



RESEARCH LETTER

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Key Points:

- InSAR data provide evidence for two pressurized magma bodies in the middle ERZ
- The stress state has changed from extensional to compressional in the middle ERZ
- The Nāpau Crater source is fed from an oceanic crustal reservoir

Supporting Information:

- Figure S1 and Tables S1 and S2

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Pressurized magma reservoir within the east rift zone of Kilauea Volcano, Hawai'i: Evidence for relaxed stress changes from the 1975 Kalapana earthquake

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Abstract We use 2000–2012 InSAR data from multiple satellites to investigate magma storage in Kilauea's east rift zone (ERZ). The study period includes a surge in magma supply rate and intrusion-eruptions in 2007 and 2011. The Kupaianaha area inflated by ~5 cm prior to the 2007 intrusion and the Nāpau Crater area by ~10 cm following the 2011 intrusion. For the Nāpau Crater area, elastic modeling suggests an inflation source at 5 ± 2 km depth or more below sea level. The reservoir is located in the deeper section of the rift zone for which secular magma intrusion was inferred for the period following the 1975 $M_w 7.7$ décollement earthquake. Reservoir pressurization suggests that in this section of the ERZ, extensional stress changes due to the earthquake have largely been compensated for and that this section is approaching its pre-1975 state. Reservoir pressurization also puts the molten core model into question for this section of Kilauea's rift zone.

1. Introduction

Kilauea Volcano's intrusive growth is by a combination of rift zone expansion and migration and by seismic or aseismic seaward movement of the south flank along a basal décollement fault at the paleoseafloor. Rift zone expansion occurs by episodic dike propagation into the shallow, brittle section of the rift zone (to a depth of 3–4 km), by episodic or secular dike dilation in the deep section of the rift zone [Delaney *et al.*, 1990; Owen *et al.*, 2000], and/or by gravitational spreading of hot olivine cumulates [Clague and Denlinger, 1994; Plattner *et al.*, 2013; Denlinger and Morgan, 2014]. The state of stress within the volcano depends largely on the time-varying frictional resistance along the onshore portion of the décollement fault [Dieterich, 1988]. At times when the resistance is low, the aseismic sliding of the south flank is associated with extension of the rift zone and of the summit [Delaney and Denlinger, 1999]. At times of high frictional resistance, the locking of the fault leads to compression of the rift zone and of the south flank. In contrast to its onshore portion, the offshore portion of the décollement fault moves in slow-slip events [Montgomery-Brown *et al.*, 2009; Foster *et al.*, 2013].

The defining event in the recent history of Kilauea was the 1975 $M_w 7.7$ Kalapana earthquake [Nettles and Ekström, 2004]. Seaward flank motion by 8 m at the surface and by more at depth [Owen and Bürgmann, 2006] changed the stress field and brought the rift zone into a state of extension, expressed by rapid rift zone expansion [Delaney *et al.*, 1998; Cayol *et al.*, 2000; Delaney *et al.*, 1990; Delaney and Denlinger, 1999] and by a reduction in the amplitude of interintrusion summit inflation after 1975. This amplitude is a proxy for the maximum overpressure that the magma reservoir can sustain [Grosfils *et al.*, 2013] and therefore for the magnitude of the tectonic background stress field [Currenti and Williams, 2014]. Eruptions in 1955 and 1960 were associated with 1–3 m of summit subsidence [Dvorak, 1992; Poland *et al.*, 2014] (and inevitably a similar amount of summit inflation), whereas the 1997 intrusion-eruption and the 1999 intrusions lacked precursory summit inflation [Owen *et al.*, 2000; Cervelli *et al.*, 2002]. The 2007 intrusion-eruption was preceded by only ~30 cm of summit inflation [Baker and Amelung, 2012; Poland *et al.*, 2012]. This change in inflation amplitude shows that the post-1975 stress field was less compressional than pre-1975. Intrusions lacking precursory summit inflation are thought to be caused by a decrease of the rift zone-perpendicular normal stress due to flank motion [Poland *et al.*, 2014; Montgomery-Brown *et al.*, 2010]. Another diagnostic for the change in stress state is the change in the ratio between eruptive and noneruptive dike intrusions [Dzurisin *et al.*, 1984]. The pre-1975 high-overpressure intrusions were more likely to erupt than post-1975 low-overpressure intrusions [Poland *et al.*, 2014].

