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A low-relief shield volcano origin for the South Kaua'i Swell

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[1] The South Kaua'i Swell (SKS) is a 110 km x 80 km ovoid bathymetric feature that stands >2 km high and abuts the southern flank of the island of Kaua'i. The origin of the SKS was investigated using multibeam bathymetry and acoustic backscatter, gravity data, radiometric ages, and geochemistry of rock samples. Most of the SKS rock samples are tholeiitic in composition with ages of 3.9–5.4 Ma indicating they were derived from shield volcanism. The ages and compositions of the SKS rocks partially overlap with those of the nearby Ni'ihau, Kaua'i and West Ka'ena volcano complexes. The SKS was originally described as a landslide; however, this interpretation is problematic given the ovoid shape of SKS, its relatively smooth, flat-to-convex surface, and the lack of an obvious source region that could accommodate what would be one of Earth's most voluminous (6×10^3 km^3) landslides. The morphology,

size, and the surrounding gravity anomaly are more consistent with the SKS being a low-relief shield volcano, which was partially covered with a small volume of landside debris from south Kaua'i and later with some secondary volcanic seamounts. A shield origin would imply that Hawaiian and possibly other hotspot shield volcanoes can take on a wider variety of forms than is commonly thought, ranging from tall island-building shields, to smaller edifices such as Ka'ena Ridge and Mahukona, to even lower-relief volcanoes represented by the SKS and possibly the South West O'ahu Volcanic Field.

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1. Introduction

[2] The Hawaiian-Emperor Chain is one of the most extensively studied in the world and has greatly influenced our knowledge of how oceanic islands form and evolve (Figure 1). The Hawaiian islands are perched on broader subsided platforms (pink areas in Figure 1) from which emanate elongate ridges that are, or once were volcanic rift zones [*Fornari*, 1987]. The platform flanks are mantled with the products of mass wasting, which range in size and character from localized turbidite channels to massive landslides [*Moore et al*., 1989; *Smith et al*., 2002; *Morgan et al*., 2007]. Some of the latter forms are the remnants of huge island sector collapses representing the most dramatic landslides on Earth [*Moore et al*., 1989, 1994; *Hampton and Lee*, 1996].

[3] Other submarine features along the Hawaiian-Emperor Chain include products of secondary volcanism, forming extensive lava fields on the flexural arches north of O'ahu (~200 km wide) and south of Hawai'i (~50 km wide) [*Lipman et al*., 1989; *Clague et al*., 1990], as well as on the northeast flank of Ni'ihau (~100 km wide) [*Clague et al*., 2000; *Dixon et al*., 2008] and around Ka'ula Island [*Garcia et al*., 2008]. Another lava field sits on a seafloor bulge southwest of O'ahu (~100 km wide) [*Moore et al*., 1989]. One interpretation of the SW O'ahu Volcanic Field (SWOVF) is that it is a veneer of secondary volcanism overlying the bulging deposits of a landslide from O'ahu [*Coombs et al*., 2004]. Alternatively, the lava and seafloor bulge together, could be part of a very low-relief shield volcano [*Takahashi et al*., 2001; *Noguchi and Nakagawa*, 2003]. The causes of the above forms of volcanism far from the hotspot center are poorly known.

[4] Another class of submarine construct that is poorly understood is represented by the large edifices protruding northwest from the Big Island of Hawai'i (Mahukona) and northwest from O'ahu (Ka'ena Ridge). Mahukona is interpreted as a separate low-relief shield volcano as evidenced by geophysical, geochronological, and geochemical data [*Garcia et al*., 1990; *Clague and Moore*, 1991; *Garcia et al*., 2012]. Ka'ena Ridge, however, is not as well studied. It has been proposed as being the submerged extension of the Wai'anae Rift Zone or an entirely separate, volcanic system [*Smith*, 2002; *Coombs et al*., 2004], and has been compared to the large submarine Hana Ridge east of Maui. Thus, Hawaiian constructional volcanism is manifested in a variety of forms from small, but extensive lava fields, to more voluminous ridges, to massive shield volcanoes.

[5] A prominent feature that is particularly enigmatic is the large bathymetric swell south of the Island of Kaua'i (Figures 1 and 2). The South Kaua'i Swell (SKS) was originally described as a submarine landslide based on the U.S. Geological Survey's, GLORIA side-scan surveys, which lacked swath bathymetry data [*Moore et al*.,

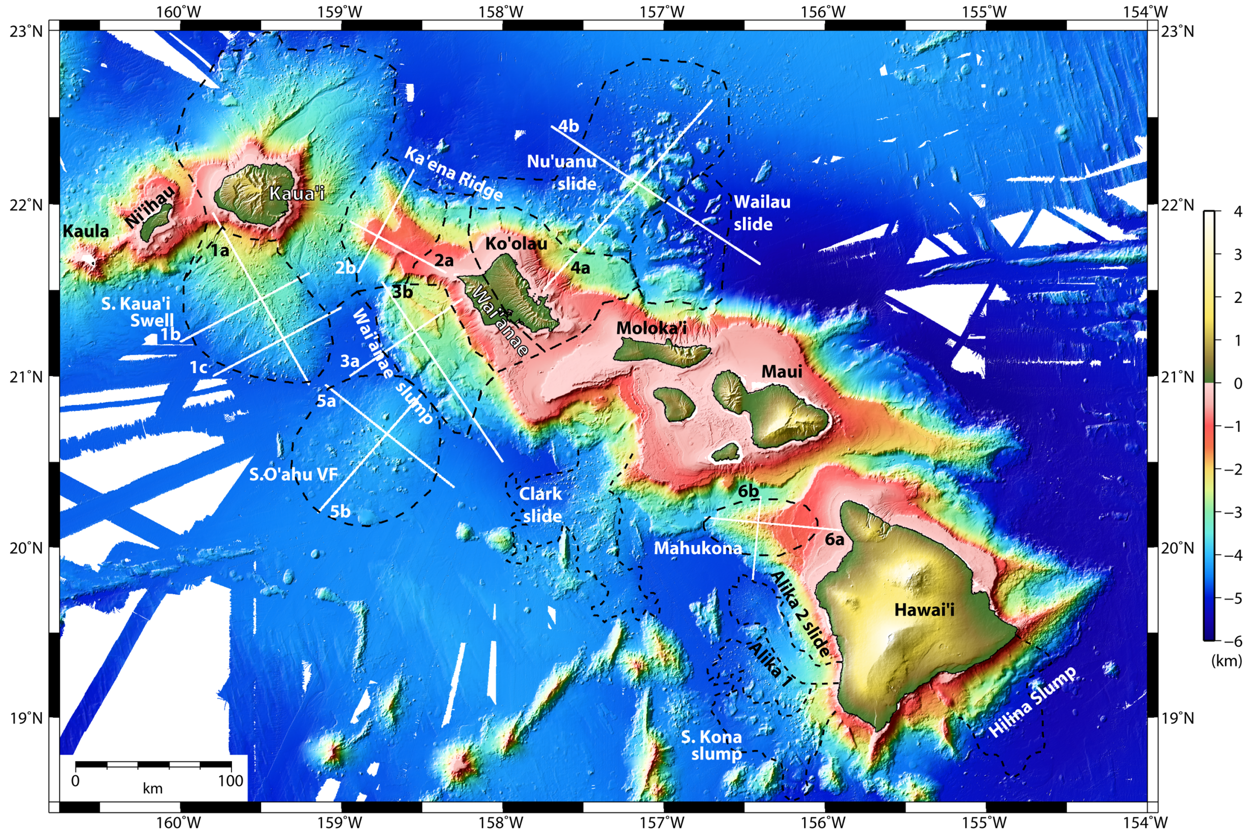

Figure 1. Multibeam bathymetry map of Hawaiian Islands, illuminated from the NW (grid available at http://www. soest.hawaii.edu/HMRG/cms). Areas discussed in the text are outlined (black dashed). White lines mark locations of profiles labeled as shown in Figure 4.

1994; *Groome et al*., 1997; *Holcomb and Robinson*, 2004]. Subsequent reconnaissance bathymetric mapping showed that the gross morphology is quite unlike other large Hawaiian landslides. For example, many of the features that were considered as debris blocks are actually cone-shaped seamounts, some with acoustically reflective lava flows (Figure 2). These morphological features led us to consider other hypotheses for the origin of the SKS: (1) widespread secondary volcanism such as the vast lava field northwest of Niʻihau, and (2) a low-relief shield volcano, intermediate in relief between Mahukona and the SW Oʻahu Volcanic Field. To test these and the landslide hypotheses, we undertook a marine expedition of the SKS in 2007 on the *R/V Kilo Moana*, operated by the University of Hawaii, during which we performed geophysical surveys and sampled rocks using Woods Hole Oceanographic Institution's JASON ROV. The results from this expedition are combined with those from three dredge hauls made from the *R/V Kilo Moana* in 2005, and samples taken during a JASON test dive in 2006. Here we report on the findings and interpretations of the multibeam bathymetry and acoustic imagery, the gravity surveys combined with an extensive local gravity dataset, and the lava geochemistry and geochronology analyses.

2. Bathymetric Data and Acoustic Imagery

[6] The South Kauaʻi Swell (SKS) is a SSE-trending, ovoid feature (~110 km x ~80 km) that spans an area of ~6.7 x 10^3 km^2 adjacent to the south flank of Kauaʻi (Figures 1–3). It stands a maximum height of 2–2.5 km above the deep abyssal seafloor and merges with the steep-sided southern margin of Kauaʻi at a depth of ~2 km. The overall surface of SKS is slightly convex, having minimal slope near a depth of 2.5 km and sloping slightly steeper at greater depths toward the surrounding abyssal seafloor (Figures 3 and 4). The swell has a central axis extending SSE, flanked by slopes dipping to the SSW and E. A few low-relief (10–30 km wide) lobes, or spur-like features, splay SSW and

