoes. From a human perspective, they are crucial to volcanic hazard studies in a heavily populated area, and to the exploitation of geothermal resources in Kenya (e.g., Tole, 1996; Mariita, 2002).

OBSERVATIONS AND MODELING

We surveyed a 400 km length of the rift during three time periods: 1997–2000, 2003–2006, and 2006–2008. The first images in this region were acquired in 1997 and 2000 by ERS1 and ERS2. Envisat has acquired two to three images per year since 2003. We identified four discrete episodes of surface deformation: Suswa and Menengai in 1997–2000, Longonot in 2003–2006, and Paka in 2006–2008. No signs of geodetic activity were seen at other volcanoes, although observations were not always possible due to loss of interferometric coherence (Fig. 1). We refined our estimates of the date, duration, and magnitude of each episode by processing additional data. Where multiple interferograms could be made, we stacked the images to reduce the effects of random atmospheric noise. Models based on spherical (Mogi, 1958) or ellipsoidal chambers or horizontal penny-shaped cracks (Fialko et al., 2001) produce circular displacement patterns similar to those observed, unlike the lobed patterns produced by fault slip or dike opening (e.g., Wright et al., 2006). For each deformation episode, we considered two candidate geometries: a point or "Mogi" source and a horizontal penny-shaped crack, as summarized in the GSA Data Repository[1] and Table 1.

[1]GSA Data Repository item 2009249, further information on tectonic setting, InSAR methods, and detailed model parameters, is available online at www.geosociety.org/pubs/ft2009.htm, or on request from editing@geosociety.org or Documents Secretary, GSA, P.O. Box 9140, Boulder, CO 80301, USA.

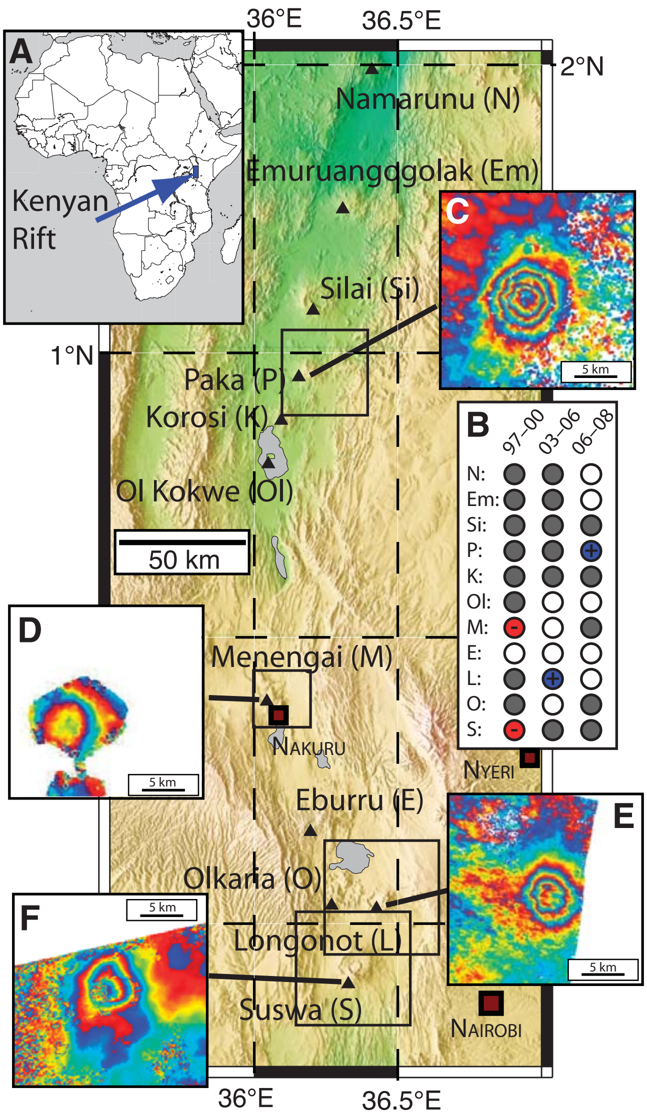

Figure 1. Geodetic activity detected at volcanic centers in the Kenyan rift. A: Location map. B: Chart summarizing the observations at each volcano during each of the three time periods initially surveyed (1997–2000, 2003–2006, 2006–2008). Red circles—subsidence; blue circles—uplift; gray circles—no displacement; empty circles—no observation due to data gaps or lack of coherence. C: Paka in 2006–2008 (stack of three interferograms), each fringe (blue-red cycle) represents 2.8 cm of displacement in the satellite line of sight. D: Menengai in 1997–2000. E: Longonot in 2003–2006 (stack of seven interferograms). F: Suswa in 1997–2000. Footprint of geodetic signature for all four volcanoes is the diameter of the trachytic shields, rather than the smaller caldera and postcaldera morphology.

