Structural and petrologic evolution of the Lihue basin and eastern Kauai, Hawaii

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ABSTRACT

The topography of the eastern part of the Hawaiian island of Kauai is dominated by the Lihue basin, a large (~110 km^2) semicircular depression bounded by steep cliffs and partly filled by late rejuvenated-stage (or post-erosional stage) volcanic material. As with other large, semicircular basins on ocean-island volcanoes, the subsurface geology and origin (e.g., structural collapse vs. fluvial erosion) of the Lihue basin are poorly understood. New analyses of samples collected from eastern Kauai and drill holes within the basin document several important features of the late-stage geologic evolution of Kauai. First, thick (>300 m) sequences of rejuvenated-stage Koloa Volcanics in the Lihue basin show systematic, basin-wide geochemical trends of increasingly incompatible elements with time, indicating a gradual decrease in the extent of partial melting of mantle sources with time. Second, beneath the rejuvenated-stage volcanics in the basin, a thin layer of postshield alkalic stage lavas (e.g., hawaiites and mugearites) overlies older shield-stage tholeiitic lavas of the Napali Member, indicating that the Lihue basin formed by structural collapse, not fluvial erosion. Third, a large (~2–5 km^3) matrix-supported breccia, interpreted as deposits of one or more debris flows, is within the rejuvenated-stage volcanics throughout the basin, and correlates with surficial exposures of the Palikea Breccia west of the basin. Isotopic compositions of the bulk breccia are similar to those of tholeiites from the east side of Kauai, and distinct from those of west Kauai tholeiites. Clasts within the breccia are dominantly hawaiite and alkali gabbro. The source region of the breccia in the steep cliffs and highlands of the central massif to the west of the basin must contain magmatic products of an extensive postshield alkalic stage, including hawaiite flows and one or more large intrusive bodies or ponded sequences of alkali gabbro.

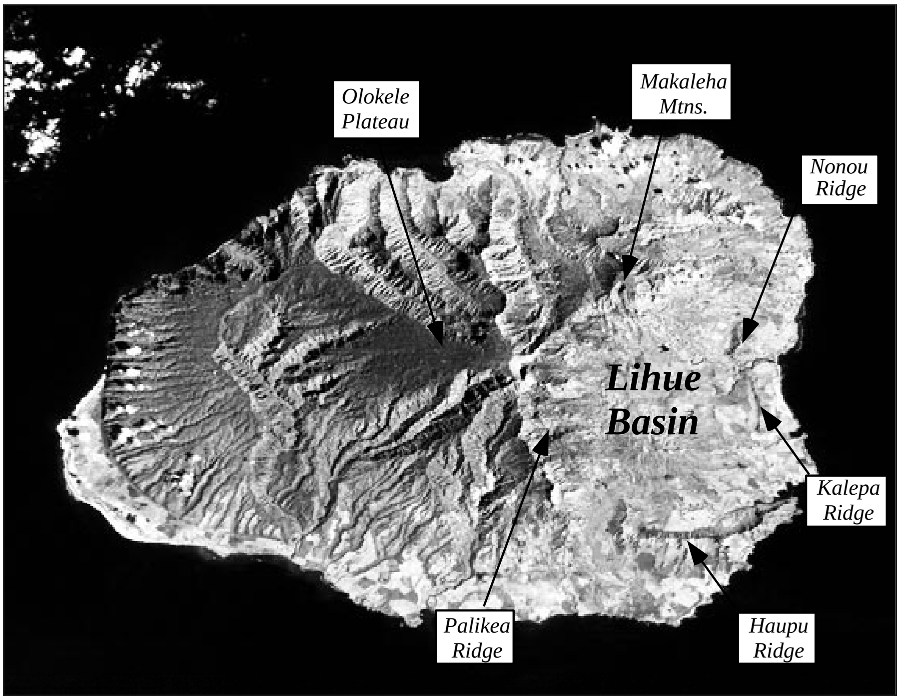

Figure 1. Landsat multispectral scanner image of Kauai taken in 1978, provided courtesy of NASA's Virtually Hawaii project, sponsored by the Hawaii Space Grant Consortium. The flat, low-lying, semicircular area on the eastern side of the island is the Lihue basin. The high cliffs on the western margin of the basin are the eastern side of the central massif, including the peaks of Kawaikini and Waialeale. The large rejuvenated-stage volcanic vent, Kilohana, can be seen in the middle of the Lihue basin. Also note the two small ridges on the eastern margin of the basin (Kalepa and Nonou Ridges), the Haupu Ridge to the south, and the Makaleha Mountains, with the summit plateau, to the north of the basin. For latitude and longitude, see Figure 2.

