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Supplementary Information for: Periodic dike intrusions

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REGIONAL TERMINOLOGY

The upper and middle East Rift Zone (ERZ) regions discussed here correspond to seismically-defined regional polygons (Wright and Klein, 2014) for the Upper East Rift zone ("ei3uer"), which is closest to the Caldera region, and Middle East Rift Zone ("ei2mer"), which is down-rift. Geologists refer to the Upper and Middle regions slightly differently, but these regional polygons are quantified in (Wright and Klein, 2014).

SEGMENTATION

Segments in this study are defined principally by longitude. In this analysis, intrusions within the same longitudinal bounds are considered repeated events because the opening occurs parallel to the flank spreading direction (least principal stress), although they do not often erupt through the same surface fissures (Fig. 3, map). This agrees with the active rift zone being several kilometers wide (Swanson et al., 1976), and may be as wide as 5 km from north to south, relative to the narrow (a couple of meters) individual dikes based on models.

A thorough analysis of historical seismicity in the Hawaiian Volcano Observatory's catalog for Kīlauea (Wright and Klein, 2014) describes characteristic clusters and gaps along the ERZ and interprets them in terms of segments separated by magma reservoirs and barriers to flow (Wright and Klein, 2014) (marked in Fig. 1). Barriers are identified as the repeatedly observed stopping points for intrusions (e.g. near Mauna Ulu), but are less well defined. Segments may also be structurally controlled, for example, by the transition from wrench faulting in the UERZ to predominantly opening mode deformation downrift of Pauahi crater.

Here we focus on the Upper (UERZ) and Middle (MERZ) east rift zone regions where there have been multiple cycles of intrusion in the last fifty years (see above for further description of the regional terminology). The initial catalog locations have been relocated using double-difference methods for the time period from 1986 to 2009 (Matoza et al., 2014). The relocated catalog shows clear clusters and gaps along the same stretches of the rift where Kīlauea's intrusions occur (Fig. 1). These clusters and gaps were noted in the initial catalog (Wright and Klein, 2014), but the features are much more compact and clearly delineated in the relocated catalog. We discuss both catalogs here, using the relocated catalog (Matoza et al., 2014) to compare subsurface locations of recent dikes (1986-2009) and the regular catalog (Wright and Klein, 2014) for its longer time history.

Segments can be identified as repeated locations of initiation and stoppage of seismic swarms, with supporting evidence from surface deformation, and b-value anomalies (Wright and Klein, 2014). Segmentation of the rift is supported by evidence for reservoirs and barriers within the ERZ that coincide with seismic segmentation boundaries. Evidence for reservoirs comes from fractionated lavas (Jackson et al., 1975, Swanson et al., 1976, Thornber et al., 2003, Orr et al., 2015), deformation (Tilling et al., 1987, Owen et al., 2000b), and b-value anomalies (Wyss et al., 2001).

For example, the 2011 Kamoamoa dike (Fig. 1, main text) appears to emanate from the magma reservoir under Makaopuhi Crater, but erupted at the surface farther downrift on the western side of Nāpau Crater. Although the relocated seismic catalog becomes sparse downrift of this location, the longer temporal duration of the catalog (Wright and Klein, 2014) suggests another barrier just downrift of Nāpau, near the end point of the eruptive fissures.

METHODS FOR NEW 2000 DIKE MODEL

The new model for the previously un-modeled 2000 UERZ intrusion was produced the same way as in prior geodetic studies of Kīlauea (Montgomery-Brown et al., 2009) with the following basic steps. First, given the simplicity of the deformation and the availability of only a single interferogram, a fixed steeply dipping (80^{o}) dike plane was placed at the deformation axis of the intrusion and extended at least 2 km past the ends of the observed InSAR signal and to a depth of 5 km. This plane is consistent with previously modeled intrusions. The fault plane was divided into sub-patches approximately 0.5 km square and a smoothing weight was determined by the L-curve criterion. Finally, a non-negative least squares algorithm is applied to determine the distribution of opening on the rectangular dislocations (Okada, 1985). The opening model is unremarkable, and comparable to the other UERZ dikes, with a maximum of 0.15 m of opening extending eastward from Pauahi crater for about 4 km.

