INSAR OBSERVATIONS OF DEFORMATION ASSOCIATED WITH NEW EPISODES OF VOLCANISM AT KĪLAUEA VOLCANO, HAWAI'I, 2007

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ABSTRACT

In June 2007, the Puʻu ʻŌʻō-Kupaianaha eruption of Kīlauea Volcano was interrupted when magma intruded the east rift zone (ERZ), resulting in a small extrusion of lava near Makaopuhi Crater. Deformation associated with the activity was exceptionally well-documented by ASAR interferometry, which indicates deflation of the summit and uplift and extension of the ERZ. Models of co-intrusion interferograms suggest that the dike was emplaced in two distinct segments. The modeled volume of the dike greatly exceeds that of the deflation source, raising the possibility that magma from the downrift Puʻu ʻŌʻō vent (dominant extrusion site at Kīlauea since 1983) contributed to the eruption near Makaopuhi, or that the magma that fed the eruption from the summit was compressible. A month following the Makaopuhi eruption, an eruptive fissure opened on the east flank of Puʻu ʻŌʻō. Interferograms, processed within 48 hours of the event, were critical in demonstrating that the magma source feeding the eruption was shallow. The eruption probably resulted from overpressure in Puʻu ʻŌʻō's magmatic system.

1. INTRODUCTION

Since 3 January, 1983, Kīlauea Volcano, on the Island of Hawai'i, has been in a state of nearly constant eruption. During 1983-1986, lava erupted from the Puʻu ʻŌʻō vent on the ERZ (Fig. 1A). The locus of activity switched 3 km downrift to the Kupaianaha vent in 1986 and moved back to Puʻu ʻŌʻō in 1992 [1]. Lava effusion between 1992 and mid-2007 was almost continuous, with sporadic interruptions caused by uprift intrusions, for example, in 1997 [2] and 1999 [3].

For the first 20 years of the Puʻu ʻŌʻō-Kupaianaha eruption, subsidence dominated the deformation field at the summit of Kīlauea [4]. In late 2003, however, summit deformation switched to inflation, which continued at varying rates through mid-2007. The rate of lava effusion from Puʻu ʻŌʻō was steady during 2003-2004 and increased in early 2005, suggesting that the summit inflation was not driven by a decrease in the eruption rate at Puʻu ʻŌʻō. Instead, the combination of summit inflation with increasing lava effusion suggests that the rate of magma being supplied to the shallow volcanic system increased. The heightened supply apparently could not be accommodated solely by eruption from Puʻu ʻŌʻō, causing magma accumulation in the summit reservoir.

2. "FATHER'S DAY" INTRUSION/ERUPTION

During the early morning (local time) of 17 July, 2007 (the "Father's Day" holiday in the USA), ground tilt and seismicity in the vicinity of Mauna Ulu (Fig. 1A) indicated the intrusion of a dike into Kīlauea's upper ERZ. The intrusion grew in four distinct pulses over about 57 hours and migrated downrift to Makaopuhi Crater, where the activity culminated in a small eruption north of the crater on 18-19 June. GPS and tilt results indicated subsidence and contraction of the summit region and widening of the ERZ during emplacement of the intrusion, and Puʻu ʻŌʻō collapsed as magma supply to the vent was interrupted [5].

Frequent ENVISAT ASAR acquisitions over the Island of Hawai'i allow for the formation of numerous radar interferograms that span the activity. As of November 2007, eleven different look angles have captured co-intrusion deformation. All the interferograms show deflation of the summit centered near Halema'uma'u Crater and a pattern of uplift and subsidence along the ERZ consistent with dike emplacement (Fig. 1B-L).

One ASAR scene was serendipitously acquired at about 22:20 on 17 June (all times reported are Hawaiian Standard Time, UTC-10 hours), during the emplacement of the intrusion. Interferograms formed using the scene have provided a unique view into the process of intrusion and proven valuable for the interpretation of the activity.