INTRODUCTION

The Lihue basin of eastern Kauai is a large (~110 km^2) topographic depression enclosed by steep-walled cliffs to the west and open to the east (Figs. 1 and 2). Such U-shaped basins are common features of ocean-island volcanoes, including those in Hawaii, Réunion, and

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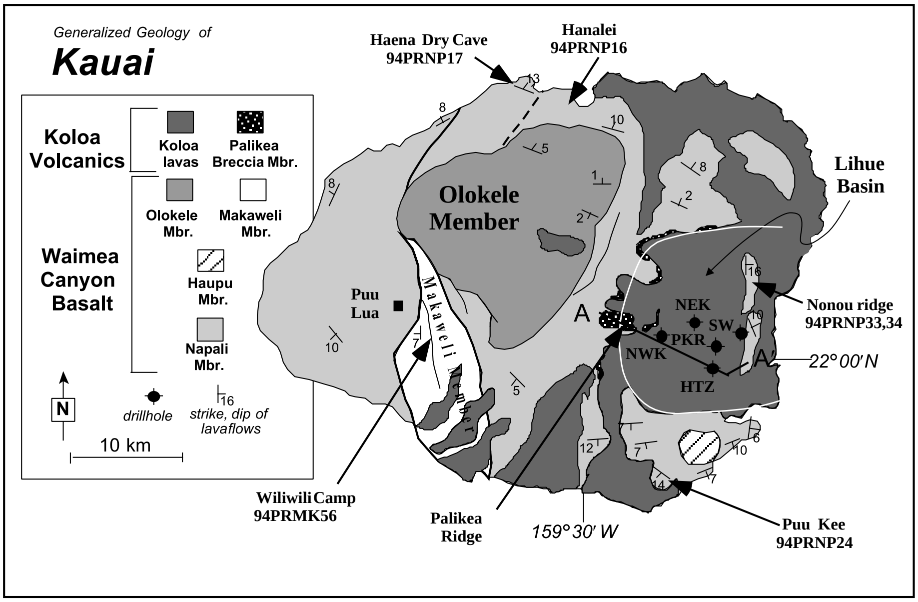

Figure 2. Generalized geologic map of Kauai (after Macdonald et al., 1960; Clague and Dalrymple, 1988) showing the primary lithologies and locations of the drill holes and other sample locations in and around the Lihue basin. A generalized cross section through the trace of A–A′ is shown in Figure 5.

the Canary Islands, and have been interpreted both as remnant calderas (Stearns and Vaksvik, 1935; Marti et al., 1996) and as downdropped blocks resulting from giant landslides or slumps (Presley et al., 1997; Gillot et al., 1994; Carracedo, 1994, 1996; Gillot and Nativel, 1989; Watts and Masson, 1995; Holcomb and Searle, 1991; Lénat et al., 1989; Duffield et al., 1982). The origin of the Lihue basin is particularly enigmatic because of the enormous topographic relief (as much as 1 km) on its western margin and the presence of a positive Bouguer gravity anomaly (generally observed at shield volcano summit calderas) in the northwest part of the basin (Krivoy et al., 1965), which is offset from the inferred central summit caldera about 20 km northwest of the middle of the basin (Macdonald et al., 1960). We present stratigraphic and geochemical results from sections and samples from the margins of the basin and from deep (>300 m) drill holes in the central and southern part of the basin that reveal several important features of the geologic and petrologic evolution of eastern Kauai. In particular this work shows that (1) lithostratigraphic evidence supports an origin by large-scale structural collapse (not fluvial erosion) for the Lihue basin; (2) clasts from a thick debris-flow layer in the basin suggest that the center of the island contains a large quantity of intrusive or slowly cooled rocks of a postshield alkalic volcanic stage more voluminous than previously recognized; and (3) temporal-compositional trends in the rejuvenated-stage lavas in the basin (not previously observed in rejuvenated-stage volcanic rocks from any Hawaii volcano) suggest a long-term, systematic decrease in extent of partial melting through the rejuvenated volcanic stage.