FLANK SLIP AND STEADY STATE MODEL

Motions on Kīlauea's decollement range from earthquakes (Ando, 1979), to slow slip (Brooks et al., 2006; Montgomery-Brown et al., 2009; Foster et al., 2013), and steady sliding (Owen et al., 2000. Interactions have been frequently documented between Kīlauea's flank motion and magma system (Ando, 1979; Delaney et al., 1993; Delaney et al., 1999; Montgomery-Brown et al., 2015; Neal et al., 2019).

A simplified steady state model is presented here (Fig. S1), not to be a definitive steady-state model, but to address the question of inter-dike stress accumulation related to flank slip. The particular details of the model may change the threshold stresses reached in the inter-dike periods, but should remain within a reasonable range. The steady state deformation model is computed with the same steps as the intrusion model in the main text.

The data used include campaign velocities from 1990-1996 (Owen et al., 2000a) and continuous GPS velocities from 2002-2004 (Miklius et al., 2005). Velocities at stations measured during both time periods are consistent, and both time spans are considered to be a relatively quiet periods at Kīlauea and representative of the background deformation. The model elements include a planar rift that follows the trend of craters (striking approximately 65^{o}) and subdivided into approximately 2 km patches with displacements and stresses computed from a dislocation model (Okada, 1985). An optimal smoothing factor is determined from an L-curve with the amount of deep opening smoothing into the flank slip at intersecting patches.

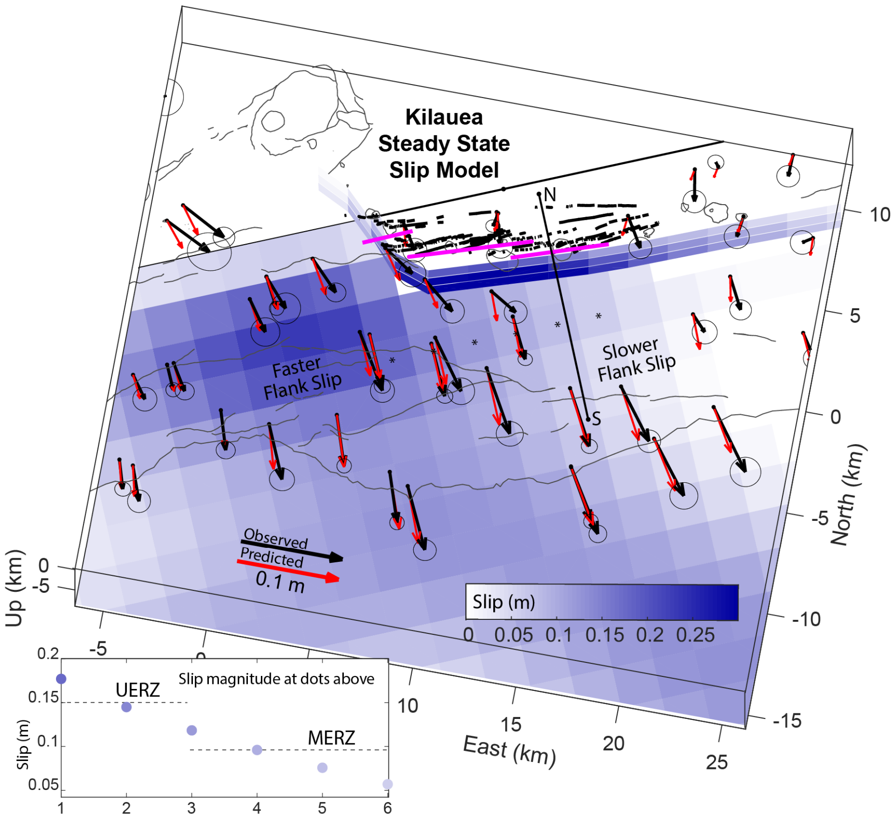

Figure S1 - Steady-state deformation model of Kīlauea Volcano with the intensity of the blue colors indicating how much opening occurs in the rift zone and how much seaward flank slip occurs on the decollement. Estimated jointly from 1990-1996 and 2002-2004 velocities. Note the gradient in deformation eastward from the highest rates of flank slip due south of Kīlauea caldera toward smaller slip rates to the east. The marked cross-section line N-S notes an example location of the cross sections shown in Fig. 2 and Fig. 4.

