Intrusive dike complexes, cumulate cores, and the extrusive growth of Hawaiian volcanoes

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[1] The Hawaiian Islands are the most geologically studied hot-spot islands in the world yet surprisingly, the only large-scale compilation of marine and land gravity data is more than 45 years old. Early surveys served as reconnaissance studies only, and detailed analyses of the crustal-density structure have been limited. Here we present a new chain-wide gravity compilation that incorporates historical island surveys, recently published work on the islands of Hawai'i, Kaua'i, and Ni'ihau, and >122,000 km of newly compiled marine gravity data. Positive residual gravity anomalies reflect dense intrusive bodies, allowing us to locate current and former volcanic centers, major rift zones, and a previously suggested volcano on Ka'ena Ridge. By inverting the residual gravity data, we generate a 3-D view of the dense, intrusive complexes and olivine-rich cumulate cores within individual volcanoes and rift zones. We find that the Hāna and Ka'ena ridges are underlain by particularly high-density intrusive material (>2.85 g/cm^3) not observed beneath other Hawaiian rift zones. Contrary to previous estimates, volcanoes along the chain are shown to be composed of a small proportion of intrusive material (<30% by volume), implying that the islands are predominately built extrusively.
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1. Introduction

[2] The main Hawaiian Islands evolve from active volcanoes on the southeastern end—Mauna Loa, Kīlauea, and Lō'ihi—to the eroded remnant of Ni'ihau Volcano 600 km to the northwest (Figure 4a). Progressive cooling and crystallization of magma in crustal reservoirs and surrounding rift zones produces rocks rich in olivine (cumulates). These cumulate cores define the long-term average zones where magma resided or transited through, prior to surface eruptions or emplacement in shallow intrusions [*Kauahikaua et al.*, 2000]. Encompassing the cumulate cores are larger zones of dense, dike-rich intrusions—intrusive complexes—comprising the magmatic plumbing system feeding each volcano. Density contrasts between these features and encompassing lava flows result in positive residual gravity anomalies [*Strange et al.*, 1965; *Kauahikaua et al.*, 2000; *Flinders et al.*, 2010] and often correlate with fast seismic velocities [*Okubo et al.*, 1997; *Park et al.*, 2009]. Here we invert a new chain-wide compilation of land and marine gravity data to estimate the volumes, average densities, and olivine percentages of intrusive complexes and cumulate cores underlying all known volcanoes throughout the Hawaiian Islands.

2. Data Reduction

[3] Our new compilation is composed of 4820 land-based measurements, including historical data [*Strange et al.*, 1965] and data from recent studies of Kaua'i [*Flinders et al.*, 2010] and the island of Hawai'i [*Kauahikaua et al.*, 2000]. Free-air anomalies (Figure 1) were produced by removing elevation contributions (for land-based data) and the WGS84 ellipsoid. The marine portion of the compilation consists of over 122,000 km of survey data collected on 140 cruises. The marine data were collected primarily aboard the University of Hawaii's R/V *Kilo Moana*, supplemented with data from the National Geophysical Data Center and the Japan Agency for Marine-Earth Science and Technology (Figure 1, inset). These data were filtered to eliminate high-frequency noise due to changes in survey speed and course and corrected for crossover errors using x2sys, a part of the Generic Mapping Tools [*Wessel and Smith*, 1991]. The standard deviation of the corrected crossings was 2 mGal.

[4] Complete Bouguer anomalies were produced by removing the effects of topography/bathymetry using a two-part prism-based terrain correction (Figure 2) [*Flinders et al.* 2010]. Within 500 km of each measurement, the water column was infilled with submarine crust (2.7 g/cm^3), using a 250 m digital elevation model (DEM) (www.soest.hawaii.edu/HMRG). The gravitational effects of subaerial mass (2.4 g/cm^3) were removed using DEMs of various spatial resolution, dependent on the distance from the measurement: a 10 m DEM within 2 km of the measurement location, 100 m DEM at distances of 2–20 km, and a 500 m DEM at distances of 20–500 km. Lastly, residual gravity anomalies were produced by removing the long-wavelength signal due to flexural deformation of the lithosphere from island loading (Figure 3), using an effective elastic-plate thickness of 30 km (Figure 2, inset) [*Watts and Cochran* 1974; *Flinders et al.*, 2010].

