A volcano bursting at the seams: Inflation, faulting, and eruption at Sierra Negra volcano, Galápagos

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ABSTRACT

The results of geodetic monitoring since 2002 at Sierra Negra volcano in the Galápagos Islands show that the filling and pressurization of an ~2-km-deep sill eventually led to an eruption that began on 22 October 2005. Continuous global positioning system (CGPS) monitoring measured >2 m of accelerating inflation leading up to the eruption and contributed to nearly 5 m of total uplift since 1992, the largest precursory inflation ever recorded at a basaltic caldera. This extraordinary uplift was accommodated in part by repeated trapdoor faulting, and coseismic CGPS data provide strong constraints for improved deformation models. These results highlight the feedbacks between inflation, faulting, and eruption at a basaltic volcano, and demonstrate that faulting above an intruding magma body can relieve accumulated strain and effectively postpone eruption.

Keywords: inflation, intrusion, geodesy, global positioning system, inferometric synthetic aperture radar.

INTRODUCTION

Most of what geologists understand about igneous intrusion comes from uplifted and exhumed ancient rocks (Breitkreuz and Petford, 2004; Marsh, 2004). However, this information is usually complex because it represents a time-integrated record that is overprinted by unrelated geologic processes. More direct observations come from active volcanoes where modern seismic and geodetic data can reveal the mechanics and time scales of intrusion, as well as causal links to eruptions (Chouet, 2003; Dzurisin, 2003). Here we describe the results of a geodetic study of Sierra Negra volcano in the Galápagos Islands that reveal the filling of a shallow sill, how the volume of this intrusion was accommodated, and the feedbacks between intrusion, faulting, and eruption. We demonstrate that the filling and pressurization of this sill eventually led to an eruption that commenced on 22 October 2005. This is the first pre-eruption sequence ever monitored at a Galápagos volcano with global positioning system (GPS), and it provides strong constraints for deformation models that differ from those of previous studies.

DEFORMATION MONITORING AT SIERRA NEGRA

Sierra Negra, a basaltic volcano with a large summit caldera, is the largest volcano in the Galápagos (Fig. 1) and last erupted in 1979 (Reynolds and Geist, 1995). Prior to 2000, deformation monitoring in the Galápagos was limited to satellite radar interferometry (InSAR), which combines radar images from two satellite passes to measure changes in the range between the satellite and the Earth's surface. Results from three different intervals during the 1990s showed that the caldera floor of Sierra Negra volcano inflated by 2.7 m between 1992 and 1999 (Fig. 1D) (Amelung et al., 2000; Yun et al., 2006). From 1992 to 1997, the pattern of inflation was nearly axisymmetric and mostly limited to the caldera floor; the maximum uplift was near the center of the caldera. This was modeled as due to intrusion of magma into a sill beneath the caldera at a depth of ~2 km (Amelung et al., 2000; Jónsson et al., 2005). In contrast, between 1997 and 1998 the maximum uplift was centered on the southern limb of a preexisting intracaldera fault system (Fig. 1B). The shift was interpreted as being due to ~1.2 m of slip along a steeply south-dipping normal fault (Amelung et al., 2000; Jónsson et al., 2005). The focus of inflation at Sierra Negra shifted back to the center of the caldera between 1998 and 1999, again interpreted as magma filling a subcaldera sill (Amelung et al., 2000).

Campaign GPS monitoring of Sierra Negra began in 2000 and during 2000–2002 showed a striking deceleration in the uplift rate previously documented by InSAR, followed by a change to subsidence of ~9 cm/yr (Fig. 1D) (Geist et al., 2006). The deflationary source was modeled as a contracting sill at a depth of 2.1 km, similar to the inflationary source of the 1990s (Amelung et al., 2000). Microgravity measurements over the same interval point to either downward magma withdrawal or segregation of bubbles from vesiculated magma as causes for contraction of the sill (Geist et al., 2006).