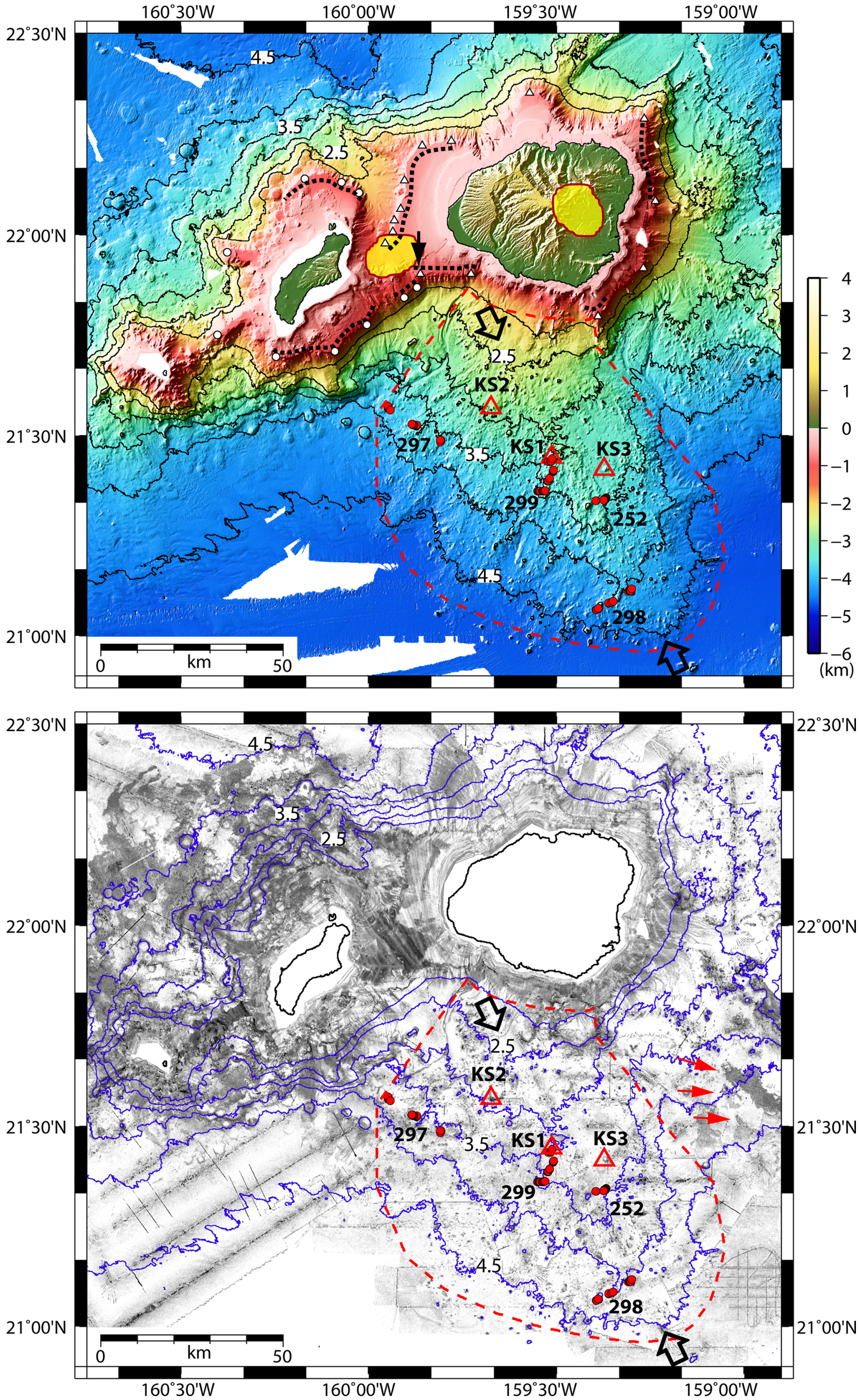

Figure 2. Continued

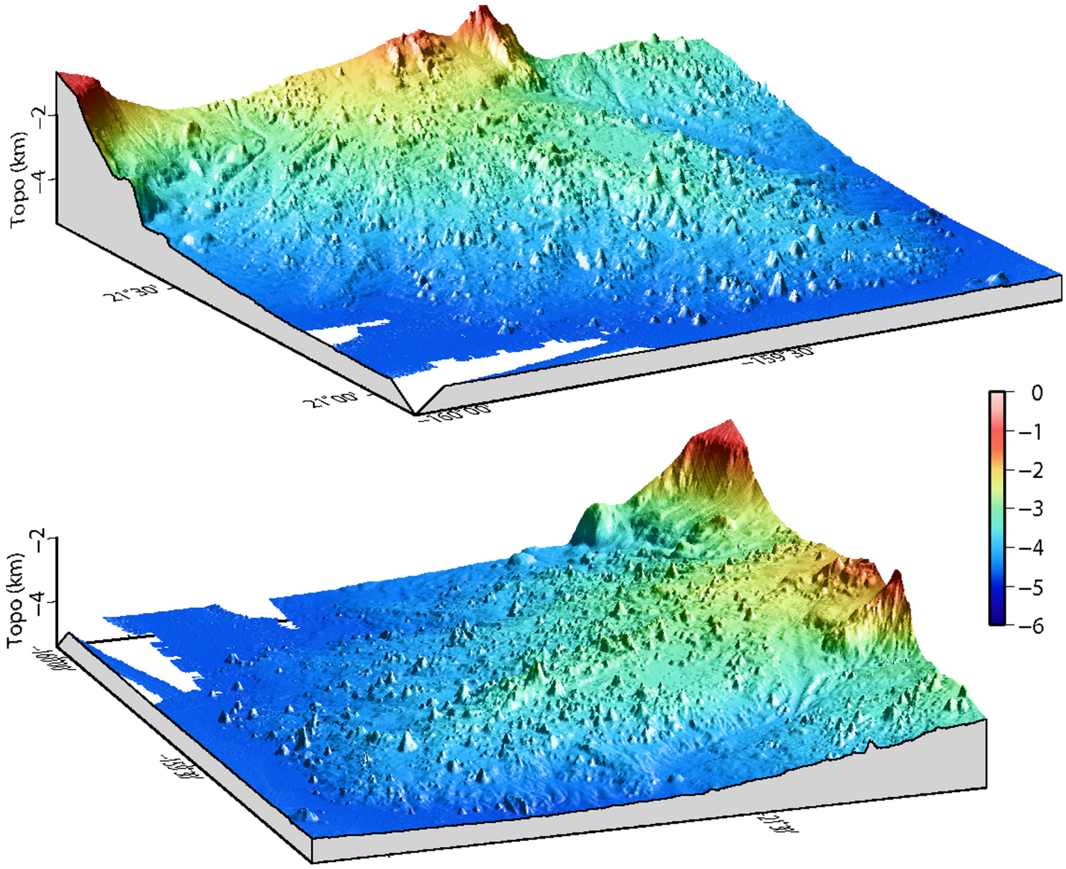

Figure 3. Perspective views of South Kauaʻi Swell bathymetry (color scale in km) from (top) azimuth of 210°, illuminated from 300°, and (bottom) azimuth of 110°, illuminated from 30°. Color bar indicates depth in km. Vertical exaggeration is about 5:1.

SE away from the central axis, producing a subtle, large-scale pinnate structure. Numerous seamounts (>400 with height > 60 m and ellipticity < 3, median and standard deviation of the major axis length is 672 ± 562 m) are present; a few are circular and smooth-topped (e.g., at 159°35'W, 21°44N), although most are more irregular in shape.

[7] The acoustic backscatter of SKS is relatively low in amplitude over large areas (light gray to white; Figure 2b), which indicates that much of the SKS is relatively thickly sedimented as was confirmed by inspection during JASON dives. Higher acoustic backscatter is found along alluvial channels extending south from Kauaʻi and on many of the seamounts (Figure 2b). Three strongly reflective areas just east of SKS (Figure 2b) were confirmed to be lava flows [*Greene et al.*, 2010]. Video from the JASON dives confirmed that the more reflective escarpments and seamounts, where

Figure 2. (a) Multibeam bathymetry data around Kauaʻi and Niʻihau from our survey (KM0718) and from the Hawaiʻi Multibeam Synthesis (http://www.soest.Hawaiʻi.edu/HMRG/cms), with 111 m grid spacing, colored and illuminated from the NW. Contours are every 0.5 km from depths of 4.5–2 km. JASON dive numbers are labeled; sample locations are marked with red circles; dredge numbers (KS1–3) are labeled with locations marked by triangles. SKS is outlined with dashed line and its central axis is marked by large arrows. Gravity anomaly highs (≥ +80 mGal) overly the inferred magmatic centers of the two shield volcanoes are marked by translucent yellow patches [*Flinders et al.*, 2010]. White symbols mark locations of identified slope breaks, interpreted as the paleo-shorelines of Kauaʻi (triangles) and Niʻihau (circles) [*Flinders et al.*, 2010]. Dotted lines indicate the sections where the slope break continues between the white symbols. Small black arrow marks where a slope-break of Kauaʻi's terrace lies above a slope-break of Niʻihau's terrace. (b) Mosaic of acoustic backscatter from KM0718 and the Hawaiʻi Multibeam Synthesis. Dark is high return, light is low return. Contours are the same as in Figure 2a. Small red arrows point to acoustically reflective areas confirmed to be young (< 0.4 Ma) alkalic lava flows as reported in *Greene et al.* [2010].

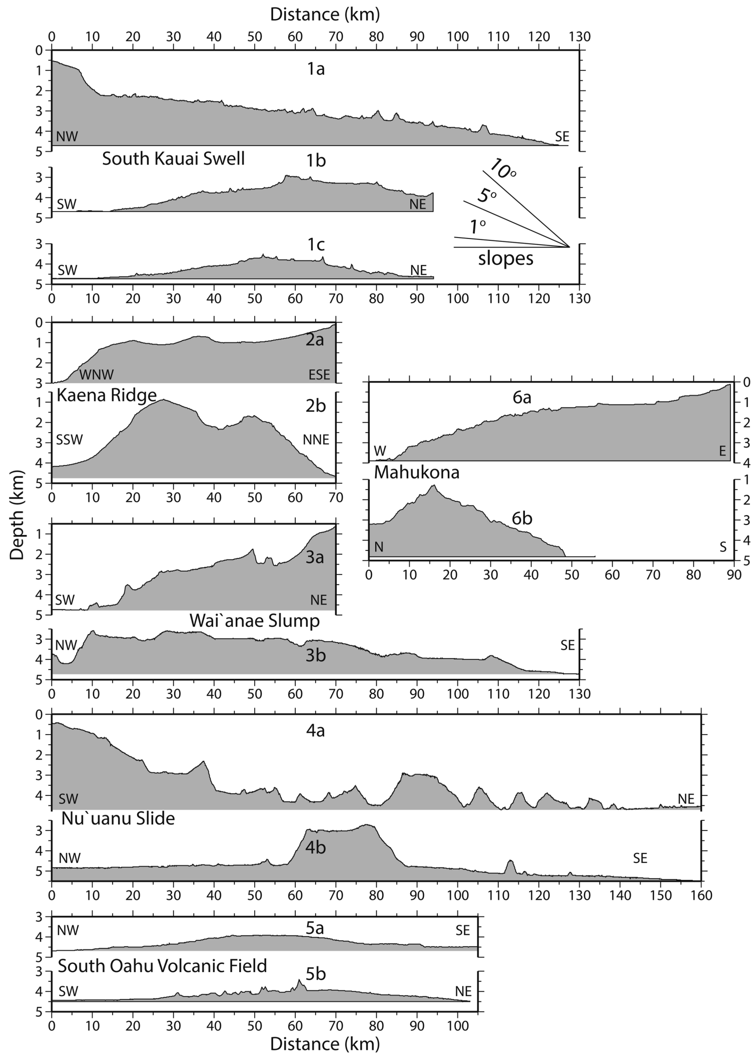

Figure 4. Profiles of various offshore features along the lines shown and labeled in Figure 1. Vertical exaggeration is 5:1. Labeled horizontal axes bound each profile triplet (for SKS) or pair of the labeled features.

we focused our sampling efforts, are generally more sparsely sedimented. The areas sampled contain loose to partially lithified sediments, fractured basement rock, talus, breccia, and few insitu pillow flows. The samples recovered from the pillow basalts were found to be young (<2 Ma) and alkalic, not tholeiitic (discussed below). The overall low and sporadic backscatter of SKS clearly contrast with the more uniformly high backscatter surrounding Niʻihau and Kaʻula (small island WSW of Niʻihau), which denotes extensive areas of flows and volcanic cones produced by secondary volcanism [*Dixon et al.*, 2008; *Garcia et al.*, 2008].