3. 3-D Inversion

[5] For inversion, the marine residual gravity data were down-sampled onto a 500 m cell-spaced geographic grid,

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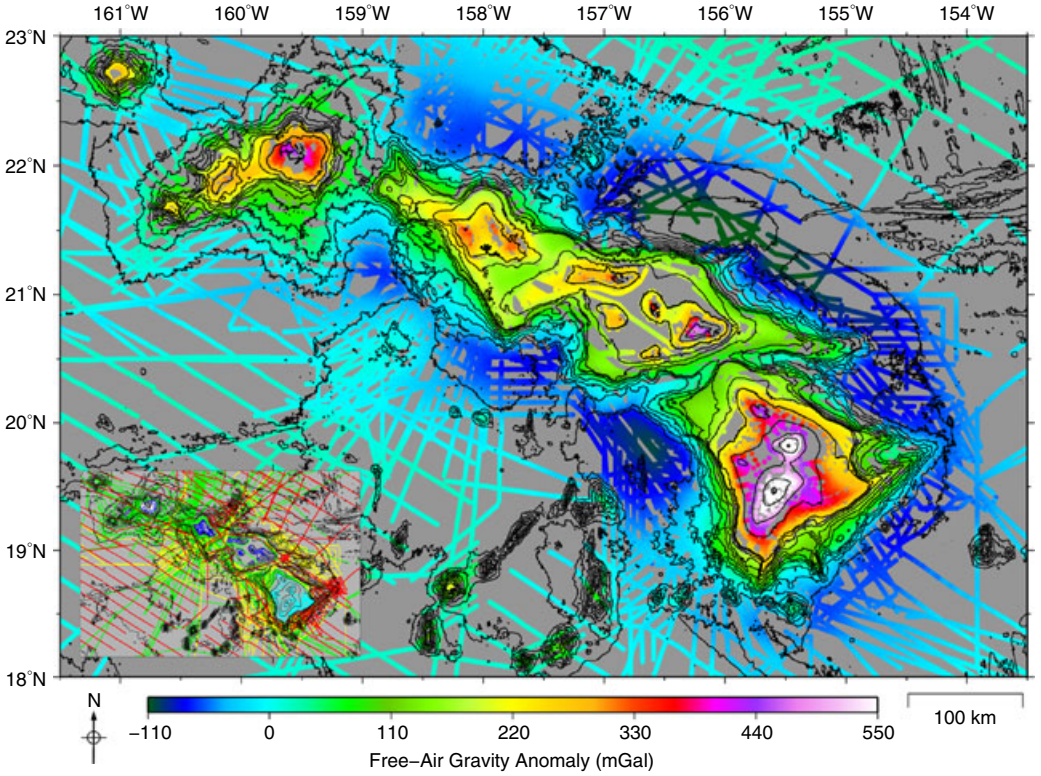

Figure 1. Free-air gravity anomalies (FAA) showing high correlation with topography and the long-wavelength swell caused by flexural loading of the oceanic crust. (inset) Color-coded source data; cyan [*Kauahikaua et al.*, 2000], blue [*Strange et al.*, 1965], white [*Flinders et al.*, 2010], green [R/V *Kilo Moana*], yellow [*JAMSTEC*], and red [*NGDC*].