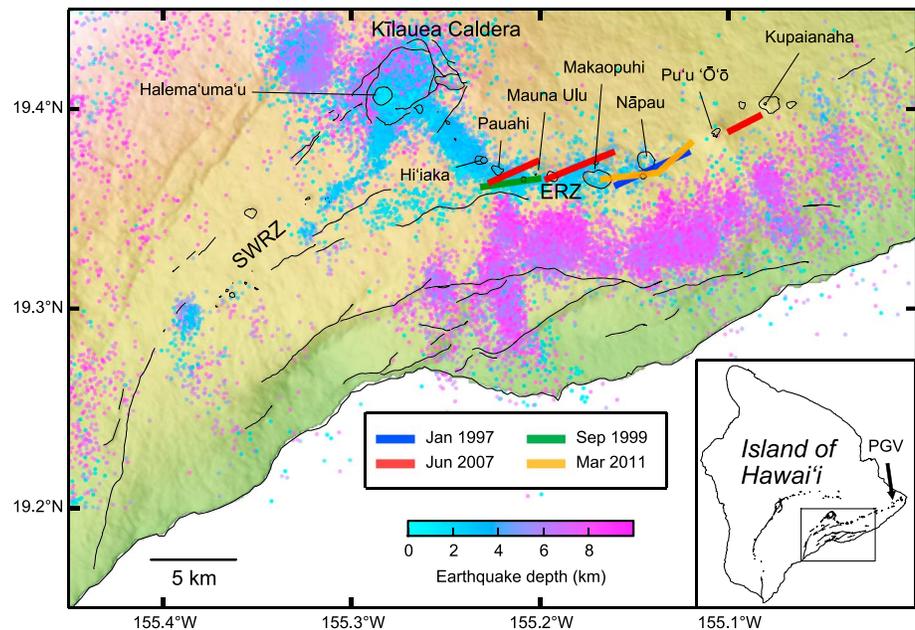


Figure 1. Base map of Kilauea Volcano showing locations of recent intrusion-eruptions in the middle east rift zone (ERZ) and earthquake locations from *Lin et al.* [2014] (color coded by depth). SWRZ: southwest rift zone, PGV: Puna Geothermal Ventures. In this paper we refer to several subsequent sections of the ERZ according to the names of the craters as Hi'iaka-Makaopuhi, Nāpau, Pu'u 'Ō'ō, and Kupaianaha rift zone sections.

An important question is whether the volcano is still responding to extensional stress imposed by the 1975 earthquake. Here we use space geodetic data to provide evidence for an inflating magma reservoir within Kilauea's east rift zone, suggesting that this section of the rift zone has returned to a more compressional stress state with enough strength to sustain overpressurized reservoirs.

2. Volcanic Activity in the Middle East Rift Zone

The post-1950 activity in the middle ERZ (Figure 1) consists of several short-lived eruptions in the 1960s, a 1969 eruption of Mauna Ulu lasting 5 years, and 13 small intrusions, some of which erupted [*Wright and Klein, 2014*]. The 1983 Pu'u 'Ō'ō-Kupaianaha eruption started with an intrusion that propagated downrift from Makaopuhi Crater and intersected the surface at Nāpau Crater to create an 8 km long eruptive fissure extending to Pu'u 'Ō'ō [*Wallace and Delaney, 1995; Rubin et al., 1998*]. The eruption continues as of today and has produced the largest outpouring of magma at Kilauea for about 500 years. The eruption is occasionally interrupted by smaller intrusions into different sections of the middle ERZ, such as the 1997 intrusion-eruption, the noneruptive 1999 intrusion, the June 2007 intrusion-eruption (Father's Day eruption) between the July 2007 intrusion-eruption, and the March 2011 Kamoamoā intrusion-eruption (Figure 1). The latter started on 5 March and produced lava fountains and spattering until 9 March [*Lundgren et al., 2013*].