3. Gravity Data

[8] Hawaiian volcanoes typically have gravity highs over their magmatic centers [e.g., *Krivoy and Easton*, 1961; *Kinoshita et al.*, 1963]; thus, gravity may be used to test the shield volcano hypothesis for the SKS. A regional compilation of gravity data [*Flinders et al.*, in press] was made for the northern Hawaiian Islands from our and other *R/V Kilo Moana* cruises, the National Geophysical Data Center (www.ngdc.noaa.gov), as well as onshore gravity [*Flinders et al.*, 2010]. Details of the gravity data processing and reduction are given in *Flinders et al.* [2010]; only the essential points are summarized here. Free-air gravity data from individual ship survey lines were hand-edited for noisy sections (typically associated with course and speed changes), broken into straight line segments, and then corrected for discrepancies between line crossings [*Prince and Forsyth*, 1984]. The standard deviation of the reduced crossing errors was ~2 mGal over the

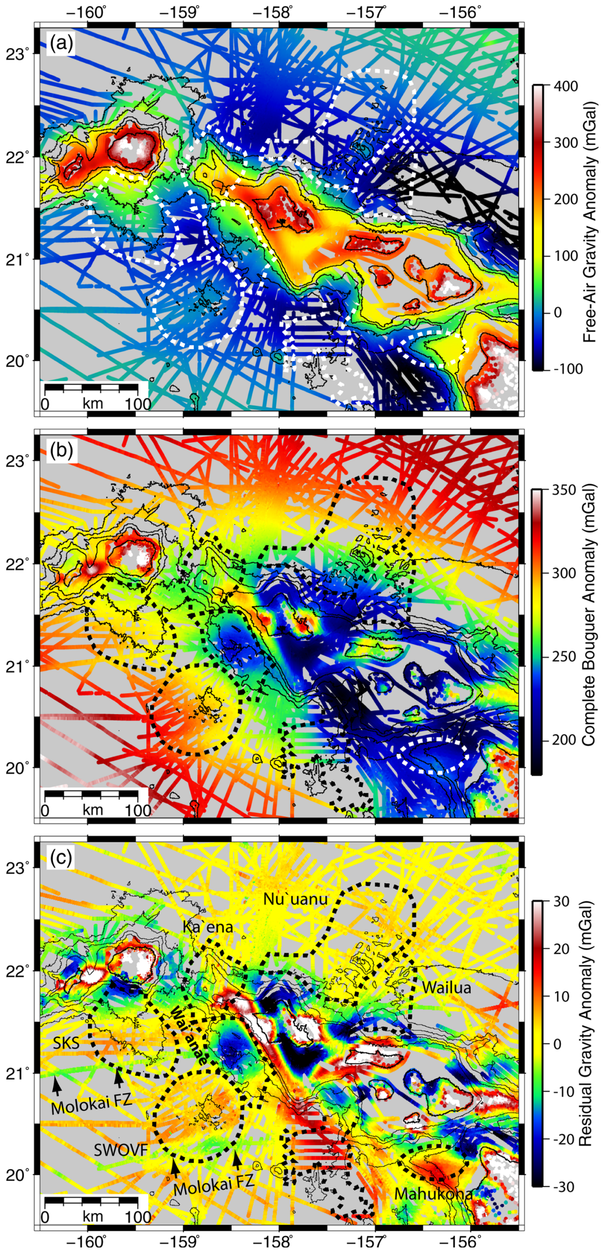

Figure 5. (a) Free-air gravity anomaly is colored along ship tracks. (b) Complete Bouguer anomaly is free-air anomaly minus the effects of submarine and subareal topography. (c) The residual gravity anomaly is the complete Bouguer anomaly with wavelengths >150 km removed. Depth contours are every 1 km and islands are outlined in black. Relevant features are outlined with bold dashed lines.

area of free-air gravity shown in Figure 5. As is common, the free-air gravity anomaly shows a strong correlation with topography.

[9] We produced a complete Bouguer anomaly (CBA) by subtracting from the free-air gravity anomaly the gravitational attraction of the submarine and subaerial topography (Figure 5b). The density of water, the crust above, and the crust below sea level were taken to be 1000, 2400, and 2700 kg/m^3, respectively [*Flinders et al.*, 2010]. Variations in the CBA reflect density structure that differs from the above reference densities. For example, short wavelength (~50 km wide) highs probably mark dense cumulate-rich crust at the centers of the Ni'ihau, Kaua'i [*Flinders et al.*, 2010], Wai'anae, and Ko'olau shields (Figure 5b). From the southwest to northeast across the island chain, the CBA is relatively high (> 300 mGal), decreases near the center of the chain (~170 mGal just west of Maui), and then increases again to the northeast. This long wavelength variation is caused by the crust-mantle interface taking the shape of an elastic lithospheric plate, which has been flexed downward by the weight of the volcano chain [*Watts and ten Brink*, 1989].

[10] To isolate the shorter-wavelength signals due to local density variations beneath the SKS and the other volcanic features and landslides, we removed wavelengths >150 km from the complete Bouguer anomaly (using the Gaussian tapered filter of "grdfilter" in the GMT software package [*Wessel and Smith*, 1995]). This filtering produces the residual gravity anomaly (Figure 5c). Over the central portion of SKS, the residual anomaly flattens to neutral or low-amplitude positive values (~5 mGal, yellow to orange in Figure 5c), similar to that over the SW O'ahu Volcanic Field (SWOVF). This low-amplitude high is interrupted to the south by a linear residual gravity low (−5 to −10 mGal, light green) that trends ENE toward the island of Moloka'i and overlies the northern branch of the Moloka'i Fracture Zone (the southern branch is evident as a similar linear low projecting toward Maui). The slightly high-residual gravity over the SKS is bounded to the north by an area of very low-residual gravity. This low-gravity anomaly resembles the low gravity on the other flanks surrounding most of Kaua'i and is most negative on Kaua'i south shelf area (~−20 mGal). This prominent low clearly separates the strong positive gravity signature on the Island of Kaua'i from the neutral-to-small positive gravity over the SKS.

[11] The gravity signatures over the SKS and SWOVF contrast with the larger-amplitude gravity highs over the Wai'anae rift zone (10–40 mGal) and the southern part of Mahukona (10–20 mGal) [*Garcia et al.*, 2012], as well as the negative residual gravity low over the Wai'anae Slump (west flank of O'ahu). The Nu'uanu (NE of O'ahu) and

Wailau (N of Molokaʻi) landslide deposits have no significant residual gravity anomalies relative to the areas immediately adjacent to them. Thus, although the gravity signatures of the SKS and SWOVF can distinguish them from the Waiʻanae Slump, their gravity anomalies alone are not distinctive with respect to the Nuʻuanu and Wailau landslide deposits.

4. Lava Samples

[12] Samples from the South Kauaʻi Swell were collected during four JASON dives and three dredge-hauls (Figure 1) to determine rock type, vesicularity, and chemical and isotopic compositions. The dives traversed many kilometers of seafloor and thus enabled numerous samples from multiple seamounts or morphologically distinct locations (see Appendix for detailed maps of dives and sample locations; supporting information).[1] A total of 110 samples were obtained from 19 seamounts at depths 2970–4170 m below sea level. Most of the 74 lava samples are breccias, consisting of lithologically identical (monomict), angular clasts. The other SKS samples include mudstones, sandstones, pebbly conglomerates with rounded, matrix-supported clasts of diverse lithologies (polymict) suggesting the clasts have been transported. For comparison, monomict as well as polymict volcanoclastic rocks were found interbedded in the submarine portion of Mauna Kea's deep drill core (∼3100 m) (HSDP2; [*Garcia et al*., 2007]). The HSDP2 monomict fragmental deposits were interpreted to be of local origin, formed as lavas erupted on steep submarine slopes, whereas the polymict breccias were thought to have formed by mass wasting on the unstable slopes of the active volcano [*Garcia et al*., 2007]. Mn coatings on the SKS samples vary from <1 to 14 mm in thickness. Glass was found on only a few samples and was mostly altered. The interiors of the SKS rocks show varying degrees of alteration from unaltered with pristine olivine, to moderate levels of alteration with partial replacement of olivine by iddingsite and, in rare cases, clay and or zeolite in the vesicles.

[13] Vesicularity shows no systematic variation with sample location or rock composition but displays a somewhat bimodal distribution with most samples having <5 vol. % or >20 vol. % vesicles. By comparison, subaerial HSDP2 lavas have mean vesicularities of 9, 11 and 18 vol.% for Mauna Loa, Mauna Kea and Kilauea volcanoes respectively, and a larger total variation (<1 to >30 vol.%) for each volcano. The HSDP2 submarine lavas tend to have lower vesicularity, averaging <3 vol.%, but ranging widely (0.1 to 19 vol.%). Offshore Hawaiʻi, highly vesicular submarine lavas are found near submarine vents (e.g., up to 33 vol.% in a tholeiitic lava from Loihi seamount) and tend to decrease with eruption depth [*Moore*, 1965; *Garcia et al*., 1995]. Thus, the highly vesicular SKS lavas (>20 vol.%) probably erupted in shallow water depths (< 1000 m) and some perhaps subaerially. Because all of the SKS samples were extracted from water depths of >2500 m, the highly vesicular lavas were probably transported from shallower depths. These lavas were collected from the western side (dive 297, water depths 3330–3770 m) and central part (dives 252 and 299 water depths 3260–3322 m) of SKS, but not from the site (298) furthest southeast from Kauaʻi. This southeastern-most dive (298) recovered rocks with vesicularities all <0.1 %. Thus, the highly vesicular lavas from SKS could be landslide debris.

5. Petrology and Geochemistry

[14] The primary objective of the petrological and geochemical components of the investigation was to identify the type of lava (tholeiitic versus alkalic) and to determine whether the SKS lavas are compositionally similar to or distinct from Kauaʻi lavas. Fifty SKS samples were analyzed by XRF for whole-rock major and trace element compositions. Nineteen of these samples were also analyzed by ICP-MS for trace elements, and by TIMS and MC-ICP-MS for Pb, Sr, Nd and Hf isotopes. Only an overview of the geochemical results is presented here to provide a basic characterization and address the origin of the swell; the geochemistry data are reported in *Swinnard* [2008], and the detailed examination of these data will be presented in a separate study [*Garcia et al*., in preparation].

[15] The SKS rocks range in composition from alkalic basalt and basanite to tholeiitic basalts and picrites (Figure 6). Only seven alkali rocks were collected, and they were from the western flank of the SKS (dive 297 and dredge KS2, Figure 2) in areas of locally high-acoustic backscatter near and on relatively smooth-topped and broad seamounts. Those from dive 297 came from an outcrop of pillow basalts. These rocks are similar in major and

[1]Additional supporting information may be found in the online version of this article.