In June 2002, a six station continuous global positioning system (CGPS) network was deployed at Sierra Negra (Fig. 1B; GSA Data Repository[1]). The CGPS data were processed using the BERNESE software (Hugentobler et al., 2001). The CGPS network consists of four single-frequency and two dual-frequency instruments; two of the stations are near the previous centers of inflation and trapdoor faulting (GV02 and GV06, respectively). From June 2002 to April 2003, the caldera floor continued the subsidence that had begun in 2000–2001. In April 2003, deformation of the caldera floor changed from deflation to inflation (Figs. 1E, 1F). The rate of inflation gradually increased throughout 2004 and into 2005. Between 1 April 2003 and 15 April 2005, station GV02 was uplifted a total of 89 cm, accompanied by 69 cm of horizontal extension across the caldera (GV03–GV06).

Elastic inflation was interrupted by an episode of inelastic trapdoor faulting marked by an m_b4.6 earthquake on 16 April 2005 (National Earthquake Information Center; http://neic.usgs.gov). The displacements associated with this faulting event were documented in extraordinary detail by the CGPS network. An epoch-by-epoch kinematic solution of the position of GV06 on 16 April 2005 shows that it was uplifted by 84 cm within 10 s (Fig. 1F), and the cross-caldera line contracted by 26 cm.

The rate of inflation did not appear to be affected by the faulting event of 16 April 2005 and continued its upward trend, eventually approaching rates of 1 cm/day at stations GV02 and GV04 (Fig. 1). We calculate that GV02 uplifted 1.22 m between 16 April 2005 and the start of the eruption on 22 October 2005. This brings the precursory

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[1]GSA Data Repository item 2006224, supplementary information on CGPS data processing, displacement vectors, and models used in the study, is available online at www.geosociety.org/pubs/ft2006.htm, or on request from editing@geosociety.org or Documents Secretary, GSA, P.O. Box 9140, Boulder, CO 80301-9140, USA.