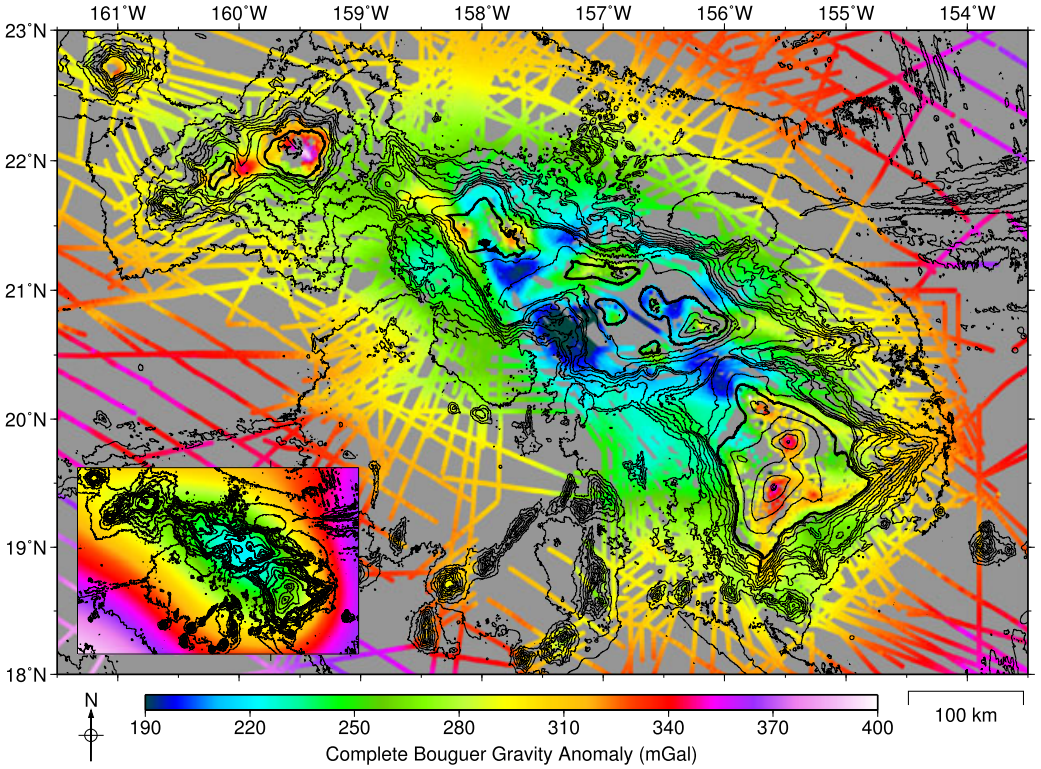

Figure 2. Complete Bouguer gravity anomalies calculated using a two-part terrain correction, one for subaerial data and one for marine data. (inset) An estimation of the long-wavelength signal due to flexural deformation of the lithosphere from island loading, using an effective elastic-plate thickness of 30 km, which is subsequently removed from the complete Bouguer data to produce the residual gravity data in Figure 3.

