The origin of Mauna Loa’s Ninole Hills: Evidence of rift zone reorganization

Jeffrey Zurek1, Glyn Williams-Jones1, Frank Trusdell2, and Simon Martin3

1Department of Earth Sciences, Simon Fraser University, Burnaby, British Columbia, Canada, 2Hawaiian Volcano Observatory, U.S. Geological Survey, Hawaii National Park, Hawaii, USA, 3School of Environmental Sciences, University of Liverpool, Liverpool, UK

Abstract In order to identify the origin of Mauna Loa volcano’s Ninole Hills, Bouguer gravity was used to delineate density contrasts within the edifice. Our survey identified two residual anomalies beneath the Southwest Rift Zone (SWRZ) and the Ninole Hills. The Ninole Hills anomaly is elongated, striking northeast, and in inversions both anomalies merge at approximately ~7 km above sea level. The positive anomaly, modeled as a rock volume of ~1200 km³ beneath the Ninole Hills, is associated with old eruptive vents. Based on the geologic and geophysical data, we propose that the gravity anomaly under the Ninole Hills records an early SWRZ orientation, now abandoned due to geologically rapid rift-zone reorganization. Catastrophic submarine landslides from Mauna Loa’s western flank are the most likely cause for the concurrent abandonment of the Ninole Hills section of the SWRZ. Rift zone reorganization induced by mass wasting is likely more common than currently recognized.

1. Introduction

Mauna Loa volcano is the largest active volcano on Earth and has erupted 15 times since 1900. Its voluminous lava flows have repaved 90% of its surface in the past 4000 years [Lockwood and Lipman, 1987], obscuring its internal structures and earlier evolution. To open a window into Mauna Loa’s history and internal structure, geophysical techniques such as Bouguer gravity are needed to image concealed structures and intrusions. Our study focuses on an anomalous surface feature, the Ninole Hills, which forms topographic highs on the southeast flank of Mauna Loa and represents the oldest exposed subaerial rocks on the edifice dated at 100–200 ka [Lipman et al., 1990; Jicha et al., 2012].

Several theories have been proposed to explain the formation of the Ninole Hills [Hitchcock, 1906; Stearns and Clark, 1930; Lipman, 1980; Lipman et al., 1990; Kauahikaua et al., 2000; Morgan et al., 2010]. Hitchcock [1906] proposed that the hills were the remnants of an older summit of Mauna Loa or a different Hawaiian volcano (Mohoakea proto-volcano). Geochemical characterization of the lava flows comprising the hills showed no appreciable difference, beyond supergene alteration, between the Ninole Hills and Holocene Mauna Loa lava flows; this led Lipman et al. [1990] to propose faulting and landslides as the formation mechanism. Several studies have suggested similar hypotheses revolving around the idea that the Ninole Hills were once the site of an active rift zone. Lipman [1980] and Kauahikaua et al. [2000] proposed the existence of a previously unrecognized orientation of the Southwest Rift Zone (SWRZ) or a proto-rift zone south of Mauna Loa’s summit to explain an elongated gravitational high. More recently, seismic velocity modeling suggested that the Ninole Hills may be a failed rift zone stretching from Mauna Loa’s summit through the Ninole Hills and out past the coastline (Figure 1) [Park et al., 2007; Morgan et al., 2010]. Each of these mechanisms will leave a distinct geophysical signature due to differences in subsurface modification. This study presents Bouguer gravity results to infer subsurface density structures and distinguish between formational mechanisms for the origin of the Ninole Hills.