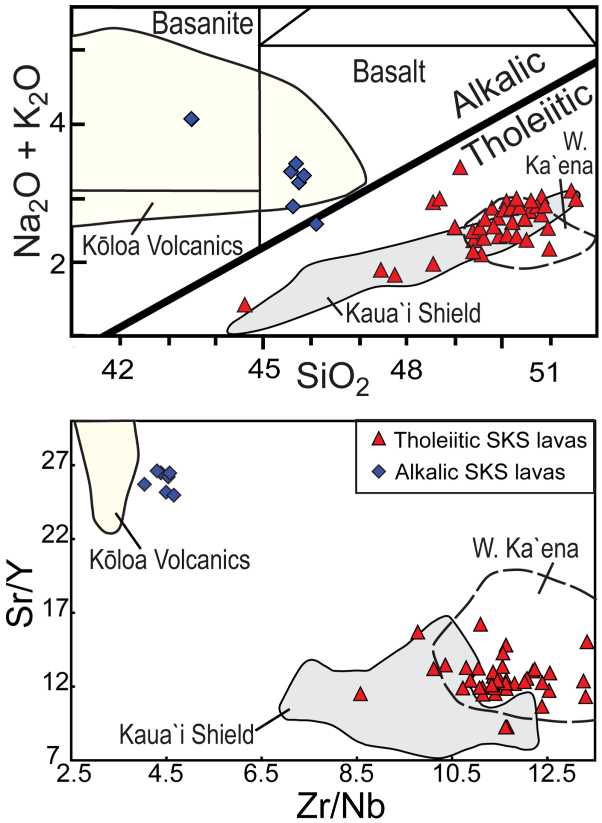

Figure 6. Major element compositions of SKS samples compared with compositions of the shield and rejuvenated (Kōloa) stages on Kaua'i and tholeiitic lavas from west Ka'ena [*Garcia et al.*, 2010; *Greene et al.*, 2010]. Red symbols denote tholeiites; blue denotes alkalic lavas.

trace element composition to the rejuvenated lavas on Kauai'i [*Garcia et al.*, 2010](Figure 6).

[16] Tholeiites are the most abundant rock type sampled and range widely in composition (Figure 6, e.g., 6–25 wt.% MgO, 0.16–0.62 K_2O wt.%, and 0.73–0.91 CaO/Al_2O_3) in the least altered samples [*Swinnard*, 2008]. The rocks show wide compositional variations at the same MgO content, which cannot be attributed to olivine addition or alteration; they must reflect distinct parental magmas. Some seamounts show a small range in composition (e.g., Zr/Nb, which is resistant to alteration, ranges 11.5–12.5 among six samples from one seamount), whereas others have a larger range (e.g., Zr/Nb ranges 10.1–13.3 among three samples from another seamount). Composition does not appear to vary systematically with position within individual dives sites or among the seven sample locations. The SKS tholeiitic compositions generally overlap with those for Kaua'i shield lavas, although some have higher $Na_2O + K_2O$ contents and Zr/Nb ratios (Figure 6), as well as somewhat lower CaO/Al_2O_3 at a given MgO (not shown) content than Kaua'i lavas, suggesting slightly distinct sources.

[17] The isotopic data for SKS lavas form two groups that correspond with the rock types: the alkalic lavas have distinctly lower $^{87}Sr/^{86}Sr$ than the tholeiites and plot close to the compositional field of the Kōloa (rejuvenated) lavas on Kaua'i (Figure 7). The tholeiites show overlap in $^{87}Sr/^{86}Sr$ and $^{206}Pb/^{204}Pb$ with tholeiitic lavas from Kaua'i and Wai'anae, as well as some from West Ka'ena.

6. Geochronology

[18] A two-pronged approach was used in dating the SKS lavas. Initially, 12 samples spanning a wide range in rock composition were analyzed by the unspiked K-Ar method at Kyoto University (see Table 1 and Appendix for details on methods used; supporting information). Two samples were analyzed also at Japan Atomic Energy Agency (JAEA) by similar method. These K-Ar methods have proven useful for dating young Hawaiian basalts [e.g., *Ozawa et al.*, 2005; *Garcia et al.*, 2012]. In addition, sixteen tholeiitic samples were analyzed by $^{40}Ar/^{39}Ar$ methods at the University of Wisconsin-Madison (Tables 2, A1, and Appendix; supporting information). The plateau ages of these samples represent a high percentage of the ^{39}Ar (all greater than 93% and 100% for 14 of 15 analyses), have low MSWD values (all <1.3 and most <0.75), and are used here as the preferred ages.

[19] Among the three samples analyzed with both K-Ar and Ar-Ar methods, two yielded remarkably consistent results: sample 297-09 gave ages 4.24$\pm$ 0.46 Ma by K-Ar vs. 4.14 $\pm$ 0.14 Ma and 4.22 $\pm$ 0.12 Ma by Ar-Ar (all errors are 2σ); sample 299-29 gave ages of 4.03 $\pm$ 0.12 Ma by K-Ar and 4.02 $\pm$ 0.13 Ma by Ar-Ar (Tables 1 and 2). For K-Ar dating of sample 299-29, the weighted mean uncorrected age is used because $^{38}Ar/^{36}Ar$ ratio was not well determined and no technical cause was identified for this problem. In another study on rocks collected from seamounts east of Kaua'i [*Greene et al.*, 2010], $^{40}Ar/^{39}Ar$ and unspiked K-Ar ages produced consistent results for young alkalic lavas (0.37 vs. 0.24 Ma) as well as for older tholeiitic lavas (3.6–4.9 vs. 4.3–4.7 Ma). Thus, we think both geochronology methods provide useful constraints for the eruption ages of the least altered SKS lavas.

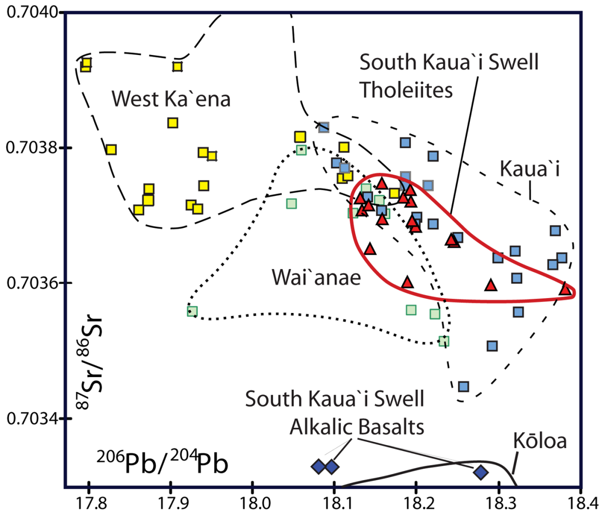

Figure 7. Isotope compositions of lavas from SKS (triangles) compared to of tholeittic basalts from near-by volcanic provinces. Data sources: SKS [*Swinnard*, 2008]; West of Ka‘ena [*Greene et al*., 2010]; Wai‘anae [*Coombs et al*., 2004]; Kaua‘i [*Garcia et al*., 2010]. The portion of Kōloa field that lies within the plot is outlined (black); the whole field spans 18.0895-18.6136 and 0.702959-0.703248 in $^{206}Pb/^{204}Pb$ and $^{87}Sr/^{86}Sr$, respectively [*Garcia et al*., 2010].

[20] The 21 new ages for tholeiitic lavas range from 3.9 to 5.4 Ma (Figure 8). We see no clear geographic pattern to the distribution of ages (see Appendix for detailed maps of sample locations and ages; supporting information). For example from Dive 252, we obtained two samples from adjacent seamounts separated by 2 km that yielded identical ages (both 4.29 Ma), and from dive 297, two samples from adjacent seamounts yielded distinct but similar ages (4.03–4.34 Ma). Whereas from the two other dives, samples from the same seamount yielded appreciably different ages (4.00 and 4.29 Ma from Dive 298, and 4.02, 4.44, 5.11 Ma from Dive 299).

[21] The frequency distributions of the ages of the tholeiites show a large cluster (16 samples) with ages 3.9–4.5 Ma, and a smaller cluster (3 samples) spans ages of 4.75–5.4 Ma (Figure 8). The oldest ages (>5 Ma) were obtained for samples from dives 297 and 299 on the central and western part of SKS (Figure 2). These areas are south and downslope of the gap in Kaua‘i’s ancient shoreline (Figure 2), and thus could well contain debris from Kaua‘i. The oldest rock (5.40 Ma, dive 297, sample 26) was sampled from a loosely stratified, alluvial deposit near the end of a submarine channel that originated at the outlet of the Waimea River. This sample is therefore our most-likely candidate for being from Kaua‘i. The SKS tholeiite ages overlap with the ages for the Kaua‘i shield (3.6–5.1 Ma [*McDougall*, 1979; *Garcia et al*., 2010]), Ni‘ihau (4.3–6.3Ma) and W. Ka‘ena (2.9–4.9 Ma), but extend to younger ages than Ni‘ihau and older ages than W. Ka‘ena.

[22] The SKS alkalic lavas are much younger (0.08–1.9 Ma, Figure 8), indicating a ~1.8 Myr hiatus in volcanism after the tholeiites. This age gap and the alkalic compositions, together, are consistent with these rocks representing a secondary volcanic phase.

7. South Kaua‘i Swell Volume

[23] Size is a critical characteristic of the South Kaua‘i Swell. The volume of SKS was computed based on the border of the swell shown in Figure 2 using two methods. Method 1 is most appropriate for landslides and method 2 for shield volcanoes. We also estimated the volumes of large Hawaiian landslides and near-by shield volcanoes (borders shown in Figure 1) for comparison.

[24] Method 1 is appropriate for landslides that formed on top of sediments infilling the flexural moat [*Watts and ten Brink*, 1989] surrounding the original shield volcanoes. We estimated the volume between the seafloor and a flat base at a depth of 4.6 km, which corresponds to the depth of the abyssal seafloor just outside of the flexural moats of Kaua‘i. Method 2 is more appropriate for a shield volcano that grew directly on top of the pre-existing seafloor. Following *Robinson and Eakins* [2006], we approximated the surface of the pre-existing seafloor as that of an elastic lithospheric plate with an effective thickness of 35 km being flexed downward by the weight of the island chain. We used a submarine crustal density of 2700 kg/m^3 and a subaerial crustal density of 2400 kg/m^3 (same as those used for computing the complete Bouguer anomaly). This model predicts a flexed surface that closely matches the shape of the basement of the pre-existing oceanic crust on the flanks of the island of O‘ahu as was modeled and seismically imaged by *Watts and ten Brink* [1989] and used by *Robinson and Eakins* [2006]. Then, we removed 0.5 km [*Robinson and Eakins*, 2006] above the modeled pre-existing basement to account for the pre-existing pelagic sediments that are not part of the volcanoes.