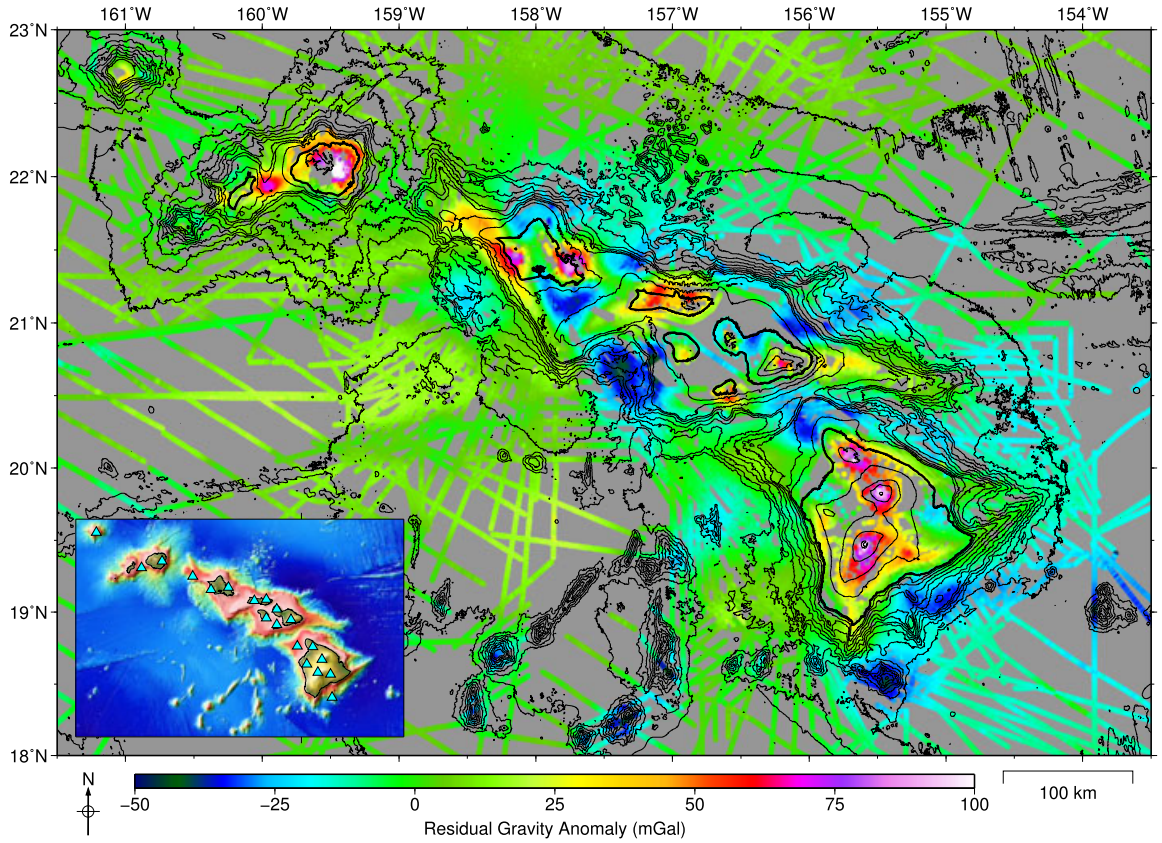

Figure 3. Residual gravity anomalies along survey tracks indicate density variations relative to 2.7 g/cm^3. The most positive anomalies are attributed to intrusive dike complexes and cumulate cores. Residual lows encompass the regions of formerly identified large landslide deposits/slumps, Cretaceous seamounts, and possibly incomplete removal of the long-wavelength flexural signal. Contours show topography/bathymetry at 500 m intervals. (inset) Bathymetry of the Hawaiian Island Chain with volcano locations.

resulting in 42,326 measurements. The cell spacing used in down-sampling the data was approximately equal to half the minimum 1 km horizontal wavelength typically resolvable by the marine data. All land residual gravity data were used. The compiled data set was subdivided into three overlapping geographic regions; Kaua‘i/Ni‘ihau, O‘ahu through Maui, and the island of Hawai‘i. Data for each region were inverted to produce 3-D models of subsurface density contrast using GRAV3D [*GRAV3D*, 2007]. The subsurface was discretized into a set of 3-D voxels, each with a constant density contrast relative to 2.7 g/cm^3, with voxels spanning 1 km in the horizontal and varying in the vertical dimension from 500 m at the surface to 1500 m at depth. The top of the model space was bound by topography/bathymetry, while the model basement, at 20 km below sea level, encompassed the base of the thickest Hawaiian volcanic crust (13 km) and 7 km of preexisting oceanic crust [*Watts et al.*, 1985]. The density distribution was found by solving an optimization problem of minimizing a model objective function while generating synthetic data that fall within the uncertainty of the observed data [e.g., *Li and Oldenburg*, 1998; *Flinders et al.*, 2010]. Inversions were subject to the constraint that densities be between 2.0 (wet sand) and 3.3 g/cm^3 (olivine). The three individual inversion models were then merged into one chain-wide model (Figure 4). These inversions provided a low misfit to the residual anomalies, ≈2 mGal, and inverting the data with a wide range of initial model parameters verified the returned inversion structure.

4. Intrusive Complexes and Cumulate Cores

[6] Negative residual gravity (Figure 3) and low crustal densities (<2.7 g/cm^3, Figure 4d) are associated with several of the previously mapped debris-avalanche deposits and slumps [*Moore et al.*, 1989], as well as Cretaceous seamounts, the Moloka‘i Fracture Zone, and possibly incomplete removal of the flexural signal. Positive residual gravity and high crustal densities (>2.7 g/cm^3) are associated with volcanic centers and major rift zones. We interpret the largest of these anomalies to correspond to underlying intrusive complexes—regions of high dike concentration—and cumulate cores (Figures 4a and 4c). We delineate intrusive complexes by the 2.85 g/cm^3 density isosurface, corresponding to 60% or more of dikes with a density of 2.95 g/cm^3 (Kīlauea 10 wt% MgO at 200°C/1500 bar-KWare Magma [*Wohletz* 1999]) in a host extrusive rock of 2.7 g/cm^3. Consistent with this definition, the 2.85 g/cm^3 isosurface lies within the 50–65% dike concentration used to define the dike-complex zone of Ko‘olau volcano by *Walker* [1986]. Cumulate cores were defined by the 3.00 g/cm^3 density isosurface, equivalent to 35% or more olivine (3.2–3.3 g/cm^3) in the intrusive complex density of 2.85 g/cm^3. Approximate uncertainties in the isosurface volumes were found by using