The 2007 intrusions and the 2011 intrusion were preceded by summit inflation and were accompanied by sudden subsidence over the summit reservoir and by collapse of the Pu'u 'Ō'ō crater floor. The 2007 activity was triggered by a surge in the magma supply rate, which also led to the creation of a new lava lake within Halema'uma'u Crater in 2008 [*Poland et al., 2012*]. The 2011 intrusion was accompanied by drainage of this lava lake [*Lundgren et al., 2013*].

3. Data and Observations

We use interferometric synthetic aperture radar (InSAR) satellite imagery of Kilauea Volcano from 2000 to 2012 (538 SAR acquisitions from the RADARSAT-1, Envisat-1, ALOS, and TerraSAR-X/TanDEM-X satellites in 18 different viewing geometries; see Table S1 in the supporting information). We conduct the following processing steps to obtain a vertical displacement time series [*Baker, 2012*]. First, for each satellite viewing

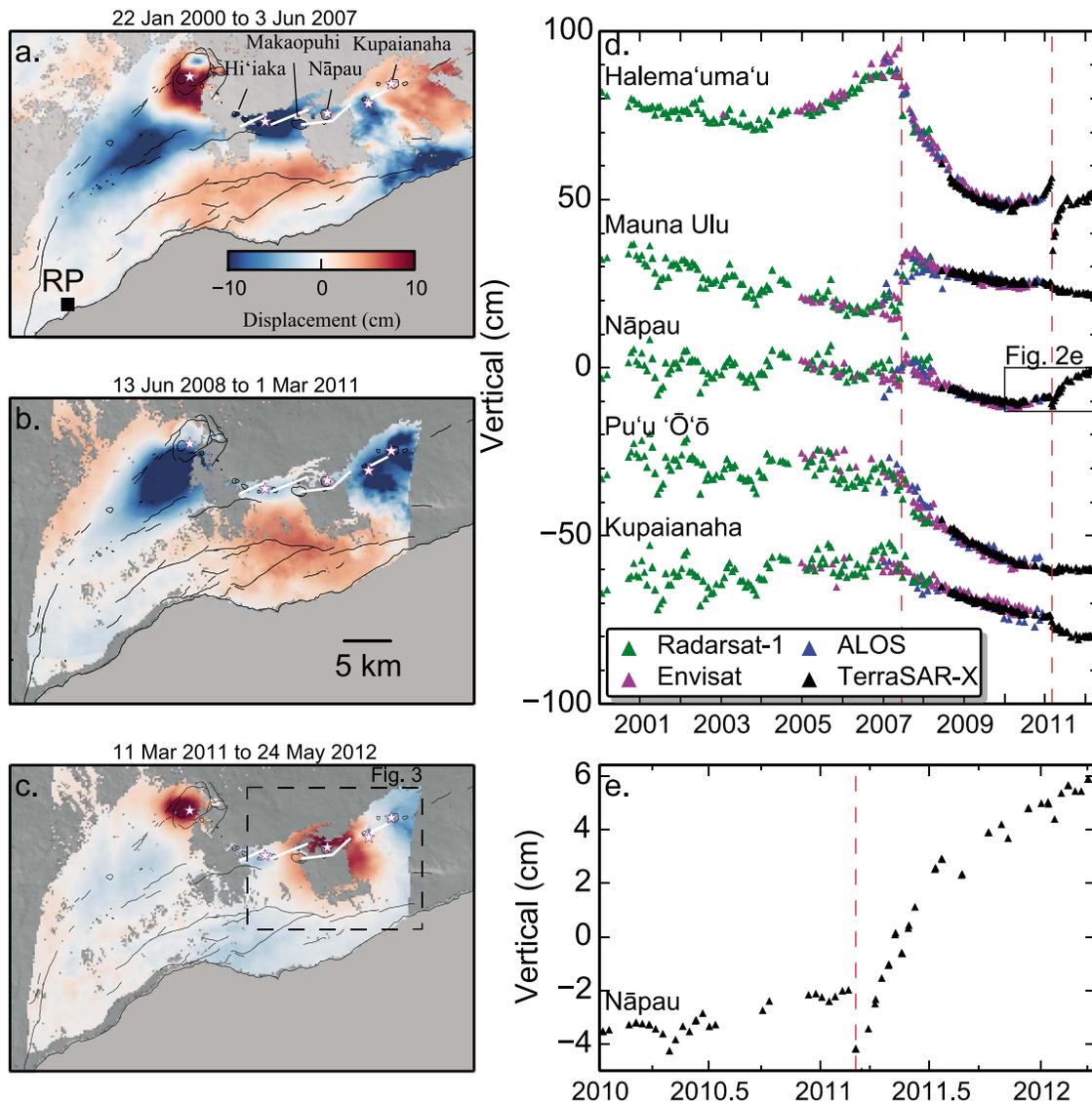


Figure 2. Vertical displacements from multisensor InSAR for (a) January 2000 to June 2007, (b) June 2008 to March 2011, and (c) March 2011 to May 2012. (d) Combined vertical displacement time series of 2000–2012 for the summit and four locations along the ERZ depicted as stars in Figures 2a–2c. (e) Jan 2010 to Apr 2012 vertical displacement time series for Nāpau Crater from TerraSAR-X. In Figure 2d, the dashed, red vertical lines denote the 2007 and 2011 intrusion-eruptions and the earliest black triangles (TerraSAR-X) denote the beginning for the time period of Figure 2b. RP: reference point.

geometry we obtain point-wise radar line-of-sight (LOS) displacement histories using the small baseline approach [Berardino *et al.*, 2002] following the procedure of Baker and Amelung [2012] but including digital elevation model error correction [Fattahi and Amelung, 2013]. Next we select a pair of ascending and descending viewing geometries with acquisition epochs separated by only a few days and linearly interpolate to obtain LOS displacements at each epoch, align them in a least squares sense to eliminate effects from the reference point selection, and combine them to vertical displacements [Wright *et al.*, 2004]. We repeat this procedure for eight other ascending/descending pairs and combine the vertical displacement histories in a minimum norm sense to a time series at 537 epochs.

Figures 2a–2c show the net vertical displacement for three different interintrusion time periods: prior to the 2007 intrusion-eruption, between the 2007 and 2011 intrusion-eruptions, and following the 2011 intrusion. We have excluded the first year following the 2007 intrusion-eruption because the vertical displacement at the summit is dominated by deformation following the 2007 intrusion as detailed in Baker and Amelung [2012]. In the first time period the Hi'iaka-Makaopuhi rift zone subsided by up to 15 cm (blue colors), the