INTRUSION MODELS

The following is a summary of the details and notes about the geodetic models referenced in the main text.

Table S1: Table of geodetically modeled upper and middle ERZ intrusions at Kīlauea volcano between 1983 and 2018. See Methods for additional descriptions.

Date	Δ Summit Volume ($10^6 m^3$)	Maximum Opening (m)	Δ Dike Volume ($10^6 m^3$)	Location
01/03/1983	Unclear	2	60-131	Nāpau and eastward
02/07/1993	None	0.5	7.4	UERZ
01/30/1997	-1.5	1.96	22.6	Nāpau
09/12/1999	-3.3	0.7	3.3	UERZ

02/23/2000*	Unk. (small)	0.06	0.49	UERZ
06/17/2007(W)	-1.88	1.7	0.79	Makaopuhi
06/17/2007(E)	”	2.2	15.7	Makaopuhi
03/05/2011	-1.7	2.8	15.6	Nāpau

*No published analysis, so a single interferogram for each event was used here for an inversion (2000 - RADARSAT; see Methods).

January 3, 1983 East Rift Zone dike

The January 1983 middle east rift zone intrusion, which started the decades-long Puʻu ʻŌʻō - Kūpaianaha eruption, began uprift of Makaopuhi crater and extended about 16 km downrift. The seismicity progressed downrift steadily at a rate of 0.7 km/hr before pausing and reactivating near Nāpau crater, and then jumping downrift (Rubin et al., 1998). Multiple authors modeled this intrusion (Okamura et al., 1988, Dvorak et al., 1986, Wallace and Delaney, 1995). The model is a 15 km long dike striking about 67^o, consistent with the trend of seismicity, the overall rift zone, and subsequent intrusions discussed below (Wallace and Delaney, 1995). Their estimates of opening range from 1.7 to 2.8 m, with the range resulting from whether a deflation source at Makaopuhi is included.

February 9, 1993 intrusion

This event was observed mostly as a seismic swarm with high amplitude tremor and pause in the Puʻu ʻŌʻō eruption during which the lava pond drained and the crater floor collapsed (Heliker et al., 1998, Heliker and Mattox, 2003, Okubo and Nakata, 2003, Wright and Klein, 2014). Subsidence was observed at the summit caldera, but no rift zone deformation was observed with ground-based instruments. A JERS-1 interferogram spanning the intrusion was analyzed. Research continues on this intrusion with a 3D boundary element model suggesting an average of 1.2 m opening spanning depths from about 0.1-4.3 km for a total volume of about $7.4x10^6$ m^3 (Moore et al., 2016, Conway et al., 2018).

January 30, 1997 intrusion

A fissure opened at Nāpau Crater on January 30, 1997, about 3 km uprift from the ongoing eruptions at Puʻu ʻŌʻō. The eruption lasted 22 hours and opened a 5.1 km long, nearly vertical dike 1.9 m wide, extending from the surface to a depth of 2.4 km (Owen et al., 2000a). The lava pond at Pu‘u ‘Ō‘ō drained during the eruption, and eruptions ceased until the end of March. This eruption was followed by an approximately six-month-long deformation transient interpreted as additional rift opening just below the eruption dike (Desmarais and Segall, 2006).

September 12, 1999 upper East Rift Zone intrusion

A small upper east rift zone intrusion recorded by GPS, borehole tilt, leveling and InSAR (Cervelli et al., 2002). The intrusion occurred slightly west of Mauna Ulu and was accompanied by swarm seismicity but lacked premonitory inflation of the summit or rift zone.

February 23, 2000 upper East Rift Zone intrusion

This small intrusion started on February 23, 2000 (Heliker and Mattox, 2003, Wright and Klein, 2014) with a seismic swarm including one M4 earthquake and subsidence observed on summit and Pu‘u ‘Ō‘ō tiltmeters. One RADARSAT interferogram courtesy of M. Poland (U.S. Geological Survey) is available with acquisition dates from January 22 to March 10, 2000, and results in a maximum of approximately 6 cm of opening.

June 17, 2007 “Father’s Day” dikes

This East Rift Zone intrusion began at the uprift segment with a small intrusion that destabilized the flank, and triggered a slow flank sliding event termed a slow slip event. This slow slip event in turn allowed additional dike opening to occur on a downrift (eastern) segment that ultimately accumulated the majority of the dike opening (Brooks et al., 2008, Montgomery-Brown et al., 2011). Only a small amount of magma erupted during this event, covering an area of only about 1500 m^2.