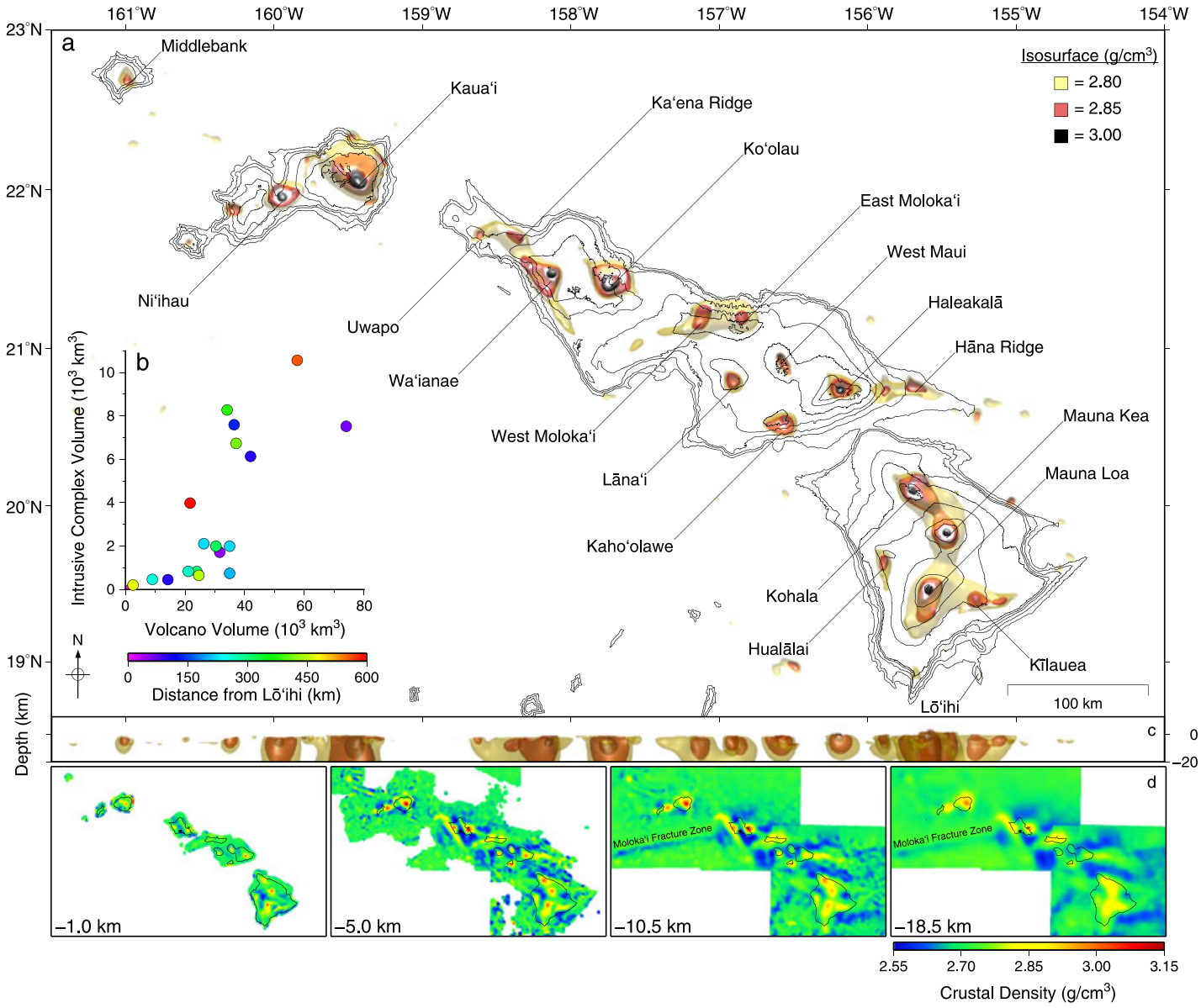

Figure 4. (a) Map view of the density isosurfaces from the inverted 3-D density model, illuminated from the NE. Red isosurfaces (2.85 g/cm^3) are attributed to intrusive complexes, black isosurfaces (3.00 g/cm^3) to cumulate cores. Contours show topography/bathymetry at 500/1000 m intervals. (b) Island volume/intrusive complex volume. (c) Isosurface view in cross section along the length of the chain, viewed from the south. (d) Density model at four depths.

the merged density model to forward model-simulated residual gravity anomalies at our observation locations. These simulated values were then reinverted, using the original uncertainty matrix, to find a new density model. A comparison of the original density model to the new model corresponded to ±25% volume uncertainty for both the 2.85 and 3.00 g/cm^3 isosurfaces.

[7] Intrusive complexes are observed beneath all volcanoes, with the maximum intrusive complex volume ranging up to 10,550 ± 2600 km^3 (Kauaʻi; Table 1). The olivine contents of the intrusive complexes, estimated as a percentage of the total isosurface volume if the average density was due to only olivine (3.2–3.3 g/cm^3) and intrusive basalt (2.85 g/cm^3), were between 2 and 25% (Table 1). Differences in the volume of individual intrusive complexes do not vary with their distance along the chain. Instead, the volumes of the intrusive complexes appear to correlate with the volumes of the associated volcanoes (Figure 4b). Volcano volume estimates were taken from *Robinson and Eakins* [2006], explicitly separating the volume of Hāna Ridge from Haleakalā Volcano, and from Sinton et al. (Kaena Volcano a precursor volcano of the island of Oahu, Hawaii, submitted to *Geological Society of America Bulletin*, 2013) for Kaʻena Ridge and Waiʻanae Volcano, where a small volume of Kaʻena Ridge (2525 km^3) has been allocated to a separately proposed volcanic center. These correlations suggest an inherent relationship between the volume of erupted lava and the total volume of intrusive material.