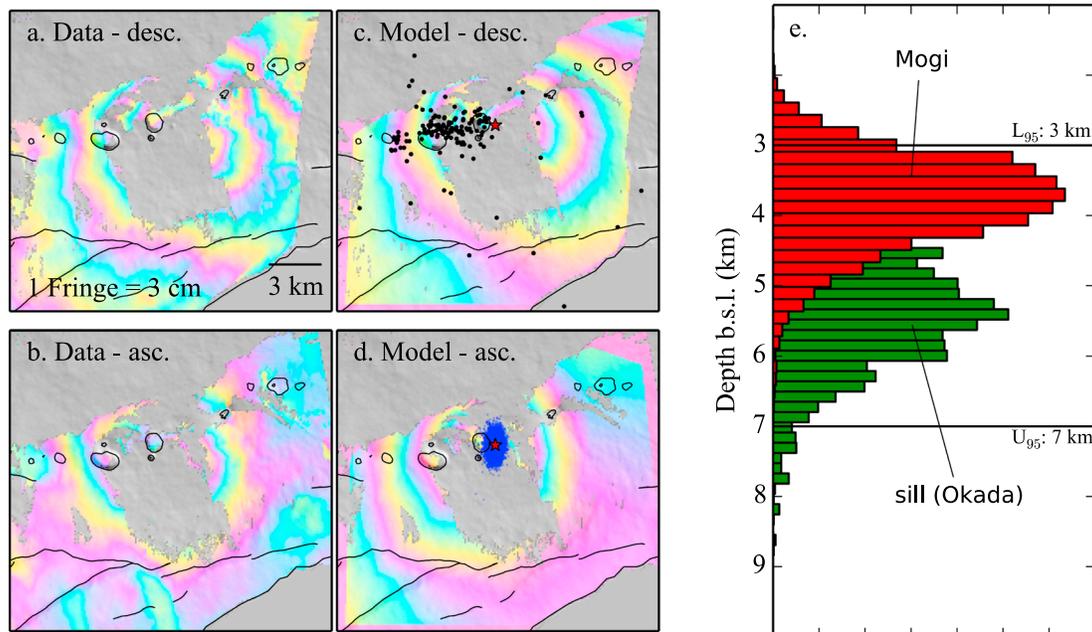


Figure 3. Elastic half-space models for the inflation around Nāpau Crater. (a) Descending and (b) ascending interferograms (11 March 2011 to 6 October 2011 and 25 April 2011 to 7 October 2011, respectively). (c) Descending and (d) ascending best fitting Mogi models. (e) Probability density distributions for the source depth below sea level obtained from Gibbs sampling for the Mogi model (red bars) and for a horizontal opening dislocation model (green bars) together with the lower (L95) and upper (U95) 95% confidence limits. Red star in Figures 3c and 3d represents the horizontal location for best fitting model, and the blue dots in Figure 3c represent the 95% confidence limits for the horizontal location. Black circles in Figure 3c are earthquake locations from the first day of the 1983 dike intrusion.

Nāpau and Pu'u 'Ō'ō sections subsided by ~5 cm, and the Kupaianaha section uplifted by ~5 cm (red colors, Figure 2a). The complex pattern in the summit area during this period is the result of subsidence until late 2003 and uplift thereafter [Baker and Amelung, 2012; Poland et al., 2012]. In the second time period the Hi'iaka-Makaopuhi and Nāpau sections subsided by ~4 cm and the Pu'u 'Ō'ō and Kupaianaha sections by 15 and 10 cm, respectively (Figure 2b). In the third period, the most significant signal along the rift zone is inflation around Nāpau Crater by more than 10 cm (Figure 2c). The displacement maps also show subsidence of new lava flows due to cooling and settling around Pu'u 'Ō'ō (Figures 2a and 2b) and along Kīlauea's shore (>10 cm in blue area located 10 km south of Kupaianaha, Figure 2a).

The vertical displacement time series for a point above the summit magma reservoir (east of Halema'uma'u) and for four locations in the ERZ (Figure 2d) provide insight into the dynamics during this 12 year period, although the early data are noisy because of the orbital uncertainties of RADARSAT-1. The summit (Halema'uma'u location) subsided from 2000 to late 2003 then inflated until 2007, deflated during and after the 2007 intrusion-eruption, reinflated in 2010–2011, and deflated during the 2011 intrusion-eruption and inflated thereafter. The Mauna Ulu location subsided at a rate of 2.5–3 cm/yr both before and after the 2007 intrusion-eruption. The Nāpau and Pu'u 'Ō'ō locations did not show significant vertical movement prior to the 2007 eruption at the resolution of our data but deflated thereafter. The Nāpau location shows subtle uplift 1 year before and rapid uplift after the 2011 intrusion-eruption (temporal details in Figure 2e). In contrast, deflation at Pu'u 'Ō'ō after 2007 continues but at a decreasing rate. The Kupaianaha location shows ~5 cm of uplift prior to 2007, followed by ~15 cm of subsidence.

4. Modeling

We use simple elastic half-space models and geophysical inverse methods to estimate the location and depth of the inflation source under Nāpau. We do not model the Kupaianaha uplift because the data are too noisy to infer a meaningful source depth. For the modeling we selected individual interferograms with good signal-to-noise ratio: a descending interferogram starting near the end of the eruption and an ascending interferogram starting about 1 month later (Figures 3a and 3b). Our data set consists of 110 data