[25] To verify our methods, we compared our volume estimates of other edifices in the area with

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Table 1. K-Ar Dating Results

Sample name	Sample site	Rock type	Alteration[a]	K_2O/ P_2O_5	LOI	K_2O (wt.%)	Lab	Sample wt. (g)	$^{40}Ar/^{36}Ar$	$^{38}Ar/^{36}Ar$	$^{40}Ar/^{36}Ar$ Init.[b]	^{40}Ar rad. ($10^{-8}cm^3$ STP/g)	^{40}Ar air (%)	Uncorrected age[c] (Ma) ± 2σ	Corrected age (Ma) ± 2σ
297-9	cone B	tholeiite	B2	1.88	−0.16	0.50	Kyoto	0.703	359.7 ± 1.0	0.1861 ± 0.0022	293.0 ± 7.0	6.9 ± 0.8	81.4	4.08 ± 0.16	**4.24 ± 0.46**
297-18	cone C	tholeiite	B2	1.52	−0.07	0.32	Kyoto	0.615	332.1 ± 0.8	0.1856 ± 0.0017	291.5 ± 5.7	4.6 ± 0.7	87.8	3.91 ± 0.16	**4.34 ± 0.64**
297-20	cone D	basanite	A2	2.71	0.61	0.74	Kyoto	0.606	304.9 ± 3.5	0.1893 ± 0.0106	302.7 ± 34.8	0.1 ± 2.0	99.2	0.23 ± 0.08	0.05 ± 0.84
							JAEA	0.597	300.6 ± 0.7	0.1862 ± 0.0011	293.4 ± 3.7	0.5 ± 0.3	97.6	0.16 ± 0.02	0.23 ± 0.12
														weighted mean corrected age from two experiments:	**0.23 ± 0.12**
297-21	cone D	basanite	A2	2.43	0.60	0.73	Kyoto	0.602	299.8 ± 0.8	0.1866 ± 0.0016	294.5 ± 5.3	0.6 ± 0.6	98.2	0.20 ± 0.04	0.25 ± 0.25
							Kyoto	0.627	298.9 ± 0.7	0.1873 ± 0.0017	296.8 ± 5.7	0.3 ± 0.8	99.3	0.21 ± 0.04	0.13 ± 0.36
							Kyoto	0.705	298.8 ± 0.7	0.1871 ± 0.0017	296.0 ± 5.4	0.4 ± 0.8	99.1	0.19 ± 0.04	0.16 ± 0.32
														weighted mean corrected age from three experiments:	**0.19 ± 0.18**
297-24	cone D	basanite	A2	1.41	1.20	0.50	Kyoto	0.614	297.6 ± 1.0	0.1878 ± 0.0030	298.2 ± 9.8	−0.12 ± 2.4	100.2	0.32 ± 0.14	−0.08 ± 15.4
							JAEA	0.128	297.7 ± 0.8	0.1874 ± 0.0016	297.0 ± 5.4	0.1 ± 1.0	99.8	0.27 ± 0.10	**0.08 ± 0.70**
297-26	Area E	tholeiite	B2	1.59	0.12	0.63	Kyoto	0.202	332.3 ± 1.0	0.1868 ± 0.0022	295.2 ± 7.4	11.1 ± 2.2	88.8	5.34 ± 0.22	**5.40 ± 1.10**
299-29	Site C	tholeiite	B2	1.79	−0.17	0.50	Kyoto	0.550	334.2 ± 1.8		295.5	5.9 ± 0.3	88.4	3.65 ± 0.20	
							Kyoto	0.455	333.0 ± 0.6		295.5	6.9 ± 0.2	86.7	4.28 ± 0.16	
													weighted mean uncorrected age from two experiments:	**4.03 ± 0.12**	
KS-2	dredge	basanite	A1	3.55	1.63	1.67	Kyoto	0.731	384.5 ± 1.6	0.1869 ± 0.0016	295.6 ± 5.0	10.1 ± 0.6	76.9	1.86 ± 0.06	**1.86 ± 0.12**
KS-3-1	dredge	tholeiite	B1	1.81	−0.50	0.48	Kyoto	0.740	410.1 ± 1.6	0.1887 ± 0.0018	301.0 ± 5.6	6.1 ± 0.4	73.4	4.05 ± 0.12	**3.86 ± 0.24**

	A1	A2	B1	B2
Freshness of olivine phenocryst	fresh	fresh	minor[d]	minor[d]
Secondary minerals in vesicles	no	present	no	present
Freshness of groundmass olivine	fresh	fresh	fresh	fresh
Preferred age in bold				

[a]Alteration criteria by thin section observation.
[b]Initial $^{40}Ar/^{36}Ar$ calculated from $^{38}Ar/^{36}Ar$ assuming mass fractionation.
[c]Mass fractionation uncorrected.
[d]Minor oxidation at the margin (<10% of the diameter).

Table 2. Summary of $^{40}Ar/^{39}Ar$ Dating Results[a]

			Total fusion	Isochron				Plateau		
Sample no.	Location	K/Ca total	Age (Ma) ± 2σ	$^{40}Ar/^{36}Ar_i \pm 2\sigma$	MSWD	Age (Ma) ± 2σ	N	^{39}Ar %	MSWD	Age (Ma) ± 2σ
252-04	Cone A	0.13	4.28 ± 0.14	296.4 ± 2.1	0.65	4.23 ± 0.14	8 of 8	100.0	0.59	**4.29 ± 0.12**
252-10	Cone B	0.18	4.33 ± 0.16	297.6 ± 2.9	0.64	4.24 ± 0.10	8 of 8	100.0	0.62	**4.29 ± 0.12**
297-04	Cone B	0.18	4.05 ± 0.24	297.0 ± 4.0	0.13	3.78 ± 0.66	8 of 8	100.0	0.14	**4.03 ± 0.22**
297-09	Cone B	0.15	4.06 ± 0.18	287.0 ± 6.5	0.85	4.59 ± 0.34	8 of 8	100.0	1.00	4.14 ± 0.14
		0.18	4.12 ± 0.14	292.3 ± 4.4	0.42	4.40 ± 0.25	7 of 8	97.2	0.43	4.22 ± 0.12
					Weighted mean plateau age from two experiments:					**4.19 ± 0.09**
298-12	Cone D	0.20	4.01 ± 0.15	297.1 ± 3.7	0.83	3.79 ± 0.46	8 of 8	100.0	0.74	**4.00 ± 0.13**
298-20	Cone D	0.13	4.60 ± 0.18	295.6 ± 1.3	1.28	4.74 ± 0.10	8 of 9	96.7	1.10	4.75 ± 0.11
		0.11	4.83 ± 0.16	296.7 ± 0.9	0.94	4.75 ± 0.09	10 of 10	100.0	1.04	4.84 ± 0.13
					Weighted mean plateau age from two experiments:					**4.79 ± 0.08**
299-04	Site A	0.08	4.53 ± 0.32	295.0 ± 0.9	0.61	4.66 ± 0.17	10 of 10	100.0	0.58	4.60 ± 0.26
		0.08	4.39 ± 0.30	295.7 ± 1.0	1.42	4.44 ± 0.16	9 of 9	100.0	1.25	4.46 ± 0.22
					Weighted mean plateau age from two experiments:					**4.51 ± 0.16**
299-08	Site A	0.07	4.34 ± 0.35	295.1 ± 2.9	0.95	4.49 ± 0.50	10 of 10	100.0	0.85	4.42 ± 0.28
		0.13	4.37 ± 0.29	296.7 ± 1.9	0.72	4.21 ± 0.35	9 of 9	100.0	0.69	4.42 ± 0.25
					Weighted mean plateau age from two experiments:					**4.42 ± 0.18**
299-15	Site A	0.10	4.11 ± 0.20	294.1 ± 5.8	1.29	4.28 ± 0.43	10 of 10	100.0	1.16	**4.17 ± 0.16**
299-20	Site B	0.13	5.26 ± 0.15	296.2 ± 2.0	0.35	5.08 ± 0.11	6 of 8	93.7	0.30	5.12 ± 0.12
		0.18	5.19 ± 0.17	295.9 ± 1.8	0.16	5.09 ± 0.12	6 of 8	96.8	0.14	5.11 ± 0.14
					Weighted mean plateau age from two experiments:					**5.11 ± 0.09**
299-21	Site B	0.09	4.48 ± 0.17	296.3 ± 0.4	0.79	4.40 ± 0.07	10 of 10	100.0	1.04	**4.44 ± 0.13**
299-23	Site B	0.13	4.02 ± 0.16	296.3 ± 3.3	0.28	3.99 ± 0.13	8 of 8	100.0	0.25	**4.02 ± 0.12**
299-29	Site C	0.17	4.03 ± 0.15	295.0 ± 2.3	0.22	4.08 ± 0.27	10 of 10	100.0	0.20	**4.02 ± 0.13**
299-33	Site D	0.11	5.10 ± 0.15	294.8 ± 1.0	0.92	5.13 ± 0.10	8 of 8	100.0	0.87	**5.07 ± 0.13**
KS-01–18	Site A	0.09	4.15 ± 0.26	295.9 ± 2.0	0.50	4.16 ± 0.22	8 of 8	100.0	0.44	**4.20 ± 0.19**

[a]Ages calculated relative to 28.201 Ma for the Fish Canyon sanidine [*Kuiper et al.*, 2008] using decay constant of *Min et al.* [2000]. Uncertainties reflect 2σ analytical uncertainties. Preferred age in bold.

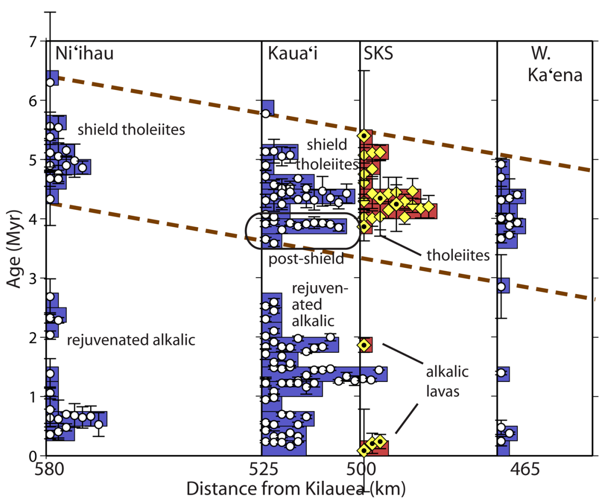

Figure 8. Histograms of age dates obtained from SKS and the adjacent edifices (ages in 0.25 Myr bins on the vertical axis and number of samples on the horizontal), superimposed with precise ages (symbols, horizontal position is arbitrary) and 2σ errors. Black dots mark K-Ar dates for the SKS samples. Each histogram is positioned horizontally according to distances between the centers of each feature and the summit of Kilauea, projected along a trajectory of the current Pacific Plate motion [*Gripp and Gordon*, 2001]. Dates of Kaua'i's post-shield are circled. Data sources: Kaua'i [*McDougall*, 1964, 1979; *Clague and Dalrymple*, 1988; *Garcia et al.*, 2010]; W. Ka'ena [*Greene et al.*, 2010]; Ni'ihau [*Sherrod et al.*, 2007].

previously published estimates. Method 1 produces a volume for the Wailau debris avalanche of 1.1 x 10^3 km^3 (Table 3), which is consistent with estimates by *Satake et al.* [2002] (1.5 ± 0.5 x 10^3 km^3), *Robinson and Eakins* [2006] (1.6 x 10^3 km^3), and *Moore et al.* [1989] (1 x 10^3 km^3). For the Nu'uanu debris avalanche, our estimate of 2.7 x 10^3 km^3 compares favorably with estimates by *Satake et al.* [2002] (3.5 ± 0.5 x 10^3 km^3) and *Robinson and Eakins* [2006] (2.4 x 10^3 km^3), but is less than that by *Moore et al.* [1989] (5 x 10^3 km^3). An important difference is that *Moore et al.* [1989] attributed a ~0.9 km thick layer within the sediments that infill O'ahu's flexural moat as part of the Nu'uanu debris avalanche (based on seismic evidence [*Watts et al.*, 1985; *Brocher and ten Brink*, 1987]), whereas *Satake et al.* [2002] and we do not. For the Mahukona, Ko'olau, Wai'anae, and Kaua'i shield volcanoes, method 2 produces volumes that match those of *Robinson and Eakins's* [2006] (Table 3) within ~8%. The above consistencies lend confidence to our methods of estimating volumes of landslides (method 1) and shield volcanoes (method 2).