TABLE 1. KEY SOURCE PARAMETERS FROM ELASTIC MODELING FOR DEFORMATION EPISODES AT KENYAN VOLCANOES

Volcano	Date	U_z (cm)	Depth (km)	Radius (km)
Suswa	1997–2000	–4.6	1.9	3.7
Longonot	2004–2006	9.2	4.1	6.2
Menengai	1997–2000	–3.0	0.7	5.2
Paka	2006–2007	21.3	2.8	6.3

Note: The dates for each event represent the bracket of time during which the deformation occurred and likely overestimate the duration of the event. Uz is the peak vertical displacement. Depth and radius are given for the penny-shaped crack model, which provides a better fit to the data. A complete list of parameters and realistic error bounds is given in the supplementary information (see text footnote 1).

Activity at Suswa and Menengai occurred between October 1997 and September 2000 when satellite acquisitions were widely separated in time. The interferograms show a roughly circular pattern of fringes centered on the caldera. The number of fringes (1.5 and 1) is equivalent to ~4.6 cm and ~2.8 cm of subsidence at Suswa and Menengai, respectively, assuming the deformation is purely vertical, as in other volcanoes (e.g., Chang et al., 2007). No surface displacements were observed at Suswa or Menengai in any subsequent interferograms (2002–2008). At Suswa, a simple Mogi source places the center of deflation within the caldera at a depth of 2.1–3.7 km. A penny-shaped crack model reduces the residuals, both qualitatively and quantitatively (see the Data Repository). Allowing a finite horizontal dimension for Suswa decreases the depth of the model source from ~3 km (2.0–3.2 km) for a point source to ~2 km (1.2–3.4 km) for the best-fitting penny-shaped crack of diameter ~7 km (6.2–9.7 km). The data coverage for Menengai is restricted due to vegetation surrounding the caldera. Inversions for model parameters attempt to match the extent of the coherent signal due to a lack of reference points in the far field. In particular, the penny-shaped crack model favors an extremely shallow source (<1.5 km) using dimensions of the caldera diameter of ~10 km. Uplift of 9.2 cm (assuming vertical deformation) occurred at Longonot between 28 June 2004 and 20 March 2006. The best-fitting penny-shaped crack model places the center of inflation within the caldera at a depth of ~4 km (1.5–5.2 km).

The largest of the events occurred at Paka during the 9 mo. period between 29 May 2006 and 5 March 2007 (Fig. 2). No deformation is seen in interferograms leading up to or following this period. The total displacement is equivalent to 21.3 cm of uplift located on the geothermally active northern flank, ~4 km northwest of the caldera. The best-fitting model (Fig. 2C) is a penny-shaped crack with a radius of 6.3 km (5.1–7.2 km) and a depth of 2.8 km (1.8–4.2 km). A series of interferograms using images from 3 July and 7 August 2006 shows that the episode consists of several discrete events, each lasting for a minimum of 1 mo (Fig. 2B). Uplift of the primary source began with 12.1 cm in July-August, and the remaining 9.1 cm occurred in August-March. The short-duration interferograms identify precursory activity at a source located ~4 km to the south of the first. Here, uplift of ~3 cm occurred during May-July, with an equal amount of subsidence in July-August. The reversal of sign is typical of an atmospheric water vapor effect in the 3 July image. We do not, however, observe features of this shape or magnitude elsewhere in the interferograms, and July is typically a dry month. The best-fitting models are a point source at 2.8 km depth or a penny-shaped crack at 1.5 km depth. Multiple interpretations based on a combination of hydrothermal and magmatic sources are consistent with the available constraints. Our preferred interpretation is that a lateral conduit existed at a depth of 2.8 km, and flow or ponding of fluids along this conduit caused the precursory pulses.