[8] Within the intrusive complexes, dense cumulate cores (>3.0 g/cm^3) were detected under the majority of volcanoes, with volumes ranging from <10 km^3 (Kīlauea) to 1,870 ± 470 km^3 (Kauaʻi). Estimated olivine content is greatest in Mauna Loa (≈ 84%) and least in Kahoʻolawe and Lānaʻi (≈42%), averaging ≈50% throughout the chain (Table 1). Cumulate cores were not present under Lōihʻi, Hualālai, West Molokaʻi, or East Molokaʻi volcanoes (Figure 4a). The four largest cumulate cores are spaced sporadically, underlying Kauaʻi (1870 ± 470 km^3), Koʻolau (1160 ± 290 km^3), Niʻihau (300 ± 80 km^3), and Mauna Loa (280 ± 70 km^3), although the volume of Mauna Loa's cumulate core is likely to be underestimated because it is still an active volcano and the cumulate core is presumably still accumulating.

5. Rift Zones and Unrecognized Volcanoes

[9] Rift-zone-related intrusive complexes are observed beneath the major submarine ridges and tend to be linear features that trace back to individual volcanoes (2.80 g/cm^3 isosurface; Figure 4a). Prominent examples include Kīlauea's East Rift Zone, the southwest rift zone of Waiʻanae, and the western rift zone of West Molokaʻi. However, these rift zones are underlain by distinctly less dense intrusions than those beneath Hāna (Haleakalā) and Kaʻena (Waiʻanae) Ridges. The rift-zone intrusive complexes along the Hāna and Kaʻena ridges are markedly atypical based on their large volumes, spatial extents, and high residual gravity.

[10] The 120 km long, 50 km wide Hāna Ridge is underlain by two dense intrusive bodies (Figure 4a), neither of which is associated with a local bathymetric high. If these features are considered to be part of the Haleakalā rift zone, they would constitute the most voluminous, dense, and distal rift-zone extension from a volcano throughout the entire chain. Alternatively, these bodies may represent the intrusive complexes of one or two shield volcanoes that did not develop beyond a juvenile stage and were later buried in rift-zone volcanics.