GEOLOGY OF KAUAI AND THE LIHUE BASIN

Kauai is the second oldest and northernmost of the main Hawaiian islands, and has generally been interpreted as the eroded remnants of a single large shield volcano (Dana, 1849; Hinds, 1930; Macdonald et al., 1960), the main shield-building stage of which lasted from before about 5.1 Ma to about 4.0 Ma (McDougall, 1979; Clague and Dalrymple, 1988). The lavas that compose the island have been divided into two main stratigraphic groups: the older Waimea Canyon Basalt, comprising tholeiitic and a few rare hawaiitic and mugearitic lava flows, and the rejuvenated-, or posterosional-, stage Koloa Volcanics, comprising highly alkalic, primitive lavas and related volcanic rocks (Fig. 2) (Macdonald et al., 1960; Clague and Dalrymple, 1988). The older Waimea Canyon Basalt is further subdivided into four members, the oldest and most widespread of which is the tholeiitic lavas of the Napali Member. The Haupu, Makaweli, and Olokele Members are primarily younger lavas that apparently ponded within enclosed or partially enclosed structural features. The thick, flat-lying tholeiitic lava flows of the Haupu Member are restricted to a small (~1.6 km^2), ovoid, fault-bounded structure in the southeast corner of the island that has generally been interpreted as a flank caldera or pit crater (Macdonald et al., 1960). The Makaweli Member is predominantly tholeiitic lavas, with two capping flows of hawaiite and mugearite (Clague and Dalrymple, 1988), all of which apparently ponded in a graben-like depression in the southern part of the island. The Olokele Member is also composed of dominantly tholeiitic lavas with one known hawaiite flow, and includes a thick section of flat-lying, apparently ponded lavas in the central part of the island. The inferred structural feature that bounds the Olokele Member is interpreted as a lava-filled summit caldera (Macdonald et al., 1960). The three hawaiite and mugearite lavas in the Olokele and Makaweli Members represent the only previously known lavas of the postshield alkalic stage on Kauai, and have ages of about 3.9 Ma (Clague and Dalrymple, 1988). The rejuvenated-stage Koloa Volcanics represent the latest volcanism on Kauai, and consist of alkalic basalt, basanite, nephelinite, and melilitite lavas and tuffs erupted primarily in the central and eastern parts of the island (Macdonald et al., 1960; Clague and Dalrymple, 1988; Maaløe et al., 1992). Radiometric ages of lavas of the Koloa Volcanics range from about 0.5 to 3.6 Ma; lavas from the eastern part of the island are younger than 1.5 Ma (Clague and Dalrymple, 1988).

Kauai is distinct from other Hawaiian shield volcanoes in the abundance and scale of observed and inferred large faults and structural-topographic features. The caldera inferred from the distribution of thick, flat-lying flows of the Olokele Member is more than 21 km in diameter, which would make it by far the largest in the Hawaiian islands. North-south–trending normal faults bisect the western part of the island, delineating both the Makaweli graben in the south, and a scarp, at least 800 m high, against which younger flows ponded in the northwestern part of the island (the Kalalau fault, Macdonald et al., 1960). GLORIA side-scan sonar imagery indicates the presence of at least two large debris fields on the north, south, and possibly east sides of the island, resulting from giant landslides (Moore et al., 1994). All of these structural-topographic (and bathymetric) features indicate a geologic history of the island that may be more complicated than previously recognized. Recent work has established that Sr, Nd, and Pb isotope compositions of tholeiites on the east and west sides of Kauai are distinct, which has been used in conjunction with structural and paleomagnetic arguments to suggest the presence of two distinct shield volcanoes on the island (Holcomb et al., 1995, 1997). Clague (1996) also interpreted Kauai as two distinct shield volcanoes, based on bathymetric interpretations of multiple rift zones radiating from either the western or eastern parts of the island.