[26] For the SKS, method 1 yields a volume of 6 x 10^3 km^3. This volume is greater than our estimates

Table 3. Estimated Volumes in Units of 10^3 km^3 Ordered Smallest to Largest

Edifice (outlines shown in Figure 1)	Volume estimates appropriate for landslides[a]	Volume estimates appropriate for shield volcanoes[b]	Estimates of *Robinson and Eakin*'s [2006]
Wailau Slide	1.1	(8.5 ± 2.0)	1.6
S. Oʻahu Volcanic Field	(2.1)	9.6 ± 3.7	
Nuʻuanu Slide	2.7	(13.4 ± 4.9)	2.4
Mahukona Volcano	(4.7)	13.0 ± 1.0[c]	13.5
Waiʻanae Slump	5.8	(15.9 ± 2.0)	
South Kauaʻi Swell	**6.0**	**14.0 ± 3.4**	
Kaʻena Ridge		14.8 ± 2.0	
Koʻolau Volcano without Nuʻuanu Slide		34.3 ± 2.9	31.7
Waiʻanae Volcano with Waiʻanae Slump and without Kaʻena Ridge		36.8 ± 3.9	
Kauaʻi without S. Kauaʻi Swell		43.5 ± 7.9	
Koʻolau with Nuʻuanu Slide		47.7 ± 7.6	
Waiʻanae with Kaʻena Ridge and Waiʻanae Slump		51.6 ± 5.8	52.9
Kauaʻi with S. Kauaʻi Swell		57.5 ± 11.0	57.6

[a]Volume above a flat abyssal seafloor at a depth of 4.6 km.
[b]Volume between the seafloor and the pre-existing oceanic basement, which flexes downward beneath the islands in the shape of elastic plate (see text). Uncertainty is based on an uncertainty of ±0.5 km of the depth of basement. Adding +0.5 km to the depth puts the basement near that imaged seismically by *Watts and ten Brink* [1989] near Oʻahu. The shown volume estimates are based on the assumption that 0.5 km of pre-existing pelagic sediment lie between the pre-existing basement and each edifice following *Robinson and Eakin's* [2006].
[c]Method 2 assumes the base of Mahukona is the surface of the pre-existing seafloor, flexed downward beneath the island chain. Here the starting point of this surface is the seafloor outside the flexural moat of the Island of Hawaii at a depth of 4.6 km. *Garcia et al*. [2012] assumed the same starting depth but used a point on the southern margin of Mahukona, which is well within the flexural moat, thus producing a volume estimate of 6 x 10^3 km^3.

for Nuʻuanu and Wailau landslides combined (3.8 x 10^3 km^3), and is comparable to our estimate for the Waiʻanae Slump (5.8 x 10^3 km^3, Table 3). Method 2 yields a volume for SKS of 14 ± 3.4 x 10^3 km^3. This volume is comparable those of Kaʻena Ridge (14.8 ± 2.0 x 10^3 km^3) and the small shield volcano, Mahukona (13.0 ± 1.0 x 10^3 km^3, Table 3). The two estimates for SKS are 14% (method 1 for landslides) and 32% (method 2 for shields) of the total volume of Kauaʻi without SKS (43.5 ± 7.9 x $10^3$$km^3$, area shown in Figure 1).

8. Origin of South Kauaʻi Swell

[27] Secondary volcanism, landslides, and shield volcanism are the three main processes that create the submarine features of the Hawaiian chain. All three processes have also played a role in the evolution of the SKS. Each is discussed and evaluated in terms of its relative importance in the formation of the SKS beginning with the most recent process.

8.1. Secondary Volcanism

[28] Lavas from secondary volcanism contrast with shield lavas in generally being more silica undersaturated, containing higher abundances of incompatible elements, originating from more depleted sources [e.g., *Fekiacova et al*., 2007] and having younger ages (by 0.6–2.0 Myr) than the associated shield lavas [*Ozawa et al*., 2005]. On land, secondary volcanism is often referred to as "rejuvenated volcanism" because it overlies shield volcanism; it is usually separated from the shield or postshield phase by a thick soil and/or sedimentary sequence [e.g., *Macdonald et al*., 1983]. In the submarine environment, secondary volcanism is generally associated with high-acoustic backscatter, indicating relatively thin sediments on these younger lavas [*Lipman et al*., 1989; *Clague et al*., 1990; *Dixon et al*., 2008; *Greene et al*., 2010].

[29] The South Kauaʻi Swell displays characteristics that differ from those of secondary volcanism. The relatively thick sediments overlying the volcanic rocks as detected by the low-acoustic backscatter and seen in JASON imagery contrast with the observations of known submarine secondary volcanism. In addition, samples collected by JASON from the SKS have variable but commonly thick Mn rinds (up to 14 mm) indicating residence on the ocean floor for several million years [e.g., *Moore and Clague*, 2004]. The exceptions are the relatively rare alkalic SKS lavas (collected at two sites), which have thin or no Mn oxide coatings. These alkalic lavas have geochemical (Figures 6 and 7) and age (0.08–1.86 Ma, Figure 8) characteristics of secondary volcanism, thus revealing that a few of the seamounts on SKS are probably secondary volcanic. However, the

dominance of tholeiitic lavas from the other sampled seamounts and their older ages indicate that most of the SKS is not related to secondary volcanism. The bulk of the SKS was derived from shield volcanism.

8.2. Landslide Origin

[30] Giant landslides are common on and around oceanic volcanoes worldwide (e.g., Canary Islands [*Watts and Masson*, 1995; *Masson et al*., 2002], Cape Verde [*Ancochea et al*., 2010], La Réunion [*Oehler et al*., 2008], Aleutians [*Coombs et al*., 2007], Stromboli [*Romagnoli et al*., 2009]); and such was the original interpretation of the SKS [*Holcomb et al*., 1988; *Moore et al*., 1989, 1994]. Submarine landslides are usually associated with oversteepened flanks of volcanoes. Steep head scarps and bounding walls commonly form amphitheater-shaped scars, which are the source region of the landslides. Landslides can occur at any time during the evolution of Hawaiian volcanoes: the preshield stage (Lō'ihi seamount, [*Malahoff*, 1987; *Fornari et al*., 1988; *Moore et al*., 1989]), the shield stage (South Kona slide; [*Moore et al*., 1994]), and after most of the volcano has formed (East Moloka'i [*Moore et al*., 1994]).

[31] Two types of massive landslides are common on oceanic islands: debris avalanches and slumps [*Moore et al*., 1994]. Debris avalanches are considered to be catastrophic events creating debris fields of giant (tens of kilometers wide) blocks or smaller blocks (tens to hundreds of meters wide) and hummocky topography [*Moore et al*., 1994]. As seen around the Canary Islands, La Réunion and Stromboli, hummocky debris avalanches often display a concave-up topographic profile that is steepest near the head wall and flattens with distance away from the volcano, eventually merging asymptotically with the abyssal seafloor [*Watts and Masson*, 1995; *Urgeles et al*., 1999; *Coombs et al*., 2007; *Romagnoli et al*., 2009]. Hawaiian debris avalanches represent some of the largest debris avalanches in the world [*Hampton and Lee*, 1996]. The Nu'uanu slide, for example, extends ~150 km away from O'ahu and is composed of intact blocks up to 35 km long by 18 km across and ~1.5 km tall [*Garcia et al*., 2006]. In contrast, the smaller South Kona, 'Ālika 1 & 2, and Clark slides are examples of more hummocky deposits made up of smaller (hundreds of meters or less across) and more uniformly sized fragments [*Moore et al*. 1994]. The 'Ālika 1 & 2 slides display well-defined chutes, bounded by levees [*Moore et al*., 1994]. In contrast to debris fields, slumps (e.g., Wai'anae and Hilina slumps, Figure 1) are characterized by deeply rooted, mostly intact blocks of flank material that slide episodically over geologic time [*Moore et al*., 1989, 1994; *Hampton and Lee*, 1996].

[32] The SKS displays some characteristics of both debris field and slumps, but fails to conform fully to either model. In support of a landslide origin, the rounded southern border of the SKS in map view is not unlike the distal outline of hummocky debris avalanches among other island chains (e.g., Canaries [*Watts and Masson*, 1995; *Masson et al*., 2002], La Réunion [*Oehler et al*., 2008], Aleutians [*Coombs et al*., 2007]). In addition, the SKS has relatively smooth, long-wavelength topography that is populated with numerous small seamounts producing a hummocky surface (Figures 1–3), superficially resembling the deposits of an 'Ālika 2-type debris avalanche [*Moore et al*., 1989]. The most compelling evidence for a landslide are the lack of clearly insitu pillow lavas where the tholeiitic samples were obtained, the highly vesicular lava samples, as well as the diversity of ages of tholeiites found in close proximity to each other, sometimes on the same seamount. These findings indicate that extensive erosion and material transport was important to the evolution of the SKS.

[33] A number of characteristics of SKS, however, are contradictory with those of other landslides. In terms of its geomorphology, the SKS has a convex surface and meets the abyssal seafloor with a distinct break in slope (Figure 4), which contrast with the form of most debris avalanches near other ocean islands as discussed above. While the noted hummocky surface resembles that of the 'Ālika 2 avalanche, the SKS differs significantly in its much larger scale (6700 km^2 versus 1700 km^2 in area [*Moore et al*. 1989]) and having larger seamounts (median width of ~700 m) than the debris of the Ālika 2 avalanche (again, widths typically 10^2 m or less). Volumetrically, if the SKS were a debris avalanche, it would represent an extreme end-member: the estimated volume above the abyssal seafloor depth of 6.0 x 10^3 km^3 (Table 3) is larger than that of the Nu'uanu slide (2.7 – 5 x 10^3 km^3), and three to six times the volumes of the largest debris avalanches of the Canary Islands [*Masson et al*., 2002]. Only two debris avalanches on Earth have been estimated to be comparable or greater in volume: the Storegga slide offshore Norway at 5.6 x 10^3 km^3 [*Bugge et al*., 1988] and the Agulhas slide off South Africa at 20 x 10^3 km^3 [*Dingle*, 1977].

[34] Relative to typical slump deposits, the ∼2–2.5 km thickness of SKS over a broad area compares favorably with the thickness and extent of, for example, the Waiʻanae slump. However, the SKS contrasts with Hawaiian slumps (or the Nuʻuanu or Wailau avalanches for that matter) by its lack of large angular blocks (Figures 1 and 4), the absence of a prominent head scarp, and the presence of a rounded, rather than an irregular margin with the surrounding seafloor. If the SKS originally consisted of one or more largely intact blocks, these blocks would have had to be extensively eroded and the area between them filled in order to erase their original blocky morphology, leaving the relatively smooth, convex-up morphology and rounded margin of the SKS. The central axis and side lobes that produce the SKS's subtle pinnate morphology is especially troublesome to explain with either a debris avalanche or a slump origin.