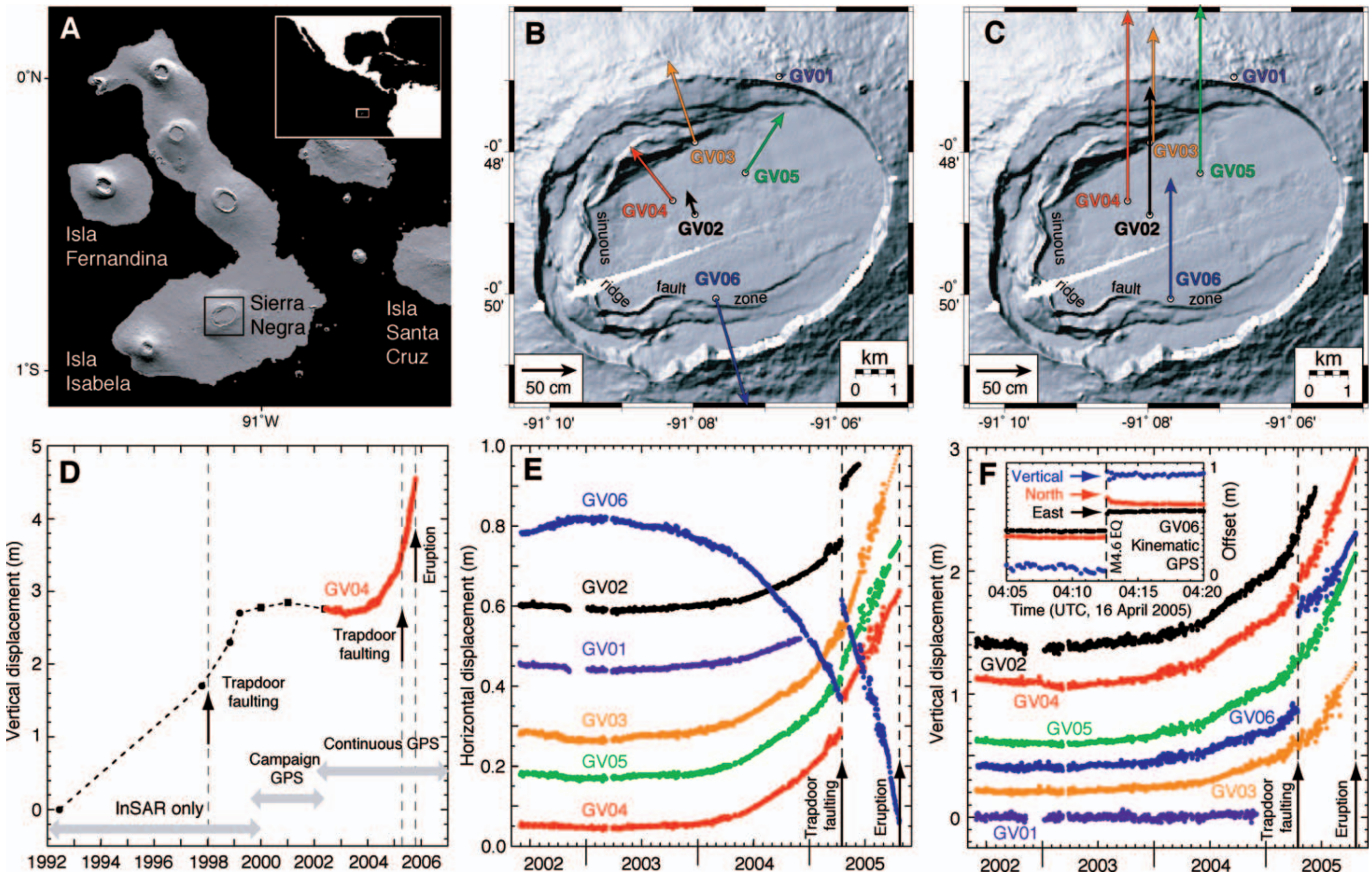

Figure 1. Continuous global positioning system (CGPS) results showing pre-eruption deformation at Sierra Negra volcano. A: Location map after Yun el al. (2006). B: Summit of Sierra Negra, showing sinuous ridge fault system, location of CGPS stations, and horizontal displacements during inflation from 1 April 2003 to 21 October 2005 (GV01 only to 3 December 2004; GV02 only to 10 June 2005). Fault-related displacements on 16 April 2005 are not included (see Fig. 2). C: Vertical displacements during inflation, as in B. D: Uplift history of center of caldera at Sierra Negra from 1992 to 2006 amounting to nearly 5 m. Times of major trapdoor faulting events and 2005 eruption are indicated. E: Horizontal displacements (north component only) at CGPS stations from 2002 to 2006, relative to stations GALA and GLPS on Isla Santa Cruz. Noise level increases after 10 June 2005, when both dual-frequency receivers had failed (GV01 and GV02). After 1 September 2005, GALA and GLPS were also down; thereafter movement at GV03 is extrapolated (dashed line) and GV04, GV05, and GV06 are shown relative to GV03. F: Vertical displacement time series, as in E. Inset shows kinematic solution for displacements at GV06 during 16 April 2005 trapdoor faulting event, relative to GV03. Vertical dashed lines in E and F show times of 16 April 2005 trapdoor faulting event and eruption on 22 October 2005. InSAR—inferometric synthetic aperture radar; GPS—global positioning system.

uplift to 2.20 m at GV02 from 1 April 2003 to 22 October 2005. Note, however, that station GV02 failed on 10 June 2005 and its vertical displacement between then and the eruption on 22 October 2005 is estimated by adding 20% to the uplift measured at nearby station GV04 during this time interval, the previous average difference between the two stations. This extrapolation is not used in the figures or in the modeling discussed here. Horizontal extension across the caldera (GV03–GV06) amounted to 97 cm between 16 April 2005 and the eruption, and a total of 1.4 m since 1 April 2003 (Fig. 1).

Interferograms made from radar scenes collected by the European Space Agency's ENVISAT satellite were examined to more fully document the spatial pattern of deformation at Sierra Negra since early 2004 (Fig. 2; Data Repository [see footnote 1]). The topographic correction used in making the interferograms is based on a merged Shuttle Radar Topography Mission (SRTM) and Topographic Synthetic Aperature Radar (TOPSAR) digital elevation model by Yun et al. (2005). One interferogram (12 February 2004–27 January 2005) shows 0.55 m of maximum radar line of sight (LOS) shortening due to caldera-wide inflation centered ~800 m SE of GV02 (Fig. 2A). A second interferogram (27 January 2005–12 May 2005), which includes the 16 April 2005 faulting event, shows a maximum LOS shortening of 1.0 m along the intracaldera fault system close to GV06 and a loss of coherence phase across the fault system (Fig. 2B). Note that ~4 months of inflation signal is superimposed on the instantaneous fault displacements in the second interferogram.