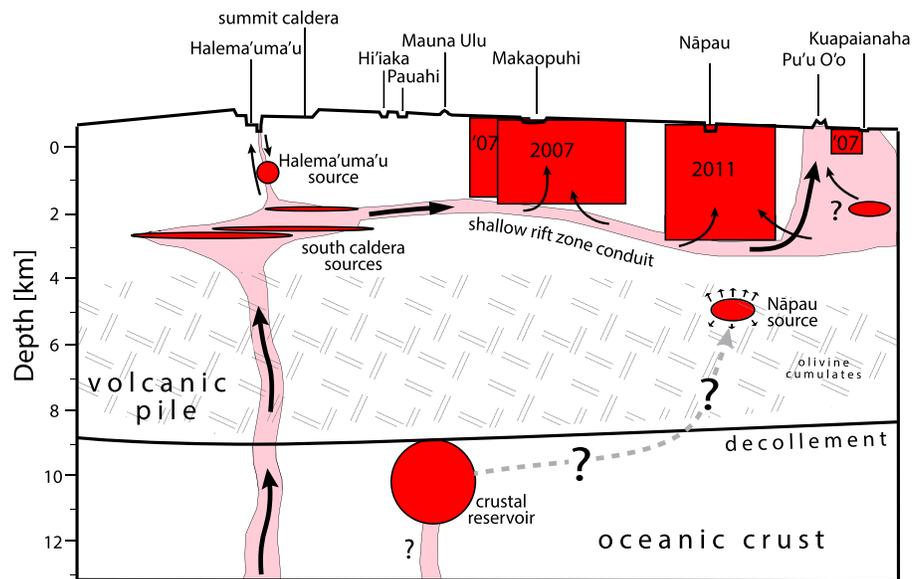


Figure 4. Schematic of the magmatic system of the east rift zone and intrusions since 2007 (not to scale). Summit magma bodies are from Baker and Amelung [2012], 2007 and 2011 intrusions are from Montgomery-Brown *et al.* [2010] and Lundgren *et al.* [2013], and crustal magma body is from Lin *et al.* [2014].

points for the descending interferogram and 80 data points for the ascending interferogram, obtained by quadtree decomposition.

The best fitting point source (Mogi model) is located ~ 100 m east of Nāpau Crater at a depth of $4.0^{+1.5}_{-1.0}$ km below sea level (bsl) with the 95% confidence intervals estimated using a Gibbs sampling approach (Figures 3c and 3d). For a horizontal opening dislocation we find a depth of $5.6^{+1.4}_{-1.4}$ km bsl (Okada model, not shown). In the following we use a midpoint source depth of 5.0 ± 2.0 km bsl since the data cannot distinguish between the two models (see supporting information Figure S1). The actual source depth is likely 1–2 km deeper because of the mechanically weaker material near the surface [Hautmann *et al.*, 2010].

5. Magma Plumbing Within the ERZ

Our data provide evidence for two pressurized magma bodies in the middle ERZ. The source under Nāpau Crater produced 10 cm of surface inflation after the 2011 intrusion-eruption. The Kupaianaha source produced 5 cm of uplift prior to the 2007 eruption. The post-2007 deflation of the Pu'u Ō'ō and Kupaianaha areas by 30 and 15 cm suggests magma loss, but this signal is overprinted by lava flow subsidence.

Our interpretation of the magma plumbing system in the ERZ is summarized in Figure 4. The Nāpau source locates in the deeper section of the rift zone between the intrarift zone conduit and the basal décollement, which is at 8.5 km depth in this area [Lin *et al.*, 2014]. The conduit fed the 2007 and 2011 intrusions that initiated at inferred depths of 3 and 3.3 km bsl [Montgomery-Brown *et al.*, 2010; Lundgren *et al.*, 2013] which is slightly deeper than the south caldera sources with inferred depths of 1.8 to 2.5 km bsl [Baker and Amelung, 2012]. The depth of the Pu'u Ō'ō-Kupaianaha reservoir is not constrained.

A magma reservoir under Nāpau Crater was inferred previously. The seismic swarm at the leading edge of the 1983 dike stopped just east of Nāpau Crater [Rubin *et al.*, 1998], and a tilt signal was recorded at about the same time a few kilometers down the rift zone. This was interpreted as the propagation of a pressure wave through a body of liquid magma [Okamura *et al.*, 1988]. The lack of seismicity in the rift zone east of Nāpau Crater (Figure 1) is also consistent with the presence of magma in this area. The close proximity of the inferred Nāpau source to the last seismic events of the 1983 swarm suggests a body with a diameter of a few hundred meters (Figure 3c).

