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

J. Biggs¹, E.Y. Anthony², and C.J. Ebinger³
¹Rosenstiel School of Marine and Atmospheric Sciences, University of Miami, Miami, Florida 33149, USA
²Department of Geological Sciences, University of Texas at El Paso, El Paso, Texas 79968-0555, USA
³Department of Earth and Environmental Sciences, University of Rochester, Rochester, New York 14627, USA

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 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 across 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 14C 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; Marita, 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 Repository1 and Table 1.

1GSA Data Repository item 2009249, further information on tectonic setting, InSAR methods, and detailed model parameters, is available online at www.geosociety.org/pubs/fl2009.htm, or on request from editing@geosociety.org or Documents Secretary, GSA, P.O. Box 9140, Boulder, CO 80301, USA.
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 (<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

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

<table>
<thead>
<tr>
<th>Volcano</th>
<th>Date</th>
<th>$U_z$ (cm)</th>
<th>Depth (km)</th>
<th>Radius (km)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Suswa</td>
<td>1997–2000</td>
<td>–4.6</td>
<td>1.9</td>
<td>3.7</td>
</tr>
<tr>
<td>Longonot</td>
<td>2004–2006</td>
<td>9.2</td>
<td>4.1</td>
<td>6.2</td>
</tr>
<tr>
<td>Menengai</td>
<td>1997–2000</td>
<td>–3.0</td>
<td>0.7</td>
<td>5.2</td>
</tr>
<tr>
<td>Paka</td>
<td>2006–2007</td>
<td>21.3</td>
<td>2.8</td>
<td>6.3</td>
</tr>
</tbody>
</table>

*Note: The dates for each event represent the bracket of time during which the deformation occurred and likely overestimate the duration of the event. $U_z$ 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).*
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 overlaying a feldspar-crystal–rich magma chamber (Macdonald et al., 2008; Espejel-García 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 hazards 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.

ACKNOWLEDGMENTS

The authors have benefited from discussions with Ray Macdonald, Peter Omenda, Falk Amelung, Scott Baker, Tim Dixon, Simon Carn, Alan Deino, Randy Keller, Celia Nyamweru, and Aftab Khan. The manuscript was significantly improved by thoughtful reviews from Tim Wright and two anonymous reviewers. Anthony was supported by National Science Foundation (NSF) grants INT 0909683 and 0332956 and Texas NHARP 003661-0003-2006. Ebinger’s work was supported by NSF grant EAR-0801801. Biggs is supported by a University of Miami Rosenstiel Fellowship, the Center for Southeastern Tropical Advanced Remote Sensing, and a Lindemann Fellowship from the English Speaking Union. This is CTSARS contribution number 21.

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Manuscript received 11 February 2009
Revised manuscript received 9 June 2009
Manuscript accepted 12 June 2009

Printed in USA