MODELING

The elastic bulging of the caldera floor leading up to the 2005 eruption is almost certainly due to intrusion of magma into a sill beneath the caldera that has been previously modeled at a depth of ~2 km (Amelung et al., 2000; Geist et al., 2006; Yun et al., 2006). Using InSAR and CGPS data from 12 February 2004 to 27 January 2005 (Data Repository; see footnote 1), we obtain a sill depth of 2.2 km and find that the sill volume was increasing at a rate of 17×10^6 m^3/yr. The average rate of volume increase before the trapdoor faulting (1 April 2003–15 April 2005) was 14×10^6 m^3/yr, based on CGPS data and using the same sill geometry, whereas the average rate between the trapdoor faulting and the eruption (16 April 2005–21 October 2005) was much higher at 64×10^6 m^3/yr.

The 2004–2005 interferograms are remarkably similar to the pattern of deformation documented by InSAR in the 1990s (Amelung et al., 2000; Jónsson et al., 2005). Despite these similarities, our modeling results of the 2005 faulting event differ significantly from the previous interpretations of the 1997–1998 event. In order to isolate the motions

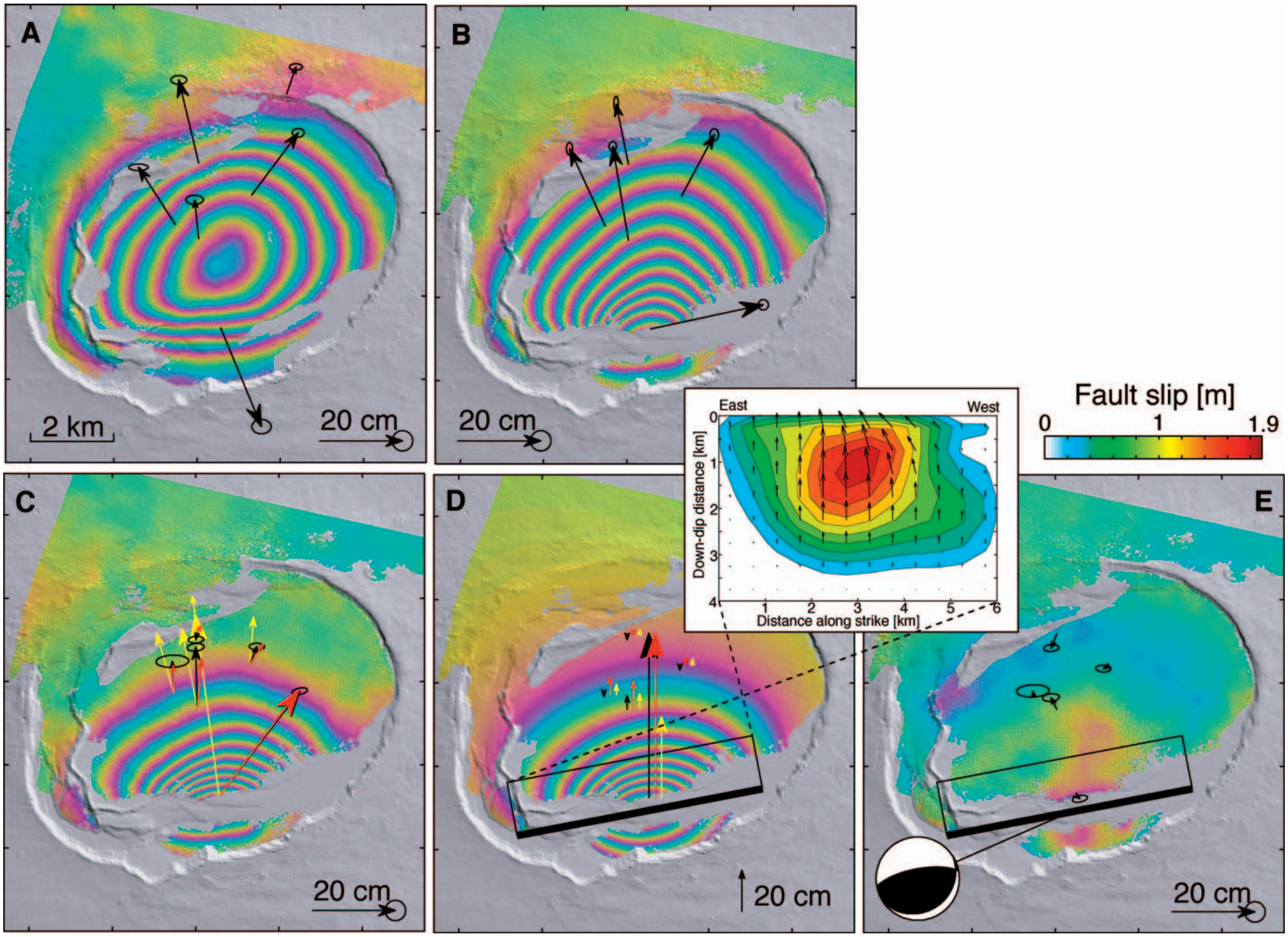

Figure 2. Inferometric synthetic aperture radar (InSAR) and continuous global positioning system (CGPS) data and comparison with trapdoor fault models. A: InSAR observations and horizontal CGPS displacements indicating uplift from 12 February 2004 to 27 January 2005. InSAR data are displayed at 10 cm range change per fringe. B: InSAR and CGPS observations from 27 January 2005 to 12 May 2005 showing effect of both uplift and trapdoor faulting. C: Same InSAR observations as in B, but corrected for deformation related to uplift and effectively only showing deformation due to trapdoor faulting on 16 April 2005. Black and red vectors show observed and predicted horizontal displacements, respectively. Yellow vectors in C and D show predicted displacements from model of Amelung et al. (2000). D: Simulated interferogram from our trapdoor fault model (inset). Black and red vectors show observed and predicted vertical displacements, respectively. E: Residual between InSAR data in C and model prediction in D with residual horizontal CGPS displacements. Focal mechanism shows modeled sense of slip.