The 35-day interferogram that spans the initial stages of the intrusion (13 May-17 June) is characterized by both summit deflation and deformation in the upper ERZ (Fig. 2A). The displacement field can be modeled by two nearly vertical dislocation sources [6] approximating opening dikes and a point source of volume loss [7] beneath the east rim of Halema'uma'u Crater (Fig. 2B-C). The eastern of the two dislocations, just west of Mauna Ulu, has a roughly E-W strike, a top 1 km beneath the surface, and opened 0.85 m (giving a volume 1.9 x 10^6 m^3). The western dislocation extends from near Mauna Ulu to Makaopuhi, strikes ENE, has a top about 0.4 km deep, and opened 0.92 m (a volume change of 3.8 x 10^6 m^3). The deflation source is at a depth of 1 km, which corresponds to the source of transient tilt events described by [4], and had a volume change of 0.5 x 10^6 m^3. The model does not fit the displacement field immediately above the dike, suggesting a complex intrusion geometry.

Proc. of FRINGE 2007 Workshop, Frascati, Italy, 26 – 30 November 2007
(ESA SP-649, February 2008)

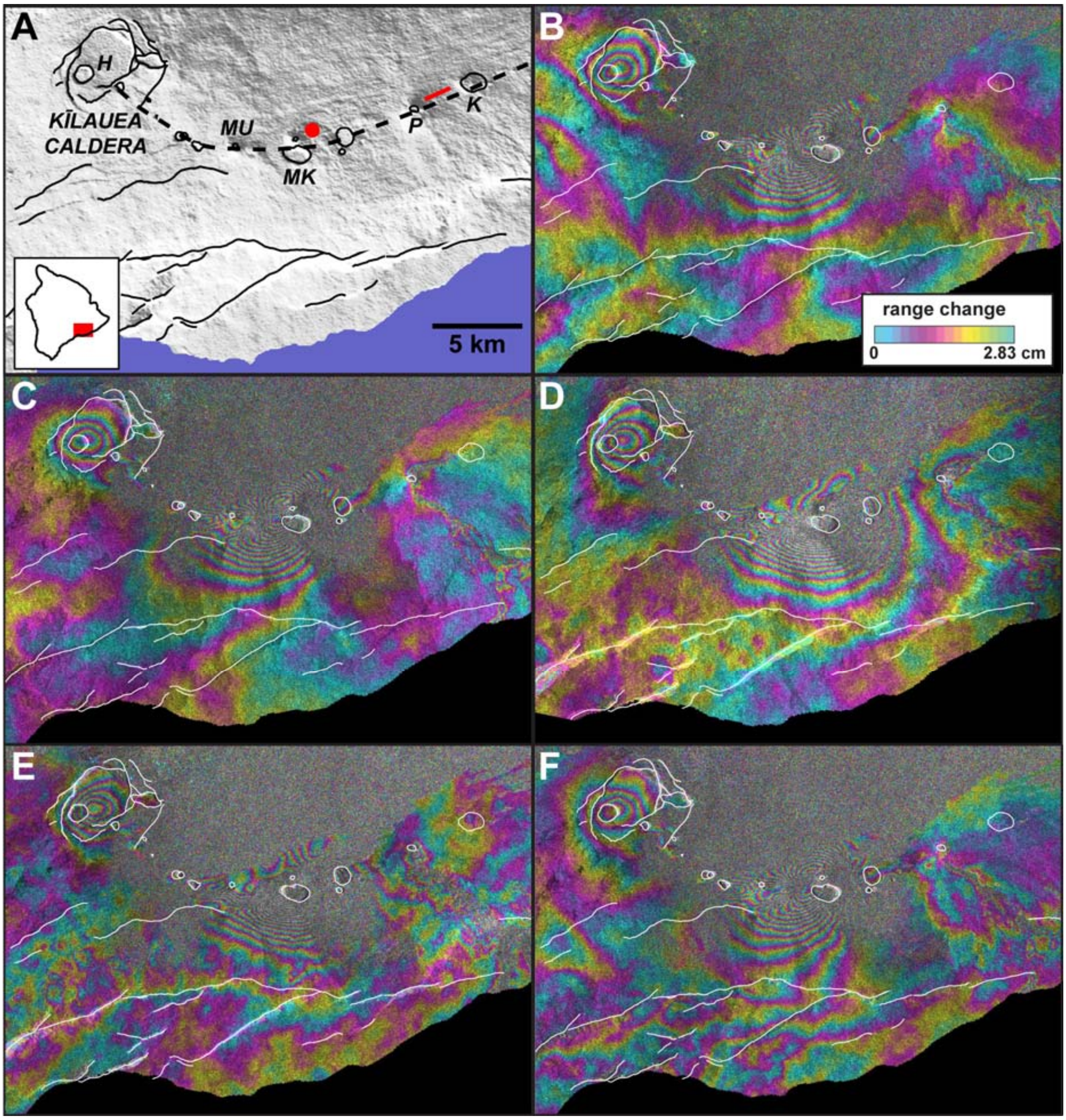

Figure 1. Interferograms spanning mid-2007 activity at Kīlauea Volcano, Hawai'i. (A) Shaded relief map showing geographic features. Dashed line marks ERZ. Red dot is location of 18-19 June eruption. Red line is eruptive fissure f 21 June. Geographic features shown by black lines. Map coverage is identical for subsequent parts. H=Halema'uma'u Crater; MU=Mauna Ulu; MK=Makaopuhi Crater; P=Pu'u 'Ō'ō; K=Kupaianaha. Modes, tracks, and dates of interferograms in subsequent figure parts are given in the table below:

Part	*Mode*	*Track*	*Start Date*	*End Date*
B	*IS1*	*322*	*20 March, 2007*	*3 July, 2007*
C	*IS2*	*93*	*13 May, 2007*	*22 July, 2007*
D	*IS2*	*200*	*21 May, 2007*	*30 July, 2007*
E	*IS3*	*157*	*24 November, 2006*	*22 June, 2007*
F	*IS3*	*365*	*28 April, 2007*	*6 July, 2007*
G	*IS4*	*136*	*11 April, 2007*	*20 June, 2007*
H	*IS4*	*386*	*25 March, 2007*	*8 July 2007*
I	*IS5*	*114*	*26 December, 2006*	*24 July, 2007*
J	*IS6*	*179*	*19 May, 2007*	*28 July, 2007*
K	*IS6*	*343*	*31 May, 2007*	*9 August, 2007*
L	*IS7*	*451*	*7 June, 2007*	*16 August, 2007*