[35] The possible source regions for a SKS landslide are Niʻihau's east flank and Kauaʻi's south flank [*Moore et al*., 1989]. Both areas show evidence of collapse based on gaps in the original shorelines of each island's shield volcano (Figures 2 and 9). Typically, the margins of the submarine platforms surrounding the Hawaiian Islands have slope-breaks, marking the most distal shorelines that formed during the shield-building volcanic phase [*Mark and Moore*, 1987]. Gaps in these slope breaks around Niʻihau and Kauaʻi were mapped by *Flinders et al*. [2010] (Figures 2 and 9a). Around Niʻihau, the volcano's missing eastern paleo-shoreline is the probable location where a large collapse occurred [*Stearns and Macdonald*, 1947]. Most of Niʻihau's southeast shoreline, however, is probably intact and can be traced to a point just below the most western extent of Kauaʻi southern shoreline (Figure 2). Thus, in order for material from eastern Niʻihau to be part of SKS, a collapse would have had to occur early enough in Niʻihau's shield stage for the southeast shoreline to rebuild (Figure 10a). About half of the dated samples from SKS are old enough (4.3–5.4 Ma) to have come from the Niʻihau shield (4.3–6.3 Ma; [*Sherrod et al*., 2007]), however, the other half of the dated SKS tholeiites are probably too young (3.9–4.2 Ma).

[36] A generous estimate for the volume of missing material from east Niʻihau is 10^3 km^3 (dimensions of ∼35 km N-S along the paleo-shorelines east of Niʻihau, ∼35 km between Niʻihau and Kauaʻi, and 1 km in average thickness). This estimate is only 17% of the volume of SKS above the in-filled moat sediments (Table 3). This discrepancy is aggravated by the fact that it is impossible for all of east Niʻihau to have collapsed to the SSE (Figure 10a): the southeast flank may have, but not the northeast flank. Hence, only about half of Niʻihau's missing flank potentially could have contributed to the SKS. Furthermore, the prominent, eastward-dipping scarp on Niʻihau's northeast flank suggests that the landslide from this area traveled to the east (and now underlies or is part of Kauaʻi [*Flinders et al*., 2010], or to the northeast, forming the debris field presently located north of Kauai [*Moore et al*., 1989] (Figures 10a and 10b). Therefore, it is unlikely that east Niʻihau contributed significantly to the volume of SKS.

[37] This leaves Kauaʻi as the main landslide source. Indeed, a ∼30 km wide gap in Kauaʻi's southern paleo-shoreline (Figures 2 and 9a) indicates that a portion of south Kauaʻi has experienced mass wasting. To evaluate whether the missing volume of Kauaʻi's south flank matches that of the inferred debris deposits, we reconstructed the area of the SKS prior to the hypothesized landslide. This was done following the methods of *Satake et al*. [2002]. First, the bathymetry points within the SKS border were deleted from the bathymetry grid. Second, several control contours were placed across the gap in data points, connecting with the real contours on either side of the SKS. The location of the pre-SKS shoreline was estimated by visually interpolating a smooth arc through the gap in the paleo-shoreline. Third, from the data surrounding the gap and the control points within the gap, a smooth surface was interpolated to fill the gap. The interpolation was done using the "surface" routine of the GMT software package [*Wessel and Smith*, 1995], which computes a continuous curvature spline in tension. The tension parameter was varied in numerous runs until a geomorphologically reasonable preswell surface was attained (Figure 9b).

[38] Subtracting the bathymetry of the reconstructed seafloor from the present-day bathymetry yields a volume of landslide debris of 2.9 x 10^3 km^3 (i.e., the volume SKS as landslide above the infilling moat sediments if their surface shoaled toward Kauaʻi, rather than remained flat at 4.6 km as assumed for method 1). The missing volume of Kauaʻi's flank is computed based on the difference in topography between the reconstructed and present-day flank (between Kauaʻi and the northern boundary of the SKS, mark in red in Figures 9a and 9b), and is ∼84 km^3. This missing volume from south Kauaʻi represents only 3% of the inferred volume of the debris.

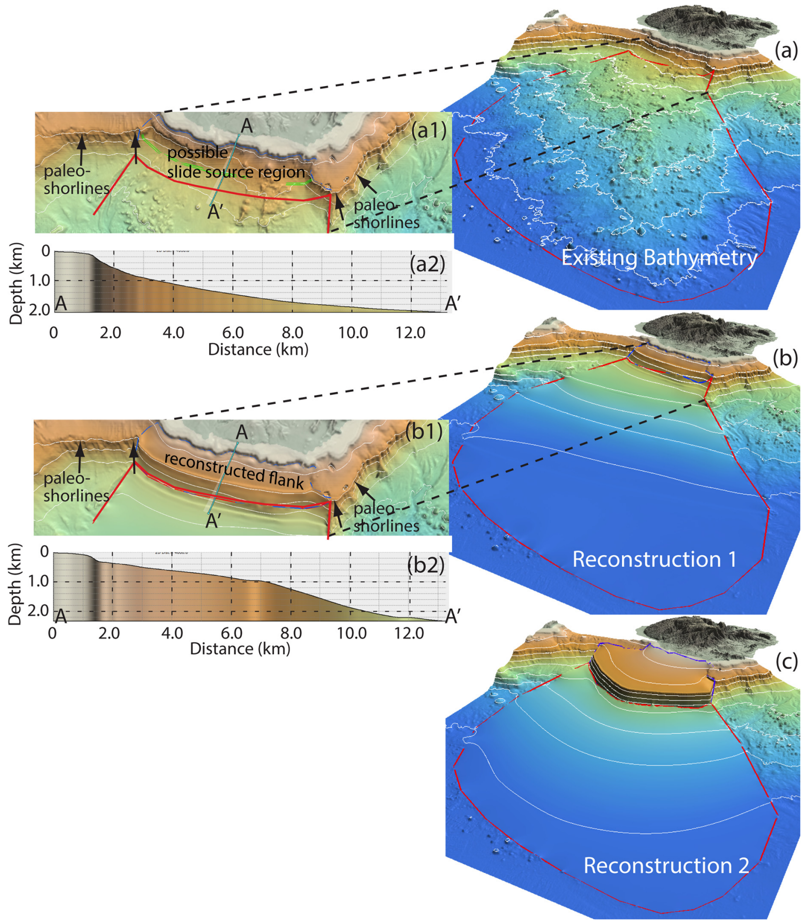

Figure 9. Perspective views of (a) existing bathymetry (b) reconstructed bathymetry in the absence of SKS, with Kaua'i's paleo-shoreline interpolated between the identified paleo-shorelines (Figure 2), and (c) reconstructed bathymetry with Kaua'i's paleo-shoreline protruding southward so that it would account for the full volume of the SKS above the shown abyssal seafloor. Contour interval is 0.5 km and vertical exaggeration is 3 : 1 (a1) Close-up and (a2) profile (location marked by A-A' of inset map) of Kaua'i's existing southern flank. (b1) Close-up and (b2) profile of Kaua'i's southern flank reconstructed in (b). No vertical exaggeration in (a2) and (b2).

[39] To adequately account for the volume of the SKS by a landslide, the prefailure shoreline along Kauai's south shore would have to display a far different and geologically problematic morphology (Figure 9c). The prefailure shoreline would need to protrude 30–40 km south of Kaua'i's current shoreline. While such a protrusion could have represented a broad rift zone extending from the Kaua'i shield volcano, land and marine gravity surveys on south Kaua'i [*Flinders et al.*, 2010] show no evidence for the remnants of dense cumulate material within the core of the rift zone as is detected beneath other Hawaiian rift zones [*Kauahikaua et al.*, 2000]. Instead, the observed gravity anomaly decreases continuously from a peak value near the center of Kaua'i, southward through Kaua'i's southern shore, and reaching a minimum in the area of the hypothetical protrusion in this geologic reconstruction (Figure 5). The crust below the area of the hypothesized protrusion has a low, rather than a high density. In addition, generating SKS from such a protrusion requires most of the debris to have travelled south and southeast, roughly parallel to the long axis of the protrusion. This behavior is counter that of most known flank failures, whereby the run-out tends to be perpendicular to established rift zones [*Swanson et al.*, 1976; *Moore et al.*, 1989; *Smith et al.*, 1999].

[40] Another possibility that would not require such a large protuberance invokes one or more landslides that incised deeper into the interior of the island and removed a wider portion of Kaua'i's south flank (Figure 10b). Subsequent to these events, the same flank would have been reconstructed by

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volcanism, a new paleo-shoreline would have formed, and then one or more small landslides would have created the present-day gap in the paleo-shoreline. Temporally, the main landslide(s) must have occurred late enough during shield-building to construct a sufficient volume, but early enough for subsequent volcanism to rebuild Kauai's south flank and create the island's roughly circular planform that exists today. A difficulty with this premise is that the overlap in ages between the SKS tholeiites (3.9–5.4 Ma) and the Kauaʻi shield stage (3.6–5.1 Ma) allows for little time for the hypothesized reconstruction. Such a massive reconstruction of the south flank of Kauai has also not been recognized in the geology of Kauaʻi [*Garcia et al.*, 2010], although a structural trough did form on the southwest flank of Kauaʻi near the end of shield volcanism (~4.0 Ma [*Macdonald et al.*, 1960]).