due to the trapdoor faulting event, it is assumed that the pattern of inflation captured in the first interferogram (12 February 2004–27 January 2005) continued until the time of faulting and after faulting took place. This pattern of uplift was scaled by the CGPS data and then subtracted from the second interferogram, yielding an interferogram that effectively isolates the deformation signal of the trapdoor faulting event on 16 April 2005 (Fig. 2C).

In a joint inversion of the fault-related CGPS and InSAR displacements (Jónsson et al., 2002), we solve for both the fault geometry and slip, and find that the best-fit elastic dislocation model (Data Repository; see footnote 1) is a high-angle reverse fault with a strike of 259° and a dip of 71° north (Figs. 2C–2E). Dip slip alone cannot match the horizontal displacements at GV06, and a small component of right-lateral strike-slip motion is required. When allowing for variable fault slip, we find maximum reverse faulting of 1.9 m, and right-lateral strike slip at shallow depths accounts for ~13% of the total geodetic moment (Fig. 2D). No evidence for inelastic deformation or site instability was found when the GV06 site was examined after the earthquake.

Amelung et al. (2000) used south-dipping normal faults and a four segment fault geometry that mimicked the surface trace of the fault system to model the 1997–1998 trapdoor faulting event. However, we found that this geometry could not match the observed CGPS displacements in 2005 (Fig. 2). We conclude that the 1997–1998 trapdoor event also occurred on a north-dipping reverse fault, because a model similar to the one in Figure 2 can also fit the 1997–1998 InSAR data (see Data Repository). This clearly demonstrates that using GPS and InSAR together provides more robust model constraints than using either data set alone.