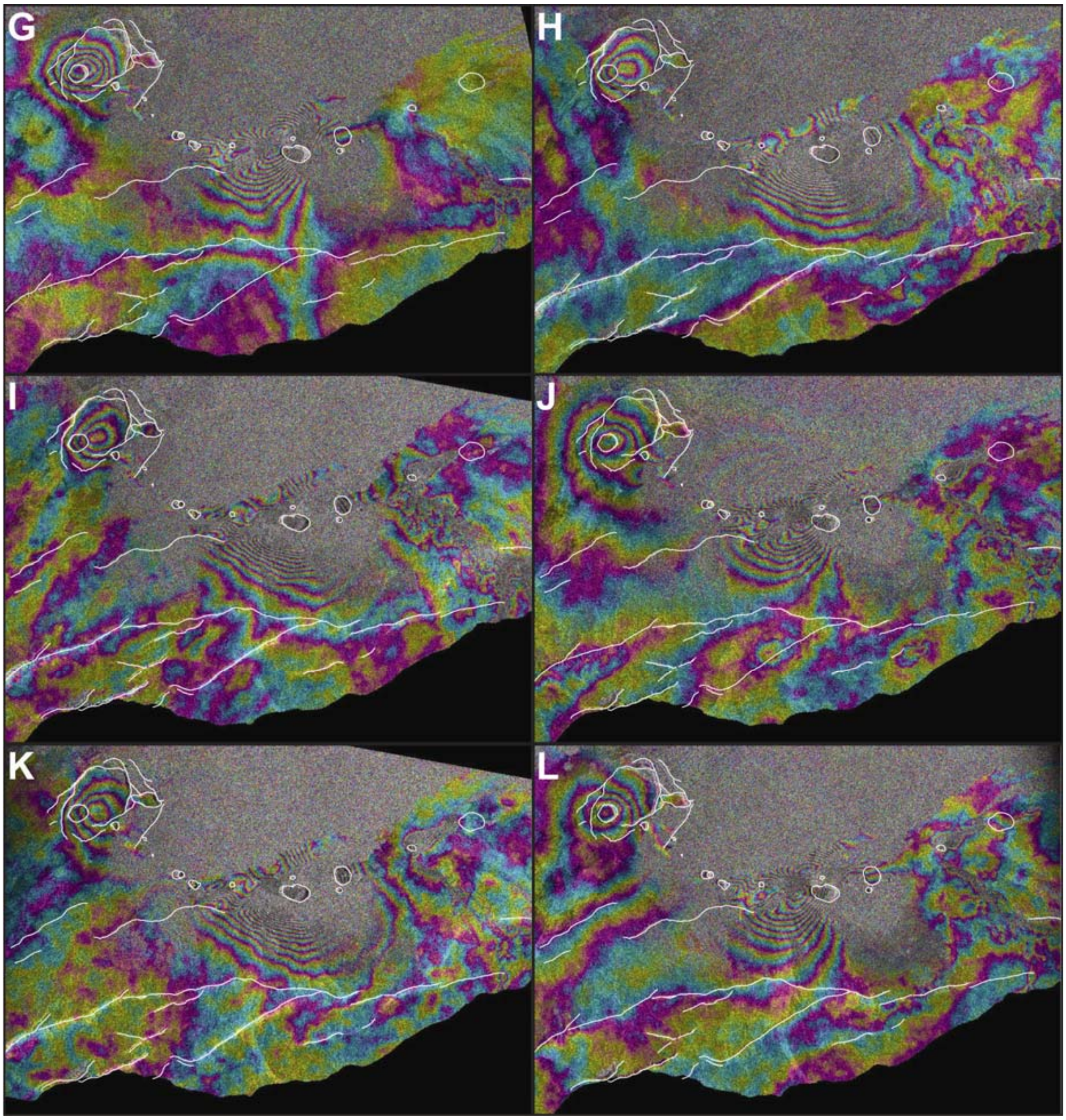

Figure 1. (cont'd)

Line-of-sight displacements in the subsequent 35-day interferogram (17 June-22 May) are significant only along the ERZ (Fig. 2D) and can be approximated by a single nearly vertical dislocation near Makaopuhi Crater (Fig. 2E-F). The dislocation is similar in location to the eastern dislocation in the model of the earlier interferogram, though it is much shallower (the top is less than 100 m below the surface), opened by 1.24 meters, and had a volume increase of 10.7 x 10^6 m^3. The model fits the broader characteristics of the displacement field but is again poor above the dike source. Data from tilt and GPS stations in and around Kīlauea's caldera indicate summit deflation from the start of the intrusion to about noon on 19 June followed by inflation from that point through 20 July (Fig. 3). The 17 June-22 July interferogram therefore includes both inflation and deflation of the summit, which apparently balance one another and result in no net line-of-sight summit deformation in the 17 June-22 July interferogram.

Though preliminary, models of these two interferograms suggest several interesting results. First, the "Father's Day" dike appears to have been emplaced in two distinct segments. Second, the modeled volume of the intrusion far exceeds (by perhaps an order of magnitude) the volume loss from the summit deflation source (with the caveat that the models give a minimal volume loss estimate, because post-17 June deflation is not apparent in the second interferogram). The "missing" volume may have come from a downrift source (for example, Puʻu ʻŌʻō, which collapsed during the intrusion sequence) or could be accounted for by compressibility of magma stored in the summit region [8,9]. Third, the bulk of the intrusion (by volume) occurred after 22:20 on 17 June. Despite their simplicity, these models suggest a complex process of magma intrusion; interferograms spanning this event will provide critical input to future investigations of the "Father's Day" and subsequent activity.