DISCUSSION

Existing seismic, magnetotelluric, and gravity data (e.g., Prodehl et al., 1997; Simiyu and Keller, 2001) image the crustal magmatic plumbing of the rift in Kenya, but our geodetic observations remain the only constraints on the time-dependent displacements at these volcanoes. The events at different volcanoes show remarkable similarities in behavior: they are of short duration, with upper bounds of 35, 21, and 9 mo. for the events at Suswa, Longonot, and Paka, respectively. Each volcano appears quiescent during other periods of observation, indicating deformation pulses much shorter than predicted by hydrothermal flow models (e.g., Hutnak et al., 2009). The best-fitting source model in each case is a horizontal penny-shaped crack, with residuals below the limits expected from the effects of atmospheric water vapor (Hanssen et al., 1999). In general, several competing source geometries can fit the data equally well (e.g., Pritchard and Simons, 2004), and the surface deformation is insensitive to

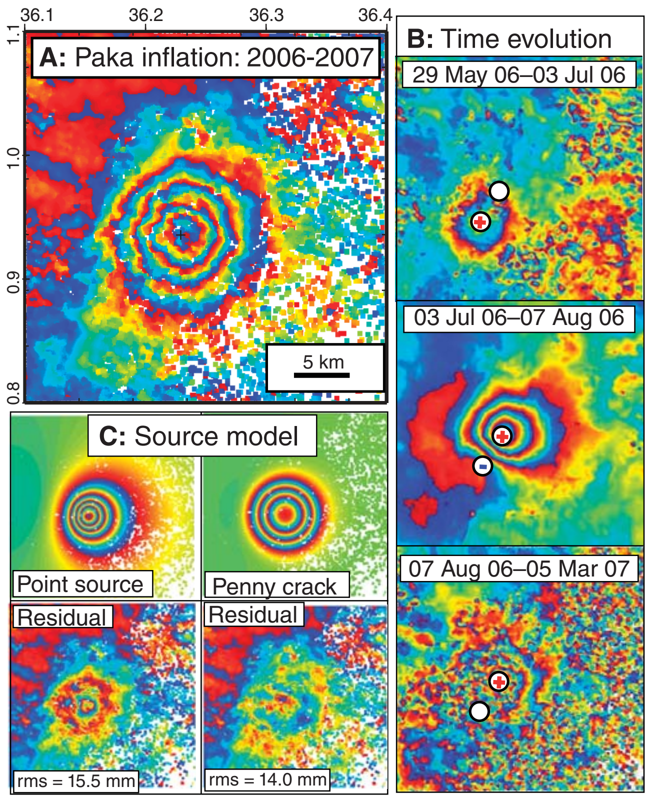

Figure 2. Inflation episode at Paka, 2006–2007. A: Stack of interferograms spanning the entire event showing the total 21 cm of uplift. B: Interferograms covering short timer periods showing precursor uplift and subsidence at a second source located ~4 km south of the main event. Uplift of the main source occurred in two consecutive interferograms. Source locations are marked by white circles; red (+)—uplift; blue (–)—subsidence. C: Best-fitting source models. Two candidate source geometries are used for each event: a Mogi (point source), or horizontal penny-shaped crack. In all cases, the penny-shaped crack model provides a better fit to data, both qualitatively and quantitatively. Each color cycle (fringe) represents 2.8 cm of displacement in the satellite line of sight. rms—root mean square residual betweeen model and data. Each subplot has the same extent.

the sides and bottom of the magma reservoir (Yun et al., 2006). However, the shallow depths at Suswa, Longonot, and Paka provide a rare example from which it is possible to make conclusive statements about the source geometry. Unlike the penny-shaped models, Mogi models overpredict the peak displacements but underpredict those on the flanks. This results in a systematic "donut"-shaped residual (Fig. 2C; Fig. DR2 in the Data Repository), pointing to a mismatch with the lateral dimensions of the chamber. The diameter of the penny-shaped sources is 8–14 km, which is broadly comparable with the dimensions of the trachyte shield volcanoes and associated gravity anomalies (e.g., Simiyu and Keller, 2001).