[11] Kaʻena Ridge is comparable to Hāna Ridge in length and maximum width but contains significant bathymetric relief, including a large (11 km diameter) flat-top cone located near the center of the ridge. Two unique gravity anomalies/intrusive complexes are seen beneath Kaʻena Ridge, a broad eastern anomaly and a more distinct western anomaly, neither of which appears to extend from the Waiʻanae rift zone (Figure 4a). Sinton et al. (submitted manuscript, 2013) showed that most of Kaʻena Ridge is chemically, structurally, and chronologically distinct from Waiʻanae Volcano and likely represents a precursor volcano to the island of Oʻahu, consistent with speculations of *Moore et al.* [1989]. Although the broad eastern gravity anomaly has no associated bathymetric high, it is likely associated with this precursor volcano (Kaʻena Volcano), with its older structure possibly buried by younger Waiʻanae flows. The western gravity anomaly is located 3 km from the center of the 11 km diameter large cone, which is thought to have formed subaerially, given the presence of massive ʻaʻa flows [*Coombs et al.*, 2004]. Geologic samples acquired during a previous remotely operated vehicle (ROV) dive appear to be geochemically similar to the rest of the ridge [*Coombs et al.*, 2004; Sinton et al., submitted manuscript, 2013]. However, given the distinction between this western gravity anomaly and the broad eastern anomaly (Figures 3 and 4a), its association with the nearby large cone, and the relatively sparse geologic sampling of Kaʻena Ridge in general (Sinton et al., submitted manuscript, 2013), it remains uncertain whether this anomaly represents an extension of the Kaʻena Volcanic system or yet another, unrecognized volcano. We refer to the western feature as Uwapo—Hawaiian for bridge, because it may span the volcanic gap between the islands of Kauaʻi and Oʻahu. While the modeled intrusive complex beneath Uwapo is small (200 ± 50 km^3), it is roughly half the intrusive-complex volume beneath Hualālai Volcano (450 ± 110 km^3).

6. Extrusive Versus Intrusive Volcano Building

[12] The gravity results indicate that individual volcanoes in the main Hawaiian Islands are composed, on average, of less than 10% dense intrusive material (>2.85 g/cm^3; Table 1). An upper bound estimate was made by decreasing the density isosurface for intrusive complexes from 2.85 g/cm^3 to 2.80 g/cm^3, approximately equivalent to changing from a 60% to 40% dike concentration and equal to the cutoff between intrusive and extrusive basalt used by *Moore* [2001]. Using this constraint and calculating an intrusive/extrusive ratio across the entire chain, results in a mean increase to only 30% intrusive material.

[13] Our estimate of a low intrusive proportion (10–30%) is contrary to prior conclusions that the Hawaiian Islands are built through predominately endogenous growth, with previous estimates that intrusions account for 65–90% of the total volume [*Francis et al.*, 1993; *Dzurisin et al.*, 1984]. These estimates were based on geologically short-term observations of the active Kīlauea Volcano, specifically heat loss over the Kupaianaha lava pond (1986–1992 [*Francis et al.* 1993]) and uplift of Kīlauea summit (1956–1983 [*Dzurisin*

Table 1. Volcanic Features and Their Cumulate Cores/Intrusive Complexes[a]