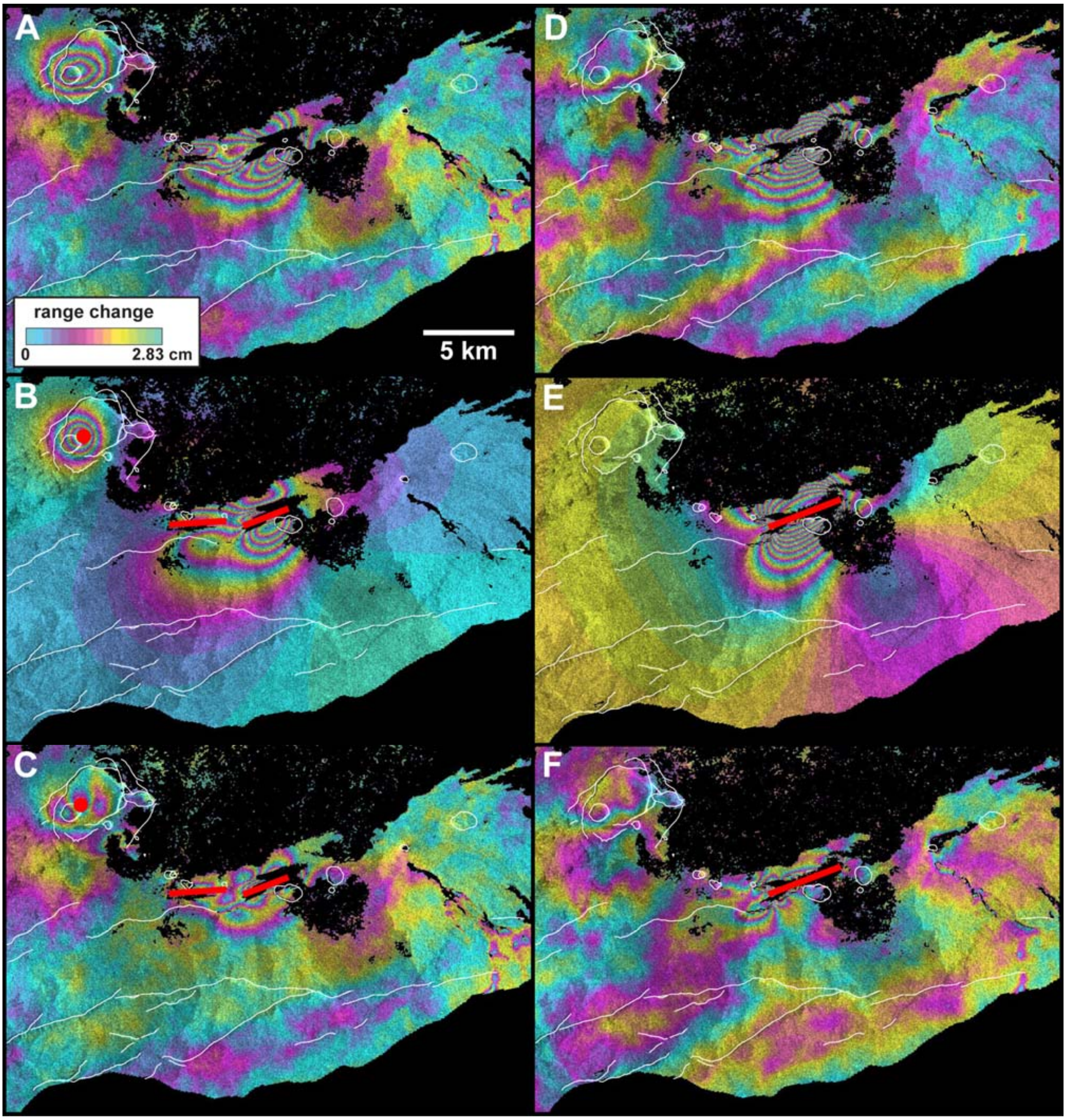

Figure 2. Models of deformation associated with Father's Day activity at Kīlauea Volcano. (A) IS2, track 93 interferogram spanning 13 May-17 June, 2007. (B) Model of interferogram in part A includes a point source of volume loss (red dot) and two nearly vertical opening dislocations (red rectangles). (C) Residual deformation after subtracting model in part B from deformation in part A. (D) IS2, track 93 interferogram spanning 17 June-22 July, 2007. (E) Model of interferogram in part D including one nearly vertical opening dislocation (red rectangle). (F) Residual deformation after subtracting model in part E from deformation in part D.