The Lihue basin, on the eastern side of Kauai, is a broad, low-lying area of ~10 km^2 with an average elevation about 100–120 m above sea level (Figs. 1 and 2) on the eastern side of Kauai. It is filled by lava flows of the Koloa Volcanics and bounded by steep cliffs of the Waimea Canyon Basalt on the west, north, and south sides. At the western margin of the basin, steep cliffs of the central massif of the island rise abruptly from the basin floor to nearly 1600 m above sea level, supporting the highest points on the island. The northern margin of the basin is bounded by the Makaleha Mountains, which are topped by a plateau about 1000 m above sea level that has been interpreted as an erosional remnant of an ancient shield surface (Macdonald et al., 1960). The south side of the basin is bounded by tholeiitic lavas of the Haupu Ridge, including the Haupu Member, consisting of thick, flat-lying flows interpreted to be a pit crater or caldera. The Haupu Member is covered by alluvium on its north side, toward the Lihue basin. The eastern boundary of the Lihue basin is less clear. Some workers place the edge of the basin at the base of two small ridges (Kalepa and Nonou Ridges, at 215 and 320 m above sea level) near the eastern edge of the island. But these ridges are discontinuous to the north and south, and the Lihue basin could also be interpreted as open to the sea on its eastern side. The southern ridge (Kalepa) has a distinctly curvilinear north-south trend, concave to the west, suggestive of caldera-boundary morphology. Both the Kalepa and Nonou Ridges comprise tholeiitic lava flows typical of the Napali Member, but these flows have unusual orientations, dipping as steeply as 16° to the east (Macdonald et al., 1960).

The surface of the Lihue basin is covered mostly by lava flows of the Koloa Volcanics, some of which probably originated from the Kilohana volcano, a large rejuvenated-stage vent in the central-southern part of the basin that reaches an elevation of 320 m above sea level, about 220 m above the surrounding plains to the north, east, and south. In most places on the west and north sides of the Lihue basin, tholeiitic flows of the Napali Member and alkalic lavas of the Koloa Volcanics are separated by a thick layer of massive, unsorted breccia. Macdonald et al. (1960) defined any breccia or conglomerate interbedded with, or directly underlying, the Koloa Volcanics as the Palikea Formation; Langenheim and Clague (1987) reduced the rank of the unit and renamed it the Palikea Breccia Member of the Koloa Volcanics. The Palikea Breccia on the west margin of the Lihue basin is an unsorted, matrix-supported breccia and contains a variety of clast sizes and lithologies (discussed in the following). The type section of the breccia facies of the Palikea Breccia Member is the Palikea Ridge, near the western margin of the Lihue basin, and is at least 213 m thick. The Palikea Breccia Member on the western margin of the Lihue basin is distinct from Palikea exposures elsewhere on Kauai, which are most commonly clast-supported conglomerates and much thinner (less than 40 m thick).

SAMPLE LOCATIONS AND ANALYSES

We collected and analyzed samples from five drill holes within the Lihue basin, as well as from subaerial outcrops in eastern and central Kauai (Fig. 2). The drill holes, which were constructed for ground-water exploration, recovered samples in the form of cuttings averaging 0.5–3 cm in diameter, every 1.5 m, to depths of 300–350 m. Cuttings from selected depths in five drill holes, the northwest Kilohana, northeast Kilohana, Puakukui Reservoir, south Wailua, and Hanamaulu Town, were analyzed for major element compositions in order to determine lithology and construct a stratigraphic section for the Lihue basin. Samples from the Hanamaulu Town drill hole were also collected at denser stratigraphic intervals and analyzed for trace element and isotopic compositions; these analyses appear in full in a complementary paper (Reiners and Nelson, 1998), but major element analyses and stratigraphic inferences from the Hanamaulu Town drill hole are shown in the figures in this study for completeness. Samples chosen for analyses from the drill holes were hand-picked cuttings averaging 0.5–3 cm in diameter. Little vertical mixing between cuttings was evident from the lithologic homogeneity of the majority of sample splits, including those adjacent to lithologically distinctive layers such as shell- and coral-rich layers, as well as from stratigraphic compositional and isotopic trends that are opposite to the expected effects of vertical mixing. Where splits did contain a minority of lithologically distinct fragments, cuttings of the dominant lithology were selected for analysis.