2. Data Reduction and Residual Gravity Field

Bouguer gravity measurements were collected in April and May 2013 at 367 locations (using a Sintrex CG-5 gravimeter; Figure 2) covering an area of ~600 km² following standard survey procedures [e.g., Rymer and Brown, 1986; Berrino et al., 1992; Battaglia et al., 2008]. Daily closures were on average 80 µGal, and elevation control was obtained via kinematic GPS at each location. The GPS data were corrected using a nearby continuous GPS base station (PIIK; Figure 1) providing a vertical positional error <10 cm. The largest daily closures...
occurred when surveying over jungle paths, dirt roads, and large changes in elevation where the gravimeter was subject to vibration and opportunities to repeat base station measurements were limited. The travel-induced data tares are the most probable cause for the large closure errors observed [e.g., Crider et al., 2008; Zurek et al., 2012]. Data reduction included terrain corrections, bathymetry, free air correction, removal of solid Earth tides, Earth curvature, and removal of the regional field. Terrain corrections were made using a clinometer to estimate the average slope of the terrain within 20 m of the measurement location and a prism method using a digital elevation model for distances greater than 20 m [Hammer, 1939]. Both sets of terrain corrections use an assumed density of 2330 kg m$^{-3}$ for topography, based on previous gravity studies on the Island of Hawai‘i [Kauahikaua et al., 2000]. Bathymetry was corrected using a density of 1028 kg m$^{-3}$ and a 50 m resolution bathymetric elevation model (www.soest.hawaii.edu/HMRG). To correct for elevation, a free air gradient of $-322 \pm 6$ μGal m$^{-1}$ measured at the survey base station was used; this is similar to those measured at the summit of Kilauea ($-327.3$ μGal m$^{-1}$ [Johnson, 1992], $-330.25$ μGal m$^{-1}$ [Kauahikaua and Mikius, 2003]).

Removal of the regional field was accomplished with a two-step inversion process using GRAV3D [GRAV3D, 2007]. This first involved the creation of a density contrast model through the inversion of a regional data set [Kauahikaua et al., 2000]. The density contrast model was then forward modeled, with each block in the survey area (down to 15 km depth) set to a 0 kg m$^{-3}$ density contrast, effectively removing the influence of any density variations within the survey area. The resulting forward model represents the survey area’s regional field. The application of the corrections described above and the removal of the regional field from the measured gravity data give the residual Bouguer anomaly field (Figure 2). The advantage in using a two-step inversion process to remove the regional field is the reduction in edge effects compared to removal through polynomial regression or derivatives. This study primarily uses a different inversion suite, GROWTH2.0 [Camacho et al., 2011], to invert the corrected data set. However, GRAV3D was chosen for removal of the regional field due to its flexibility and ease of use manipulating large density models (see Figure S1 in the supporting information).

The residual Bouguer map (Figure 2) shows anomalies in two locations, one in the region of the Ninole Hills (center of the figure) and the other under Mauna Loa’s SWRZ (lower left portion of the figure). No significant (>12 mGal) positive anomalies are present off the strike of the SWRZ or the Ninole Hills. The lowest relative...
The gravitational field (0 mGal; Figure 2) is south of the Ninole Hills, on the edge of the survey area, and located away from obvious topographic features. Although on the edge of the survey area, the gravity low is unlikely to be composed of only edge effects or error in data reduction as it is present in the data prior to terrain corrections and regional field removal. Furthermore, Moore and Chadwick [1995] identified slump and landslide deposits just off shore (Figure 1), and the Ka‘ōīki-Honu‘apo fault system is also in this region, both of which would be consistent with low gravitational field.

Due to difficult terrain and limited access, gravity measurements were concentrated near trails and four-wheel drive-accessible roads. This led to an unequal spatial distribution of measurements, and thus, the resolution varies depending on survey point density. Individual roads and paths have station spacing of 250 m, 500 m, or 1000 m, and therefore have minimum resolvable wavelengths of 500 m, 1000 m, and 2000 m, respectively. Due to the lack of station coverage, survey points to the NE, it is not possible to determine the extent of the anomaly beneath the Ninole Hills to the northeast. However, given that the anomaly is over 5 km in length, it is likely that it does not abruptly end and continues beyond the edge of the survey area. Likewise, it is not possible to determine conclusively if the SWRZ and the anomaly beneath the Ninole Hills connect, although they likely do.

To place the positive anomaly beneath the Ninole Hills in context, it is important to compare it to other positive anomalies that have been described on the Island of Hawai‘i [Kauahikaua et al., 2000]. Due to differences in data reduction, the size of different volcanic edifices, and their cumulate cores, comparing the maximum slope of anomalies rather than their magnitude is a meaningful approach. The positive anomaly associated with the Ninole Hills has a maximum seaward slope of 3 mGal km\(^{-1}\) (averaged over 10 km). The perpendicular seaward slope of positive anomalies associated with rift zones are 3 to 4.5 mGal km\(^{-1}\) (averaged over 10 km). Positive anomalies associated with the summits of volcanoes, with steeper slopes, Kohala, Hualālai, and Mauna Kea on the Island of Hawai‘i have on average between 4.5 and 5 mGal km\(^{-1}\) (averaged over 10 km). Kilauea and Mauna Loa summit anomalies are outliers with 3.5 and 6.5 mGal km\(^{-1}\) (averaged over 10 km), respectively. This comparison suggests that the positive Bouguer gravity anomaly beneath the Ninole Hills is more similar to those at rift zones then anomalies found at the summits.