There are many other observations for magma storage within the ERZ. Most rift zone eruptions start by expelling old, cool, and differentiated magmas remaining from previous intrusions, before hotter, more primitive magmas

from the summit or deeper sources are erupted [Wright and Fiske, 1971; Garcia and Wolfe, 1988; Helz and Wright, 1992; Garcia et al., 2003; Pietruszka and Garcia, 1999; Thornber et al., 2003]. Geodetic data prior to 1983 have recorded the inflation and/or deflation of magma reservoirs at Makaopuhi Crater and in the Pu'u 'Ō'ō-Kupaianaha area [Dzurisin et al., 1984; Tilling and Dvorak, 1993]. The Makaopuhi source may have been activated during the 1997 Nāpau intrusion [Owen et al., 2000; Segall et al., 2001]. Poland et al. [2014] report uplift near Kupaianaha between late 2003 and 2007. Evidence for past shallow magma storage also includes numerous pit craters along the middle ERZ [Okubo and Martel, 1998] and a dacite melt encountered at ~2.5 km depth by a drilling operation at the Puna Geothermal Venture well field (Figure 1) [Teplow et al., 2008].

Our interpretation of the post-2011 Nāpau signal differs to that of Lundgren et al. [2013]. They did not consider any deeper inflation sources and interpreted the signal as caused by the dilation of the deeper section of the intruded dike. Transient deformation lasting several months was also observed after the 1997 intrusion and interpreted as caused by middepth dike dilation in response to a stress perturbation by the intruded dike [Desmarais and Segall, 2007]. We note that the reported post-1997 uplift of 3–5 cm of two GPS stations in the Nāpau area (stations NUPM and KTPM), and the extension between these two stations (located on opposite sides of the rift zone), could also be consistent with inflation of the Nāpau source.

6. Implications

The Nāpau Crater uplift after the 2011 intrusion is the first well-documented inflation in the middle ERZ since the 1983 intrusion. This inflation is significant because the storage reservoir is located in the deeper section of the rift zone for which expansion was inferred from 1975 through at least 1996 [Delaney et al., 1990; Owen et al., 2000]. Reservoir pressurization suggests that expansion of this section of the rift zone has slowed or stopped and that the stress state has changed to a more compressional state, which is more conducive to the storage of magma in reservoirs than to the propagation of dikes. If this interpretation is correct, we would expect changes in the mode of rift zone expansion farther uprift where the observed subsidence suggests that deep rift zone expansion may be continuing (Figures 2a and 2b).

An alternative explanation for reservoir inflation could be pressure reequilibration after the withdrawal of magma to feed the eruption. We can rule this out because the 2011 intrusion-eruption was not associated with any reservoir deflation [Lundgren et al., 2013].

The Nāpau source at a depth of 5 km or more is not consistent with the view that the entire deeper section of the ERZ is a magma storage zone, as sometimes inferred from the lack of seismicity below 4 km and implied by the molten core model for Kīlauea's deep rift zone [Johnson, 1995]. A mushy body with significant percentage of melt would not have the strength to sustain the overpressure in a reservoir. The Nāpau source favors the view of a largely solidified olivine cumulate body in the deeper portion of the ERZ, inferred from a positive P wave anomaly of 5–10% [Park et al., 2009; Lin et al., 2014]. A cumulate body might sustain the overpressure although it could yield after years depending on its temperature.

The Nāpau inflation continued through at least mid-2012, while the Pu'u 'Ō'ō eruption continued. Therefore, and because of its depth of ~5 km, it is unlikely that the source is fed from the summit reservoir through the intermediate-depth conduit. We speculate that the source could be fed from the recently discovered reservoir in the oceanic crust under Mauna Ulu [Lin et al., 2014].

7. Summary

The area around Nāpau Crater inflated by as much as 10 cm after the 2011 intrusion-eruption due to the intrusion of magma into a storage reservoir at 5 ± 2 km depth bsl. This is the first well-documented observation of intrarift zone inflation since the onset of the current eruption in 1983 and shows that the deeper section of the rift zone is capable of sustaining pressurized magma reservoirs, raising questions about the notion of a partially molten core [Johnson, 1995; Delaney and Denlinger, 1999] at least for this section of the rift zone. The gradual adjustment of the ERZ to stress changes imposed by the 1975 earthquake appears to be completed, at least locally. The stress state below Nāpau has changed from extensional, facilitating deep dike dilation, to more compressional, supporting pressurized magma storage zones. Another less well-constrained inflating source is suggested under Kupaianaha. This observed mode of magma accumulation differs from that currently observed at Mauna Loa, where magma accumulates in subvertical dike-like bodies [Amelung et al., 2007].

Acknowledgments

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