Volcano/Rift	Volume (km^3)	Isosurface (g/cm^3)	Avg. ρ (g/cm^3)	Core/I.C.[a] Vol. (km^3)[b]	Olivine Content (%)	Core/I.C. (% of Volcano)[c]	Volcano/Rift	Volume (km^3)	Isosurface (g/cm^3)	Avg. ρ (g/cm^3)	Core/I.C.[a] Vol. (km^3)[b]	Olivine Content (%)	Core/I.C. (% of Volcano)[c]
Lōihi	1,700	2.85	2.89	10	9–12	1	Kīlauea	31,600	2.85	2.88	1,700	6–7	5
Mauna Loa	74,000	2.85	2.91	7,500	12–16	10			3.00	3.03	<10	40–51	<1
		3.00	3.18	280	74–94	<1	Pu‘u ‘Ō‘ō		2.85	2.87	460	5–7	<1
									3.00	3.01	<10	37–47	<1
Hualālai	14,200	2.85	2.87	450	6–7	3	Mauna Kea	41,900	2.85	2.90	6,150	10–13	15
									3.00	3.03	230	39–51	1
Mahukona	13,500	N/A	N/A	N/A	N/A	N/A	Kohala	36,400	2.85	2.90	7,600	11–14	21
									3.00	3.02	240	37–48	<1
Kaho‘olawe	26,300	2.85	2.90	2,100	12–16	8	Haleakalā	34,900	2.85	2.92	2,000	15–19	6
		3.00	3.02	50	37–47	<1			3.00	3.05	230	45–58	1
							Hāna Ridge	34,900	2.85	2.88	750	6–7	2
Lāna‘i	21,100	2.85	2.90	850	11–14	4	West Maui	9,000	2.85	2.94	450	19–25	5
		3.00	3.02	30	37–48	<1			3.00	3.12	70	59–76	1
West Moloka‘i	30,300	2.85	2.87	2,000	4–5	7	East Moloka‘i	23,900	2.85	2.87	850	4–5	3
Wai‘anae	37,100	2.85	2.90	6,750	11–14	18	Ko‘olau	34,100	2.85	2.93	8,300	18–23	24
		3.00	3.03	270	41–52	<1			3.00	3.04	1,160	42–54	3
Uwapo	2,525	2.85	2.88	200	6–8	8	Ka‘ena	24,575	2.85	2.86	650	2–3	3
Ni‘ihau	21,700	2.85	2.91	4,000	14–17	18	Kaua‘i	57,600	2.85	2.94	10,550	19–25	19
		3.00	3.02	300	38–49	1			3.00	3.07	1,870	49–63	3
Middlebank	N/A	0.15	2.87	350	5–6	N/A							

[a]I.C. = intrusive complex.
[b]For the 2.85 g/cm^3 isosurface, volumes rounded to nearest 50 km^3; for 3.00–3.10 g/cm^3 isosurfaces, volumes rounded to nearest 10 km^3.
[c]Reservoir volume as a percentage of the volcano volume is the ratio of the calculated reservoir volume to the volcano volume.

et al., 1984]). Given our conclusion of primarily extrusive growth, the minimization of the chain-wide residual gravity anomaly by a submarine density of 2.7 g/cm^3, and that the majority of each volcano is built during its tholeiitic shield stage (≈95% [*Clague and Dalrymple* 1987]), we conclude that the majority of each volcano (>70%) is likely composed of submarine extrusive flows formed during the main shield stage. The disparity between previous estimates of extrusive/intrusive ratios and our own may be due to the limited time (years) and localization (Kīlauea Volcano) of prior observations or a change in the extrusive/intrusive ratio throughout a volcano's growth.

[14] Voluminous extrusive growth also contrasts with the dominantly intrusive nature of continental volcanism as well as the formation of normal oceanic crust and flood basalt provinces [e.g., *Crisp*, 1984; *White et al.*, 2006]. In continental settings, magma travels greater path lengths through relatively thick and low-density continental crust and thus is more likely to intrude [*White et al.*, 2006]. Oceanic flood basalt provinces also require magma to penetrate thick crust (≈30 km or more [*Crisp*, 1984]), additionally having numerous source dikes that span a wide region, leading to a larger intrusive contribution. At mid-ocean ridges, most of the crust is constructed within a vertical accretion zone, proximal to the ridge axis, and the thickness of the intrusive material is controlled by the local temperature structure [*Hooft and Detrick*, 1993]. In contrast, Hawaiian volcanism originates from magma that penetrates a relatively thin crust <20 km (oceanic crust plus the volcano [*Watts et al.*, 1985]). Additionally, magma travels from depth to the near surface primarily through a single central vertical conduit [*Okubo et al.*, 1997; *Kauahikaua et al.*, 2000] and typically one or two rift zones. While intrusions occur in the central conduit and rift zones, magma retains sufficient mobility such that the major volume of the volcano is formed from lavas erupted well away from these localized sources.

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