We also collected and analyzed three subaerial samples from the type section of the Palikea Breccia Member, at Palikea Ridge, on the west side of the Lihue basin (Table 1). These samples include two of the dominant and distinct types of clasts within the breccia and one sample of matrix (here defined as those parts of the rock in which individual clast sizes are less than about 1–2 mm in diameter). Sr and Nd isotope compositions of samples from the Hanamaulu Town drill hole and from subaerial samples collected in various parts of the island were also determined and have been included to aid the interpretation of the provenance of Palikea Breccia Member samples (Table 2).

Major element analyses were performed by X-ray fluorescence spectrometry at CHEMEX (Vancouver, Canada) laboratories; analytical precision is better than 0.5%. The Sr and Nd isotope analyses on acid-leached subsamples were conducted at the University of Washington using procedures described in Nelson (1995). See Table 2 for further analytical details.

RESULTS

Lihue Basin Drill-Hole Samples

A combination of compositional and textural criteria was used to distinguish lithologies of samples recovered from the drill holes (Table 1, Fig. 3), primarily emphasizing the distinctions between tholeiitic lavas of the Waimea Canyon Basalt (which have relatively high SiO_2 and low alkalis), alkalic and primitive lavas of the rejuvenated-stage Koloa Volcanics (with low SiO_2, high MgO and CaO, and relatively high alkalis), and lavas of the postshield alkalic stage (relatively high alkalis and low MgO). Lithologic distinctions within the postshield alkalic-stage lavas (e.g., alkalic basalt, hawaiite, and mugearite) follow the nomenclature of Le Bas et al. (1986). Samples with alkalic basalt compositions and gabbroic or doleritic textures are referred to as alkali gabbros. Where we distinguish between lithologies of the Koloa Volcanics, we use the modal classification used by Clague and Dalrymple (1988), in which rocks with modal plagioclase but no nepheline are referred to as alkalic basalt, rocks containing modal nepheline and plagioclase are referred to as basanite, and rocks with modal nepheline but no plagioclase are referred to as nephelinite.

Low-Temperature Alteration. Many of the drill-hole samples, especially samples of breccia or alluvial layers, show evidence of considerable low-temperature alteration; the matrix of some samples contains a fine-grained green clay, and some phenocrysts have been replaced by iddingsite or other clay minerals. This alteration is reflected in high loss on ignition (LOI, Table 1) in major element analyses, typically between 2 and 8 wt% (although some breccia samples have >10 wt% LOI), the result of high H_2O contents in clay, serpentine, or other low-temperature minerals in many of the samples (compositions reported in Table 1 are normalized to a volatile-free basis). Samples of breccia and alluvial layers are more highly weathered than other samples from the drill holes (higher LOI), and some breccia samples have high TiO_2, P_2O_5, and total iron contents, and low CaO and SiO_2, which are unusual in Hawaiian lavas, and probably reflect extensive alteration rather than primary lava compositions. Although samples of the Koloa Volcanics are less