### 3. 3-D Inversions

Two gravity inversion suites, GRAV3D [GRAV3D, 2007] and GROWTH2.0 [Camacho et al., 2011], were used to invert the Bouguer gravity data in order to obtain density contrast models beneath the survey area. Only
results from GROWTH2.0 are presented due to its greater ability to handle data sets with irregular station spacing; a detailed discussion of the two inversion suites and inversion sensitivity can be found in Figure S1. The size of each cell (height 520 m to 1500 m and areal extent of 0.1 to 6 km$^2$) in the inversion models were determined by GROWTH2.0 based on distance from the edge of the data set and data resolution. GROWTH2.0 was able to invert the data with density contrast end-members from ±185 kg m$^{-3}$ to ±900 kg m$^{-3}$, each inversion resulted in positive linear anomalies beneath the SWRZ and the Ninole Hills. Density bounds outside of these two end-members resulted in a failure to converge on an inversion solution. The resulting inversion from density bounds of ±185 kg m$^{-3}$ contained many short wavelength perturbations forcing a fit to much coarser data and also produced the largest volume, ~3200 km$^3$ (Figure S3), of positive density contrast from beneath the Ninole Hills to the bottom of the model. In contrast, inversions using the maximum density bounds, ±900 kg m$^{-3}$, showed only sparse bodies and produced the lowest anomalous volume of ~500 km$^3$ (Figure S4).

In the optimized inversion model (based on the stability of inversion structures and approximately halfway between end-member bounds; Figure 3; ±400 kg m$^{-3}$), the two distinct density anomalies beneath the SWRZ and the Ninole Hills begin at 0 m above sea level (asl) and nearly merge at ~7 km asl with a total positive volume of ~1220 km$^3$. The merging of these two anomalies suggests that both the SWRZ and the Ninole Hills anomalies share the same root. The linearity of the model density contrasts beneath the Ninole Hills is persistent in every inversion regardless of the starting density bounds suggesting that a linear structure runs under the Ninole Hills at depth.

4. Anomalous Mass, Density Contrast, and Intrusion Size

The calculated anomalous mass in each inversion model is $\sim 1 \times 10^{15}$ kg with each differing by less than 2% from each other. To calculate the size of any intrusions suggested by the inversion models requires assumptions of the average density with depth. Due to the lack of density information within the Ninole Hills, the only constraints available are from drill holes (e.g., Keller et al., 1979; Moore, 2001). From these studies we assume that subaerially erupted basalts have an average density of 2300 kg m$^{-3}$ (for dry basalt) to 2500 kg m$^{-3}$ (basalt below the water table) and submarine basalt from 2700 kg m$^{-3}$ to 2900 kg m$^{-3}$. Intrusive complexes are then assumed to have densities in excess of 2900 kg m$^{-3}$. Without making assumptions regarding subsidence due to volcanic loading near the Ninole Hills, we apply both ranges to the optimized inversion model. Furthermore, due to data resolution, intrusive volume calculations begin at ~1000 m asl. Based on these assumptions, the density anomalies map out the 2900 kg m$^{-3}$ or 3100 kg m$^{-3}$ isosurfaces and contain ~1200 km$^3$, which represent a significant additional mass, requiring a mechanism to concentrate it beneath the Ninole Hills.

5. Formational Mechanisms

It has been suggested that the Ninole Hills were created by a number of mechanisms including: the eruptions of a protovolcano (Hitchcock, 1906), landslide/fault blocks (Lipman et al., 1990), and a separate Ninole Hills rift zone (Park et al., 2007; Morgan et al., 2010). Each mechanism has a different expected gravitational field; therefore, the processed gravity data should enable us to discriminate between these hypotheses. If the Ninole Hills were the location of a centralized proto-volcano summit, the expected gravity signal would be circular and centered above a dense intrusive complex (e.g., Zurek and Williams-Jones, 2013). The measured gravity field cannot exclude a protovolcano summit as it appears circular; however, the Bouguer gravity anomaly centered on the Ninole Hills is at least 5 km in length (Figure 2), may extend further to the northeast, and 3-D inversions allude to a connection with the SWRZ at depth at its SW extent, suggesting a more elongate structure. Geochemical work by Lipman et al. (1990) shows that the chemistry of the hills are not appreciably different from other Mauna Loa lavas and therefore rule out the possibility that the Ninole Hills was a separate and different volcano. Furthermore, seismic data shows a P wave velocity anomaly stretching from Mauna Loa’s summit to the Ninole Hills and a gravity anomaly [Kauahikaua et al., 2000] striking NS from the summit (Figure 4). Taking all the data together suggests that the Ninole Hills was not the site of a protovolcano.