The 2007 intrusion occurred in two segments. The first to intrude was the smaller up-rift (western) segment. The western segment appears to be above the inferred magma reservoir between Hi‘iaka and Pauahi Craters, but remained contained within its region, perhaps because it was unable to pass through the Hi‘iaka and Pauahi barriers. The second down-rift (eastern) segment had a clear down-rift propagation direction, and it crossed (possibly above?) two barriers. At its deepest extent, the eastern segment that erupted on the northern side of

Makaopuhi of this dike nearly reaches the "ring structure" (Matoza et al., 2014) (Fig. 1). The small eruption site, however, was near the down-rift tip of the dike.

March 5, 2011 "Kamoamoa" Eruption

This description of the Kamoamoa eruption is summarized from Lundgren et al. (2013). Following months of inflation across Kīlauea, the Kamoamoa eruption began March 5 with the intrusion of a typical ~5 km long and 2-3 km deep dike between Makaopuhi and Nāpau Craters. The intrusion began at the rift zone and drew magma from beneath Puʻu ʻŌʻō and then the summit reservoir. This event had a significant erupted component estimated at about 18.3 million cubic meters. Maximum opening reached 2.8 m by the end of the eruption, but the dike continued to expand for 2 months following the eruption, similar to the transient deformation following the 1997 dike.

SEISMIC CATALOG PERIODICITY ANALYSIS

As a geodesy-independent analysis of intrusion periodicity at Kīlauea, we also determine the recurrence intervals between swarms identified as "traditional intrusions" (Wright & Klein, 2014). We use the HVO catalog to determine where the swarm activity occurs during the intrusions showing that the swarms in the UERZ have 7 to 8 years between swarms whereas an interval of ~14 yrs occurs between swarms in the MERZ.

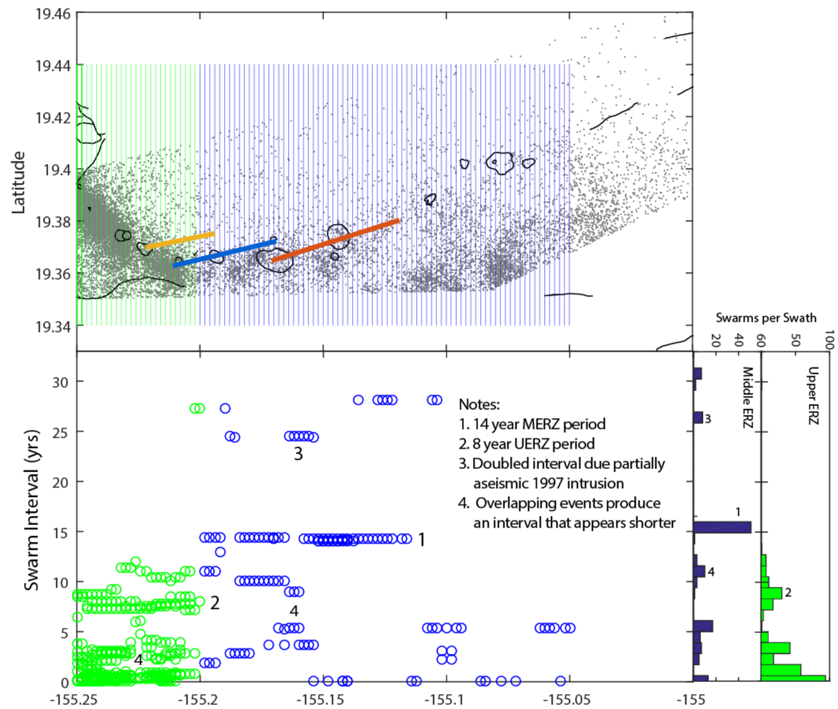

Figure S2: The recurrence of "traditional intrusion" swarms computed in 0.002° swaths highlighting the 14 year period in the MERZ and 8 years in the UERZ independent of geodetic observations. This is to supplement the geodetic observations, and prevent any past sampling bias that may exists through non-continuous geodetic monitoring.

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