TABLE 1. MAJOR ELEMENT COMPOSITIONS OF LIHUE BASIN DRILL HOLE AND PALIKEA RIDGE BRECCIA SAMPLES

Sample locality	Sample name	Depth (m)	Unit or lithology	SiO_2	Al_2O_3	Fe_2O_3*	Cr_2O_3	MgO	CaO	MnO	Na_2O	K_2O	TiO_2	P_2O_5	LOI
NEK Drill hole	95NEK335	102.1–103.6	Breccia	50.09	12.43	16.17	0.12	9.95	6.49	0.29	1.00	0.32	2.87	0.27	12.93
	95NEK395	120.4–121.9	Breccia	50.17	12.16	13.36	0.09	11.53	8.26	0.19	1.33	0.28	2.41	0.23	8.22
	95NEK445	135.6–137.2	Koloa	42.54	9.90	15.47	0.06	15.10	11.95	0.20	0.90	0.45	2.93	0.50	6.24
	95NEK495	150.9–152.4	Koloa	42.94	10.94	14.10	0.05	14.16	13.10	0.18	0.90	0.35	2.61	0.67	6.66
	95NEK675	205.7–207.3	Koloa	44.69	11.66	14.08	0.08	11.49	12.73	0.19	1.76	0.82	2.14	0.36	5.08
	95NEK890	271.3–272.8	Koloa	46.93	11.76	13.44	0.07	11.53	11.09	0.17	1.51	0.53	2.49	0.49	6.40
SW Drill hole	95SW135	41.1–42.7	Koloa	43.28	11.61	14.83	0.06	12.15	11.61	0.22	1.96	0.91	2.93	0.45	2.06
	95SW185	56.4–57.9	Breccia	43.66	16.56	17.73	0.09	8.22	8.16	0.18	0.84	0.32	3.69	0.55	11.43
	95SW220	67.1–68.6	Breccia	42.45	18.12	18.77	0.08	7.55	6.59	0.23	1.00	0.53	4.08	0.59	12.75
	95SW255	77.7–79.2	Koloa	42.80	11.83	14.73	0.04	11.81	12.97	0.19	1.43	0.71	2.87	0.61	4.15
	95SW280	85.3–86.9	Koloa	42.48	9.90	15.40	0.07	15.58	11.59	0.20	1.14	0.56	2.75	0.34	2.60
	95SW315	96.0–97.5	Koloa	41.91	10.80	14.85	0.04	12.64	13.17	0.19	1.43	0.78	3.42	0.76	4.05
	95SW385	117.3–118.9	Koloa	45.59	12.22	14.12	0.05	11.24	10.82	0.19	1.72	1.02	2.55	0.48	5.25
	95SW450	137.2–138.7	Koloa	43.17	10.69	14.08	0.07	13.71	12.46	0.18	2.08	0.47	2.57	0.51	4.60
	95SW510	155.4–157.0	Koloa	43.83	11.16	14.48	0.06	12.36	12.58	0.19	1.43	0.75	2.57	0.58	4.95
	95SW585	178.3–179.8	Koloa	43.79	10.85	13.79	0.05	13.24	11.91	0.19	2.40	0.88	2.37	0.54	1.60
	95SW715	217.9–219.5	Koloa	42.68	12.64	15.46	0.08	13.43	11.51	0.20	0.62	0.46	2.52	0.42	8.05
NWK Drill hole	95NWK165	50.3–21.8	Koloa	45.61	11.11	14.11	0.08	13.61	10.34	0.18	1.75	0.74	2.16	0.31	1.50
	95NWK210	64.0–65.5	Koloa	43.18	11.00	15.05	0.05	13.64	11.72	0.21	1.39	0.53	2.76	0.47	2.99
	95NWK265	80.8–82.3	Breccia	41.34	15.56	28.45	0.10	5.60	3.25	0.70	0.12	0.26	4.19	0.43	16.94
	95NWK290	88.4–89.9	Breccia	41.31	11.89	22.81	0.08	9.81	7.22	0.38	0.06	0.13	5.07	1.23	14.47
	95NWK340	103.6–105.2	Koloa	42.58	10.98	14.06	0.06	12.93	12.70	0.19	2.16	0.79	2.96	0.59	2.87
	95NWK405	123.4–125.0	Tholeiite	50.06	12.58	12.87	0.06	9.71	10.00	0.16	1.55	0.21	2.51	0.27	6.30
	95NWK495	150.9–152.4	Tholeiite	50.44	11.52	12.62	0.09	11.53	9.44	0.17	1.55	0.27	2.14	0.23	7.44
	95NWK775	236.2–237.7	Tholeiite	52.15	11.36	12.48	0.06	11.73	7.56	0.17	1.32	0.56	2.34	0.26	12.08
	95NWK920	280.4–281.9	Tholeiite	53.23	12.60	13.88	0.11	10.54	5.44	0.18	1.15	0.25	2.39	0.23	12.11