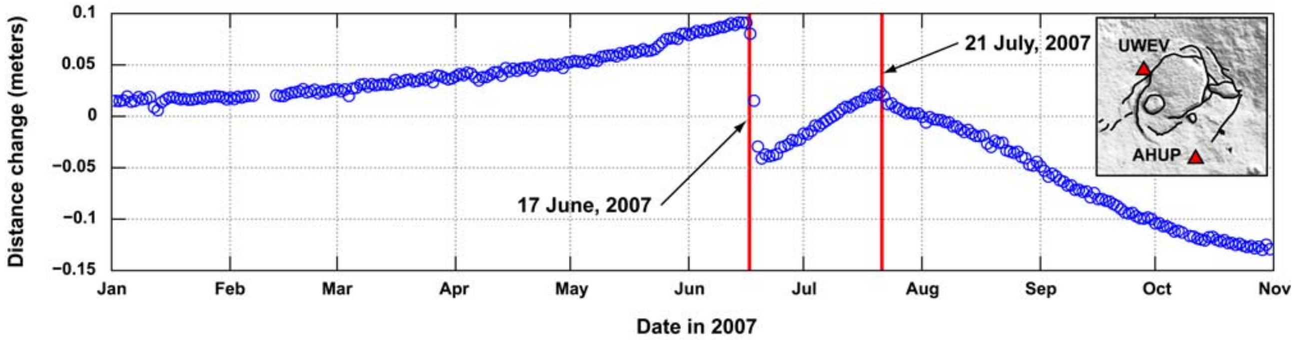

Figure 3. Distance change between GPS stations UWEV and AHUP, which span most of Kīlauea's summit caldera (see inset for station locations) during January-November 2007. Positive distance change (extension) is interpreted as inflation of the summit and negative distance change (contraction), deflation.

3. 21 JULY FISSURE ERUPTION

After a pause of nearly two weeks, activity returned to Pu'u 'Ō'ō on 1 July and formed a pond at the bottom of the collapsed crater. The surface of the pond rose over the subsequent two weeks as the crater filled with lava, and on 13 July new vents began to form along the crater walls, above the lava lake. At about 00:00 on 21 July, Pu'u 'Ō'ō began to deflate rapidly, the lava lake drained, and an eruptive fissure opened on the east flank of the cone (red line on Fig. 1A). The fissure consisted of four segments that extended 2 km from the east rim of Pu'u 'Ō'ō to the base of Kupaianaha. The segment closest to Pu'u 'Ō'ō ceased erupting by about 08:00 on 21 July, and within two weeks only the segment farthest from Pu'u 'Ō'ō (designated "Fissure D") was still active. As of 15 November, Fissure D continues to erupt and has replaced Pu'u 'Ō'ō as the dominant site of lava extrusion.

Line-of-sight deformation in interferograms spanning 21 July is highly localized around Pu'u 'Ō'ō and the area of the fissure eruption, especially compared to deformation associated with the "Father's Day" intrusion/eruption (Figs. 1C, D, I, J, K, L). The limited extent of surface displacements indicates a very shallow source, probably less than a few hundred meters below the surface. The fissure was most likely a result of overpressure in the Pu'u 'Ō'ō magmatic system, as suggested by the formation of eruptive vents along the crater walls during 13-20 July.

4. DEFORMATION AFTER 21 JULY

Following the start of the 21 July fissure eruption, GPS results indicated steady deflation of Kīlauea's summit (Fig. 3). Interferograms that span time periods after 21 July suggest two sources of volume loss beneath the summit: the shallow magma body just east of Halema'uma'u that contracted during the "Father's Day" eruption (location 1 in Fig. 4) and a deeper reservoir beneath the south caldera (location 2 in Fig. 4). Both of these sources are sites of long-term magma storage at Kīlauea's summit [4]. Analysis of numerous post-July 21 interferograms suggests that the shallow Halema'uma'u source was initially the primary site of deflation but declined in importance through August and September as contraction of the south caldera source became the dominant summit deformation signal.