DISCUSSION

Although a sparse seismic network exists in Galápagos, it was not operational during 2003–2005 and only data from the global network are available. The 16 April 2005 earthquake had a magnitude of m_b4.6 (National Earthquake Information Center; http://neic.usgs.gov). A simple calculation of the moment based on the preferred dislocation model is 5×10^{17} Nm (Kanamori and Anderson, 1975), equivalent to an M_w5.8 earthquake, assuming a shear modulus of 30 GPa. The discrepancy between geodetic and seismic moments, which was also observed associated with the 1997–1998 faulting event (presumed to be related to an M_w5.0 earthquake on 11 January 1998), could be caused by an aseismic component to fault slip (Amelung et al., 2000). However, CGPS data from the 16 April 2005 earthquake (Data Repository; see footnote 1) clearly show that the fault slip was instantaneous (Fig. 1F). Therefore, we propose that the discrepancy may be caused by a combination of the underestimation of seismic magnitude from using body waves (m_b), as well as a lower elastic modulus and seismic attenuation in the shallow crust at Sierra Negra.

Although the 16 April 2005 earthquake is the clearest example, other earthquakes detected in the months preceding the October 2005 eruption (National Earthquake Information Center; http://neic.usgs.gov) may represent slip on the intracaldera fault system. The m_b4.0 earthquake on 23 February 2005 was associated with 4 cm of horizontal displacement at GV06 and 1 cm at GV02, and the m_b4.6 earthquake on 19 September 2005 caused 2 cm of horizontal displacement at GV05 and GV06. In addition, InSAR data suggest that the 19 September 2005 earthquake may be associated with faulting ~2 km east of GV06. An M_w5.5 earthquake occurred just 3 h before the eruption began on 22 October 2005, unfortunately during a period when the CGPS network was down, so we have no information about its cause. This event may have been related to the start of magma intrusion that culminated in the eruption.

The peak rate of uplift observed at Sierra Negra before the 2005 eruption (~1 cm/day) is relatively high, but not unprecedented. Similar inflation rates were observed at Krafla volcano, Iceland, during its 1975–1984 rifting episode (Björnsson, 1985). However, the cumulative vertical displacement of nearly 5 m since 1992 at Sierra Negra is extraordinary and is apparently the largest caldera-wide precursory inflation ever measured at a basaltic volcano. Most intereruption inflation episodes at other well-monitored basaltic volcanoes, including Kilauea and Mauna Loa, Hawaii, and Krafla, Iceland, produce no more than 1.5 m of uplift (typically <1 m) and have durations that are usually <1 yr (Dvorak and Dzurisin, 1997; Newhall and Dzurisin, 1988). This implies that the strain imposed by ~1 m of inflation at those volcanoes is usually enough to cause intrusion of magma to the surface. However, at Sierra Negra the amount of uplift recorded by CGPS between April 2003 and October 2005 was 2.2 m, and if the previous InSAR results since 1992 are included, this total increases to 4.9 m. The total intereruption uplift could potentially be much more, because the amount of uplift between 1979 and 1992 is unknown. A rough estimate of the intrusive volume since 1992 is 130×10^6 m^3, based on a variable-opening sill model used to fit the 2004–2005 observations and simply scaled to a maximum uplift of 5 m.

The repeated episodes of trapdoor faulting are likely responsible for the extraordinary magnitude and duration of precursory inflation observed at Sierra Negra. Cyclic trapdoor faulting relieves some of the strain produced in the roof of the magma reservoir by inflation, and this effectively postpones the time when an eruption would otherwise occur. Trapdoor faulting is self-perpetuating: once faults are established, they are zones of weakness that repeatedly fail. The trapdoor faults apparently are located above the edges of the sill, a geometry predicted for fractures developing due to sill growth (Fialko et al., 2001). The fault scarps near the 1997–1998 and 2005 trapdoor events are 10–20 m high (Jónsson et al., 2005), and the western section of the intracaldera fault system has scarps >100 m high, formed by faulted, uplifted, and tilted lava flows (Fig. 1B) (Reynolds and Geist, 1995). Our results suggest that the sinuous ridge formed by incremental faulting during many trapdoor events, driven by the accumulation of magma in a shallow sill.

In hindsight, when the amount of inflation since the 16 April 2005 faulting event approached the level that had caused previous failures, it was a sign that another faulting event or an eruption was near. If it is established that this is a cyclic pattern, then it is possible that earthquakes and eruptions might be forecast at this volcano on the basis of uplift related to shallow intrusion. In any case, these data show that inflation, faulting, and eruption are intimately intertwined at Sierra Negra and deformation there is a window into subsurface processes that may have predictive value in the future.

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