The Ninole Hills rift zone was first proposed by Park et al. [2007] to explain seismic tomography data. However, if the proposed rift zone existed, residual gravity measurements should increase toward the center of the structure due to the likelihood of denser intrusive material (e.g., Broyles et al., 1979; Kauahikaua et al., 2000).
Two parallel gravity profiles, along roads (Figure 2) that would have approximately traversed the proposed rift zone perpendicularly, did not detect an anomalous density; therefore, the gravity data do not support the existence of a separate failed rift zone beneath the Ninole Hills (Figures 3 and 4). A recent review on the growth of Hawaiian volcanoes suggests that the original interpretation by Park et al. [2007] and Morgan et al. [2010] tied the high-velocity zone beneath the Ninole Hills to the continuation of Kīlauea’s SWRZ [Lipman and Calvert, 2013]. Furthermore, Jicha et al. [2012] provides age constraints for the submarine extension of the SWRZ that suggests that it has been active for more than 470 ka, including the time when the Ninole Hills formed. In order for both the proposed Ninole Rift zone and the SWRZ to be active simultaneously, a junction angle between them approaching 120° would be expected [Oertel, 1965; Reches and Dieterich, 1983]. However, the approximate orientation of the two rift zones would have been between 45 and 90°, which has not been documented in any geologic setting.

Lastly, if the Ninole Hills represent slump blocks and landslide scarps, characteristically basaltic flows and faults are low density and should generate a gravitational low. Although there is a negative anomaly in the

![Figure 3. Smoothed density contrast depth slices (starting at –1000 m asl) from the optimized GROWTH2.0 inversion with density bound of ±400 kg m⁻³ and residuals for each station. Positive density variations shown in red correspond with interpreted intrusive material based on a zero density contrast obtained from drill holes [e.g., Keller et al., 1979; Moore, 2001]. Elevation contour interval of 100 m.](image-url)
southern portion of the survey area (Figure 2), it is not situated beneath the Ninole Hills. A large dense body beneath the Ninole Hills is not consistent with the topographic feature being created by faulting and landslides but is consistent with intrusive material. While the Bouguer gravity data suggest that faulting and landslide blocks are not the primary cause of the Ninole Hills, the hills would almost certainly have been subsequently modified by the widespread mass wasting documented across the southeast flank of Mauna Loa [e.g., Lipman et al., 1990].

6. Rift Zone Migration or Reorganization

The substantial Bouguer gravity anomaly beneath the Ninole Hills, elongated SW-NE, is consistent with a large intrusive complex that likely connects with the SWRZ. Furthermore, previously documented north trending dikes exposed on the south flank of one of the Ninole Hills [Lipman et al., 1990] together with recent geologic mapping by Trusdell and Lockwood [2015] are consistent with the former presence of a rift zone since the number of dikes decreases rapidly away from rift zones [Walker, 1987].

The data presented here do not support the previous suggestions for the creation of the Ninole Hills such as a previous volcanic summit, Ninole Hills rift zone, or faulting and landslides but rather can be explained more comprehensively by rift zone migration or reorganization of Mauna Loa’s SWRZ. The migration of Hawaiian rift zones was first suggested by Swanson et al. [1976]. Lipman [1980] followed with detailed work on the possible migration of Mauna Loa’s SWRZ supported by geologic field evidence. Rift zone migration was also invoked to explain the large bends in Hawaiian rift zones [e.g., Lipman, 1980; Swanson et al., 2014].