Following 21 July, localized, elongated subsidence began in the ERZ between Mauna Ulu and Makaopuhi (location 3 in Fig. 4), near an area of profuse steaming that formed during the "Father's Day" activity. The subsiding area is similar to the easternmost model dike segment (Fig. 2E) in both location and orientation. Subsidence in this region is probably a result of cooling and contraction of a shallow dike that intruded as part of the "Father's Day" activity and may be within 100 meters of the surface as suggested by models shown in Fig. 2E.

Subsidence after 21 July was also significant on the east flank of Pu'u 'Ō'ō (location 4 on Fig. 4). The subsidence follows the trend of the fissure and is present on lava flows erupted since 21 July; it is therefore probably a result of cooling and contraction of both lava flows erupted on or soon after 21 July and the shallow intrusion that fed the eruption.

Another site of post-21 July deformation is the ERZ itself. Following the start of the 21 July fissure eruption, GPS receivers indicated contraction of the rift zone near both Makaopuhi Crater and Kupaianaha. Subsidence downrift of Pu'u 'Ō'ō (location 5 in Fig. 4) is especially apparent in interferograms that span time periods after 21 July. Contraction of the ERZ suggests that rift-stored magmas are contributing to the Fissure D eruption. Storage of magma in the ERZ and later eruption is not a new idea. For example, mineral assemblages in lava erupted between Makaopuhi and Pu'u 'Ō'ō in 1997 clearly indicated several years of storage in the rift zone [2,10]