In many settings, volcanic uplift is unambiguously associated with magma intrusion in the shallow crust. However, recent observations at calderas such as Long Valley, Yellowstone, and Campi Flegrei document subsidence not associated with eruption and CO_2 emission levels too high to be explained by magmatic pulses. Surface displacements may be the result of the migration of hydrothermal rather than magmatic fluids (e.g., Wicks et al., 1998; Chang et al., 2007; Hutnak et al., 2009). Differentiation between magmatic intrusion and thermal expansion or pressurization of the caldera is clearly fundamental to the development of predictive models for volcanic eruptions, and in evaluations of seismic and volcanic risk (e.g., Battaglia et al., 2002). We base our interpretation on the pattern, depth, and timing of the displacements within the framework of previous geological and geophysical studies (e.g., Omenda, 1998; Simiyu and Keller, 2000; Velador et al., 2003). The fringe patterns are concentric and centered on the volcanoes. Although ultimate geothermal heat sources are volcanic, the geothermal water-flow patterns are fault-controlled and rely strongly on rift basin structure rather than proximity to individual volcanoes. The geothermal systems are almost continuously active from historic and well data, whereas the observed geodetic activity occurs in discrete episodes separated by quiescent periods of at least 10 years. The episodic nature is more consistent with discrete pulses of magma arriving in the shallow crust. This consideration alone does not discount the possibility that discrete pulses of deformation could be caused by changes in the hydrothermal system triggered by magmatic pulses in the mid- or lower crust. Simultaneous observations of gravity and deformation have shown that volume changes in both magmatic and hydrothermal systems are required to explain periods of rapid inflation and deflation at Campi Flegrei, Italy (Gottsman et al., 2006). Inflation of deeper magmatic sources causes dilatation of overlying rocks, opening new and self-sealed fractures, increasing permeability, and decreasing pore pressure (Wicks et al., 1998; Chang et al., 2007). Thus, short-duration episodes of deformation such as those reported here are likely to be driven by volume changes in the magmatic system and amplified by the response of the shallower hydrothermal system.

The depth of the deformation sources at Suswa, Paka, and Longonot (2–4.5 km) is close to the boundary between magmatic and hydrothermal systems, consistent with deformation occurring within a volatile-rich cap to the magma chamber overlying a feldspar-crystal–rich magma chamber (Macdonald et al., 2008; Espejel-Garcia et al., 2008). Our ability to distinguish the source on the basis of depth is limited by our knowledge of the magmatic and hydrothermal systems, and it could be improved by additional information from seismic and magnetotelluric studies. Hypocenters for the Olkaria geothermal site place the heat source at ~6 km (Simiyu and Keller, 2000). Seismicity occurs in swarms, and tremor and low-frequency events indicate the attenuating effects of one or more fluid phases. Longonot and Suswa volcanoes show narrow negative anomalies superposed on broader positive anomalies corresponding to the edifices, consistent with shallow low-density chambers; data are too sparse to interpret shallow structures at Paka and Menengai (Fig. DR1).

The observations reported here demonstrate the presence of active magmatic systems beneath Suswa, Longonot, Menengai, and Paka volcanoes. Combined with observations from the active Oldoinyo Lengai volcano, this new information has clear implications for geothermal resources and volcanic and seismic hazard and informs the genetic relation between magma intrusion and faulting. Although seismicity levels in the Eastern rift are comparatively low, multiple ground-rupturing earthquakes have occurred in this region (e.g., Zielke and Strecker, 2009). A dike intrusion at Gelai volcano, Tanzania, initiated with fault slip and may be linked to the 2007–2008 eruption of nearby Oldoinyo Lengai volcano (Baer et al., 2008; Calais et al., 2008; Biggs et al., 2009). Field and petrological studies point to the importance of mafic dike injection to drive magma mixing and eruption (Macdonald et al., 2008). The short-term implications in terms of eruptive behavior are unclear; although many eruptions and dike intrusions are preceded by ground deformation, many inflation episodes do not culminate in eruption or dike intrusion (e.g., Amelung et al., 2000). Furthermore, many eruptions, including the 2007–2008 eruption of Oldoinyo Lengai, occur without any local deformation (Baer et al., 2008; N. d'Oreye, 2009, personal commun.). Volcano hazard analysis requires deformation, seismicity, and gas monitoring both on and off the volcanic edifices, and determination of how pulses of activity are distributed in time. Coeval microgravity, seismicity, and gas surveys can distinguish between magmatic- and hydrothermal-induced deformation, and continuous monitoring is required to constrain the duration of individual episodes. The other volcanoes of the Kenya rift that show no geodetic activity may simply be between episodes: a longer period of observation is required to judge their level of activity.

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