Bouguer gravity surveys along Kilauea’s East Rift Zone clearly show an asymmetrical gravitational field centered on the present axis of the rift zone due to rift zone migration [Bryceson et al., 1979]. If the migration...
of Mauna Loa’s SWRZ was slow and steady we would expect to see a constant westward increase in the gravitational field due to the shallowing of intrusives as one reached the axis of the modern rift zone. However, a constant increase in the gravitational field toward the modern (or current) rift zone axis was not observed. Instead, we see two gravitational highs beneath the modern SWRZ and the Ninole Hills. Furthermore, the imaged anomaly directly beneath the Ninole Hills could be up to 1200 km$^3$ in volume.

If continuous rift zone migration is the cause of the high-density structure beneath the Ninole Hills, it would require long-lived activity. Sustained activity in the vicinity of the Ninole Hills would build a large intrusive complex and potentially produce the observed gravity signal. However, there is no supporting evidence to suggest why the Ninole Hills would have been a preferential pathway for magma ascent or why it would have ceased to be one as the rift zone migrated. If rift zone migration does not occur at a constant velocity, then relatively rapid migration would leave behind areas with larger intrusive volumes creating a positive Bouguer anomaly in the gravitational field toward the axis of the rift zone.

Gravitational instability of volcanic piles has been shown to cause edifices to spread through slow deep seated gravitational slope deformation, faulting, and landslides [e.g., Lipman et al., 1988; Clague and Denlinger, 1994; Delaney et al., 1998; Benz et al., 2002; Park et al., 2009]. Variations in rift zone migration velocities necessitate rapid changes to the gravitational stability of the edifice. While not yet recognized for Hawaii’s volcanoes, a geologically instantaneous reorganization of rift zones of Anaga volcano (Tenerife, Canary Islands) has been suggested due to a large mass wasting event [Walter et al., 2005]. Based on $^{40}$Ar/$^{39}$Ar dates, geologic mapping, and aerial photograph lineament mapping, Walter et al. [2005] argues that Anaga volcano originally had straight east west rift zones. These are thus approximately contemporaneous with the Ninole Hills 100–200 ka ago. An event capable of changing the edifice stress field, such as a large mass wasting event like the Alīka debris flows, then caused a geologically instantaneous reorganization of Mauna Loa’s SWRZ. Given the number of large mass wasting deposits identified around the ocean island volcanoes, we suggest that reorganization and rapid movement of rift zones are not uncommon, however generally unrecognized.

Events capable of causing drastic changes to Mauna Loa’s internal stress field in the last 200 ka include large mass wasting events and possibly the buttressing of Mauna Loa by Kīlauea Volcano [e.g., Lipman et al., 1988; Coombs et al., 2006]. Mass wasting, such as the Alīka-1 and Alīka-2 debris flows, on the west flank of Mauna Loa, has together transported 200 to 600 km$^3$ of material [e.g., Lipman et al., 1988] and been dated at 200–240 ka [Felton et al., 2000; Rubin et al., 2000] and 127 ka, respectively [McMurtry et al., 1999]. These are thus approximately contemporaneous with the Ninole Basalt (100–200 ka [Lipman et al., 1990; Jicha et al., 2012]). The removal of more than 100 km$^3$ of material due to either of the Alīka debris flows [Lipman et al., 1988; Felton et al., 2000; Morgan et al., 2010] would have changed the stress/strain on the edifice potentially causing Mauna Loa’s SWRZ to jump northward or migrate faster than before the event. The effect of Kīlauea buttressing Mauna Loa’s south flank would have also significantly affected the stress/strain fields within Mauna Loa, potentially changing deformation patterns causing relatively rapid changes to any SWRZ migration. The most recent model for the age of Kīlauea suggests that it is ~275 ka [e.g., Calvert and Lanphere, 2006] and the timing of buttressing is unconstrained. It is not currently possible to determine which mechanism, buttressing, landslides, or both could have caused the change in gravitational stability of Mauna Loa to lead to changing its rift zone orientation. However, of the above processes, instability due to mass wasting would be the most catastrophic and consequential.

Geologically fast rift zone migration or orientation change can also explain the preservation of the Ninole Hills, as a stable rift zone will create a topographic high along its axis. When the rift zone moves westward, the old rift axis will shelter land seaward from lava inundation. Although it is not possible to conclusively determine the mechanism responsible for the imaged density anomaly beneath the Ninole Hills, we interpret the gravity data as evidence of an early Mauna Loa Southwest Rift Zone [Lipman, 1980; Kauahikaua et al., 2000]. This study suggests that migration or offsetting of rift zones by large landslides is likely more important to the development and modification of basaltic island volcanism then previously recognized.