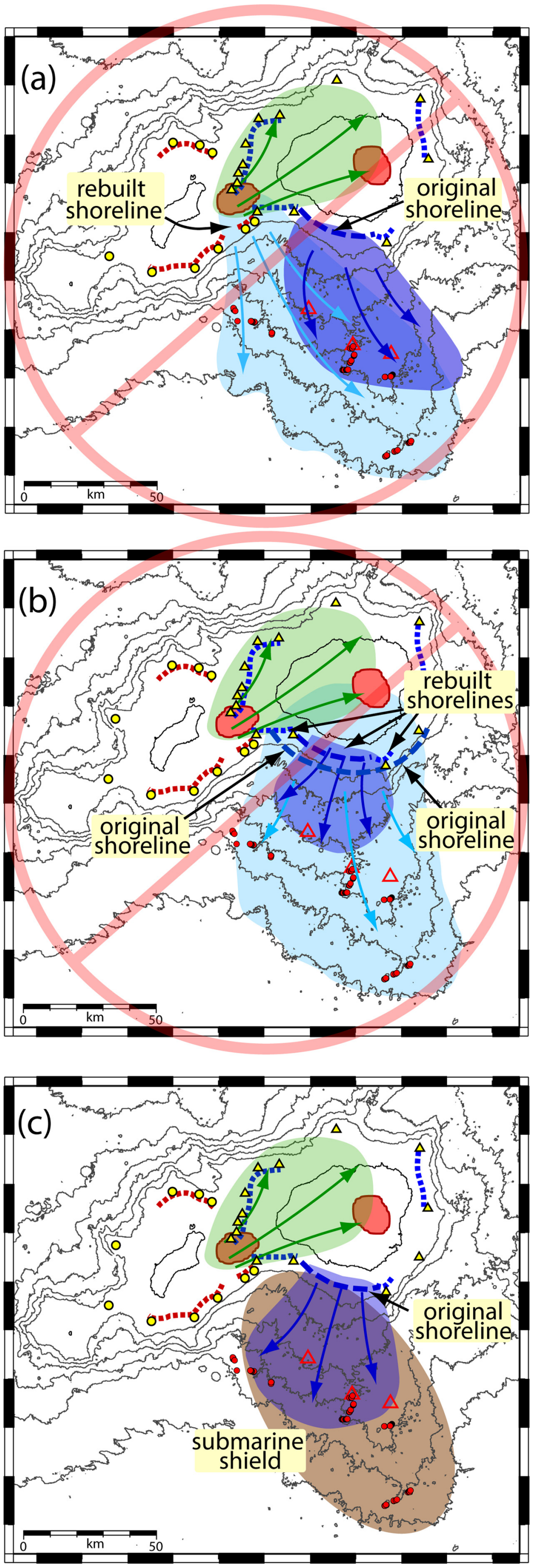

Figure 10. Illustrations of hypothesized origins of the SKS overlain on existing bathymetry (contoured at 500 m). Small red symbols mark sample locations as in Figure 2. Large red ovals mark gravity highs over the inferred magmatic centers of Kauaʻi and Niʻihau [*Flinders et al.*, 2010]. Small yellow symbols and short dashed curves show mapped slope breaks, interpreted as paleo-shorelines of Niʻihau (red) and Kauaʻi (blue) [*Flinders et al.*, 2010] (see also Figure 2). Long dashed curves are hypothetical paleo-shorelines that have been destroyed by landslides on the south flank of Kauaʻi. (a) SKS is composed of approximately half of the collapsed mass of east Niʻihau (light blue), overlain by debris from Kauaʻi's missing southern paleo-shoreline (dark blue). The other half of Niʻihau's east flank collapsed northeast (light green) (b) SKS is composed of deposits from a massive sector of the south flank of Kauaʻi (light blue). Kauaʻi's southern flank was then rebuilt by volcanism, and later experienced a small collapse on to the SKS (dark blue). Figures 10a and 10b are unlikely as discussed in the text. (c) Most likely, the SKS is an elongate, low-relief shield volcano that never reached sea level (light brown). It was later partly covered with the small volume of debris from Kauaʻi's missing southern paleo-shoreline (dark blue).

[41] Ultimately, the most fundamental problem for a landslide origin of the SKS is the lack of a suitable source region. It would be extremely incongruous for one of Earth's largest submarine landslides to have its amphitheater scar almost completely filled by subsequent volcanism. In summary, the lack of a source, the large size of the SKS, and the deviations in morphology from other submarine debris avalanches and slumps lead us to conclude that the main volume of SKS is probably not a landslide deposit.

8.3. The SKS as a Low-Relief Shield Volcano

[42] An alternative origin for the SKS is a low-relief shield volcano. Perhaps most contradictory to

a shield origin, is the evidence provided by the geology, vesicularity, and irregular age distribution for widespread mass wasting. A massive landslide origin is a simple explanation, but an alternative explanation is one or more relatively small landslides from Kaua'i's missing southern shoreline, which veneered a large area of a SKS shield volcano. Ambiguous evidence for a shield origin includes the geochemistry (Figures 6 and 7) and the range of ages (Figure 8) obtained from the SKS. These data are consistent with either a massive landslide from Kaua'i, or a separate shield of similar composition and age to Kaua'i, perhaps partially overlain with a small amount of material from Kaua'i.

[43] Weakly supportive of a low-relief shield is the residual gravity anomaly. On one hand, the lack of a strong positive residual gravity anomaly over the SKS (Figure 5) could be consistent with a landslide origin. While on the other hand, this finding is also consistent with a low-relief shield volcano, in which magmatism was not strongly focused to a central accumulation zone but was instead more distributed. A more distributed magmatic plumbing system, in fact, may be expected for such a broad, low-relief volcano. Mahukona is a taller, but still low-relief feature that also does not display a large gravity high over its summit [*Garcia et al.*, 2012] (the gravity high over the southern part of Mahukona (Figure 5) is largely attributed to a submarine extension of Hualalai's rift zone). The negative gravity anomaly separating the high over Kaua'i from the low-amplitude high over the SKS is, again, difficult to explain with a landslide origin. Instead, this observation is consistent with Kaua'i's south flank being composed of low-density debris from Kaua'i, and most of the volume of SKS comprising higher-density, intact lava due to shield volcanism.

[44] The most supportive evidence of a shield origin is the overall morphology and size. This evidence includes the smooth long-wavelength topography, convex surface, and large continuous height of the SKS, which resembles parts of Ka'ena Ridge and Mahukona (Figures 1 and 4). The ~14 x 10^3 km^3 volume of the hypothesized SKS shield volcano as measured from the top of the pre-existing seafloor is comparable to some small Hawaiian volcanoes (e.g., Mahukona, 13 x 10^3 km^3 and Ka'ena Ridge, ~15 x 10^3 km^3 from Table 3; West Maui, 9 x 10^3 km^3 and Hualalai 15 x 10^3 km^3 from *Robinson and Eakins* [2006]). The proposed SKS volcano is lower in relief than the other Hawaiian volcanoes but higher than the South West O'ahu Volcanic Field (SWOVF).

[45] The existence of a SKS shield would also reduce the large distance between adjacent shield volcanoes represented by Wai'anae and Kaua'i. Without a SKS shield, the spacing between the centers of Wai'anae and Kaua'i is ~140 km or nearly twice the typical spacing of 72±37 km between adjacent Hawaiian shield volcanoes [*ten Brink*, 1991]. With the SKS shield, the average spacing between the three shields is closer to the typical spacing (average of ~90 km with ~130 km between the SKS and Wai'anae and ~50 km between SKS and Kaua'i). If Ka'ena Ridge is also a separate volcano, the average spacing between the four volcanoes also fits with the typical spacing (average of ~63 km based on distances of ~50 km, ~100 km, ~50 km for Wai'anae-Ka'ena, Ka'ena-SKS, SKS-Kaua'i, respectively).

[46] In summary, although there is no evidence requiring a shield origin, this explanation has the least profound contradictions with observations and employs the most straightforward geologic processes as presently understood. We therefore suggest that a low-relief shield is the most likely origin for the major (>90%) volume of the SKS.

[47] Figure 10c illustrates the model of most of the SKS forming as low-relief shield volcano. This model has the construction of the SKS shield (3.9–5.4 Ma, Tables 1 and 2) overlapping with the mid-to-late shield phase of Ni'ihau (4.3–6.3 Ma; *Sherrod et al.* [2007]) and the shield phase of Kaua'i (4.0–5.1 Ma; *McDougall* [1979]; *Garcia et al.* [2010]). The SKS shield was later partially overlain by a small volume of debris from Kaua'i, as indicated by the gap in Kauai's southern paleoshoreline. These debris contributed to some of the topography between the SKS and Kaua'i and to the negative residual gravity in this area. Finally, a few monogenetic, alkalic seamounts formed between 1.9 and 0.2 Ma during a secondary volcanic phase.

[48] As a shield volcano, the SKS would be very unusual on Earth given the combination of its appreciable area (6700 km^2), low relief (2–2.5 km) and thus low slope (< 1.5°, Figure 4). By comparison, Mauna Loa on the Island of Hawaii has slopes of 5–10° on land and slopes up to 18° offshore. Iceland is well known for having a number of small, low-slope volcanoes (29 documented by [*Rossi*, 1996] with a median slope of 2.7°).

These Icelandic volcanoes, however, are much smaller (diameters of 0.5–11 km, heights of 12–520 m) and monogenetic, thus probably representing a different type of volcano than a SKS shield, the latter of which presumably would be composed of many eruptive events. The feature most similar to the SKS that we know of on Earth is the SW O'ahu Volcanic Field (slope ~0.5°), whereas the areally extensive lava flows north of O'ahu and southeast of the Island of Hawai'i [*Lipman et al*., 1989; *Clague et al*., 1990] may represent the most extreme examples of volcanism over a broad area with little, or in this case, no relief.

[49] While unusual for Earth, large shield volcanoes with such low slope, in contrast, are more common on other planets. The largest shield-like edifices on Venus, for example, have lateral dimensions (hundreds of km) a few times greater than the SKS, and slopes (< 1°–3°) [*Stofan et al*., 2001] comparable to the SKS. On Mars, the tallest volcanoes are much steeper than the SKS, but at least twenty Martian volcanoes have areas of the same order (10^3 km^2), and slopes much lower than the SKS [*Baratoux et al*., 2009]. A swarm of about 30 volcanoes on Syria Planum, identified by *Baptista et al*. [2008], have smaller areas (80–1400 km^2) than, but comparable slopes (0.2°–1°) to the SKS. This comparison leads us to question whether there are some general physical conditions promoting the formation of broad, low-slope shields that occurred on Mars and Venus, were active at the Hawaiian hotspot during the creation of the SKS, but otherwise rarely occur on Earth. That said, few terrestrial oceanic volcano chains are as well surveyed as the Hawaiian Islands, so there may be other edifices like SKS that are as yet not recognized. A shield origin for the SKS would imply that shield volcanism in Hawaii, and on Earth in general, spans a range of sizes and shapes from the large island-building shields, to smaller edifices protruding from the islands such as Mahukona and Ka'ena Ridge, and finally, to even lower-relief volcanoes represented by the SKS and possibly the SW O'ahu Volcanic Field.

9. Conclusions

[50] The SKS is a 110 km x 80 km ovoid bathymetric feature with a convex surface, punctuated with numerous small (<1 km wide) seamounts. Most of the SKS has a low acoustic backscatter indicating relatively thick sediment cover as confirmed by JASON dive images. The residual gravity over SKS is negative on the very northern part of the SKS and neutral or slightly positive over the central portion. Lavas from two of the seamounts sampled are alkali basalts with ages of 0.2–1.9 Ma, and thus represent a phase of secondary volcanism. The majority of the SKS samples are tholeiitic and have ages of 3.9–5.4 Ma, which are coeval with Ni'ihau's mid-to-late shield phase and Kaua'i's shield phase. The SKS tholeiites have $^{87}Sr/^{86}Sr$ and $^{206}Pb/^{204}Pb$ compositions similar to those of Kaua'i, West Ka'ena, and Wai'anae.

[51] A landslide origin, as originally proposed, is problematic. Morphologically, the SKS is unlike any other landslide of comparable size. The most profound discrepancy is that the estimated volume of SKS above the surrounding seafloor (6 x 10^3 km^3) is greater than almost all other estimates for landslides on Earth, however, there is no obvious source region that could have housed this enormous volume. A landslide origin of SKS requires subsequent shield volcanism to nearly completely fill the scar of a massive sector collapse and to construct Kaua'i's circular planform—a requirement that is in conflict with the overlap in ages of Kaua'i and the SKS tholeiites as well as the lack of geologic evidence on Kaua'i for a major sector collapse.

[52] Among the three hypotheses that were evaluated for the origin of the SKS, the low-relief shield volcano model most readily explains the geomorphologic and geophysical evidence. The shield was later mantled by mass wasting events from Kaua'i, which created the gap in the southern paleo-shoreline. Subsequently, a few isolated secondary volcanic seamounts formed on the SKS, further complicating its geologic history. The large area and low slope of the SKS make it a rather unusual terrestrial shield volcano, although not unlike many volcanoes on Venus and Mars.

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