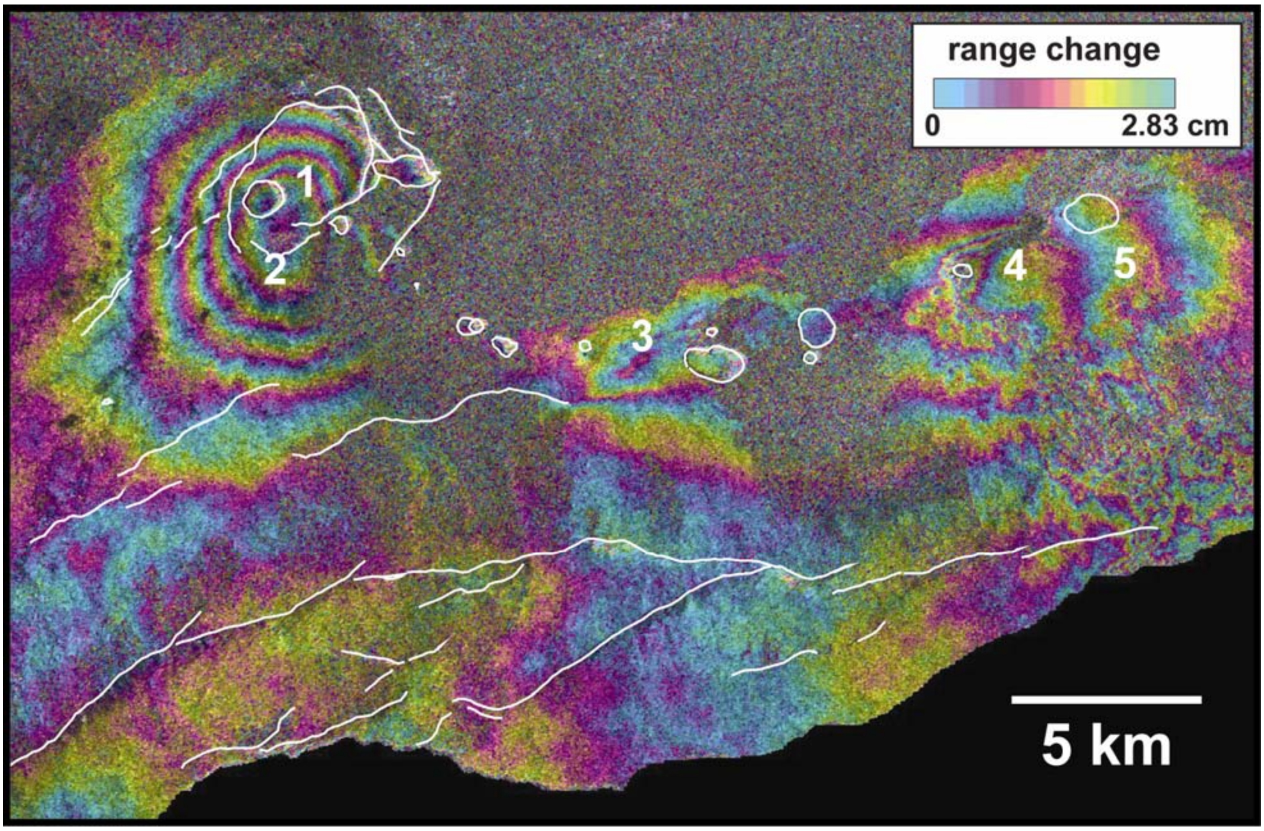

Figure 4. ASAR beam mode IS2, track 93 interferogram spanning 22 July-5 November, 2007. Numbered locations are discussed in the text.

5. DISCUSSION AND CONCLUSIONS

ASAR interferometry provided key insights that aided interpretation of intrusive and eruptive activity at Kīlauea Volcano in mid-2007. Interruption of the Pu‘u ‘Ō‘ō-Kupaianaha eruption starting on 17 June, 2007, was the result of an intrusion and subsequent eruption near Makaopuhi Crater, uprift of Pu‘u ‘Ō‘ō. Magma intruded as part of two distinct dike segments, the modeled volume of which greatly exceeded the volume of contraction of the summit magma reservoir. About a month later, interferograms spanning the 21 July fissure eruption indicated a shallow magma source feeding the eruption, which probably resulted from overpressure in the Pu‘u ‘Ō‘ō magma system.

The experience at Kīlauea during mid-2007 supports the use of satellite radar interferometry as a tool for both operational volcano monitoring and geophysical research. Although tilt and GPS data are critical for near-real-time hazards assessment, the high spatial resolution provided by radar interferograms is more conducive to rapid interpretations of activity over large areas. For example, a qualitative assessment of the depth to the magma source associated with the July 21, 2007 fissure eruption was possible from only visual inspection of interferograms spanning the event. The localized nature of the deformation, which could not be known from the limited ground-based geodetic data, was clear evidence of a shallow magma source for the fissure – an interpretation with important implications for future potential activity. A deeper source would be more likely to propagate downrift toward populated areas; thus, interferograms can be important for hazards assessment efforts. Timely availability of ASAR data further enhances the use of interferometry as a hazards assessment tool. ASAR data acquired shortly after both the 17 June intrusion onset and 21 July fissure eruption were downloaded from the European Space Agency and formed into interferograms within 48 hours of each event.

Interferograms spanning the “Father’s Day” and 21 July eruptions proved invaluable for monitoring and interpretation of activity at Kīlauea Volcano. ASAR and other SAR datasets will obviously be critical components in future modeling efforts and interpretations of those events. Further, interferometry is clearly a valuable hazards monitoring and assessment tool and will doubtless provide important insights into future volcanic activity in Hawai’i and elsewhere, while continuing to further research efforts into how volcanoes work.

ACKNOWLEDGEMENTS

All ASAR data referenced in this report were provided by the European Space Agency through Cat-1 project 2765. GPS data result from collaboration between the U.S. Geological Survey's Hawaiian Volcano Observatory, Stanford University, and the Pacific GPS Facility at the University of Hawai'i. I am especially grateful to the ESA Help Desk and Francesco Palazzo for making ASAR data available via ftp soon after acquisition. Ingrid Johanson (USGS – Menlo Park) and Don Swanson (USGS – Hawaiian Volcano Observatory) provided constructive reviews of an earlier version of this contribution.

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