	95NWK995	303.3–304.8	Mugearite	51.38	20.74	10.44	0.00	1.89	6.11	0.25	3.29	2.47	2.18	1.25	8.51
PKR Drill hole	95PKR155	47.2–48.8	Koloa	43.97	11.96	14.43	0.04	12.06	12.41	0.17	0.71	0.72	3.03	0.49	6.27
	95PKR180	54.9–56.4	Koloa	40.10	9.43	15.99	0.03	15.37	12.76	0.19	0.83	0.41	3.88	1.01	6.41
	95PKR210	64.0–65.5	Breccia	48.42	17.49	19.12	0.13	6.39	3.65	0.19	0.49	0.26	3.61	0.26	15.61
	95PKR255	77.7–79.2	Breccia	45.78	16.17	17.70	0.09	9.57	5.52	0.22	0.75	0.35	3.47	0.36	12.38
	95PKR300	91.4–93.0	Breccia	45.26	15.77	17.92	0.13	10.07	5.82	0.22	0.57	0.32	3.51	0.41	13.14
	95PKR350	106.7–108.2	Koloa	43.42	11.36	15.08	0.04	11.71	10.87	0.19	2.33	1.09	3.21	0.70	2.83
	95PKR375	114.3–115.8	Koloa	44.91	12.44	15.26	0.09	11.25	10.68	0.17	1.27	0.85	2.59	0.49	4.79
	95PKR500	152.4–153.9	Koloa	43.31	10.84	14.36	0.05	13.39	12.30	0.19	1.51	0.86	2.63	0.56	3.28
	95PKR525	160.0–161.5	Koloa	42.90	10.81	14.66	0.06	13.41	12.52	0.19	1.37	0.64	2.80	0.64	4.64
	95PKR695	211.8–213.4	Koloa	42.96	11.31	14.76	0.09	14.20	12.35	0.18	0.79	0.37	2.55	0.44	5.94
	95PKR710	216.4–217.9	Koloa	42.56	11.77	15.18	0.13	12.88	13.07	0.18	0.67	0.30	2.74	0.52	6.93
	95PKR725	221.0–222.5	Koloa	42.28	11.73	15.67	0.10	11.38	13.68	0.19	0.96	0.41	3.02	0.59	8.36
	95PKR900	274.3–275.8	Hawaiite	50.73	15.67	11.20	0.02	4.88	8.25	0.15	3.77	1.61	2.95	0.77	4.69
	95PKR930	283.5–285.0	Alkalic basalt	48.06	15.40	14.36	0.03	6.36	8.03	0.17	2.50	1.17	3.28	0.64	6.32
	95PKR950	289.6–291.1	Alkalic basalt	47.47	15.59	13.98	0.01	7.52	10.42	0.15	1.48	0.52	2.53	0.32	8.15
	95PKR1050	320.0–321.6	Alkalic basalt	46.61	19.56	13.87	0.06	5.98	6.55	0.20	1.76	0.96	3.60	0.86	11.06
	95PKR1075	327.7–329.2	Mugearite	50.91	19.04	10.16	0.01	2.12	6.91	0.26	4.47	2.56	2.20	1.35	5.34
	95PKR1135	345.9–347.5	Tholeiite	51.68	11.92	12.75	0.00	12.72	7.37	0.17	0.80	0.19	2.19	0.21	8.49
HTZ Drill hole (Palikea Breccia only)	95HTZ265	80.8–82.3	Breccia	46.32	10.34	15.37	0.11	15.66	7.93	0.18	1.66	0.19	1.99	0.24	2.10
	95HTZ290	88.4–89.9	Breccia	49.97	13.95	12.53	0.09	7.50	10.06	0.15	2.28	0.28	2.82	0.38	6.15
	95HTZ315	96.0–97.5	Breccia	48.32	10.35	13.15	0.13	15.46	8.34	0.21	1.45	0.35	2.01	0.25	7.38
	95HTZ335	102.1–103.6	Breccia	49.56	11.83	12.58	0.11	11.73	9.00	0.18	1.87	0.42	2.45	0.28	5.54
Palikea Ridge	97PRQKP2	N.A.†	Breccia matrix	49.41	13.33	13.25	0.07	12.21	6.93	0.19	1.30	0.52	2.50	0.29	10.93
	97PRQKP5	N.A.†	Alkali gabbro (clast)	47.56	15.78	12.57	0.01	5.74	9.68	0.13	2.58	1.48	3.77	0.71	4.57
	97PRQKP6	N.A.†	Hawaiite (clast)	50.32	17.19	11.30	0.04	4.17	7.25	0.17	3.73	2.18	2.61	1.05	2.95

Note: All major element oxides reported as wt%, normalized to a volatile- (LOI-[loss on ignition]) free basis. LOI is reported as measure of extent of alteration of sample. NEK—northeast Kilohana; SW—south Wailua; NWK—northwest Kilohana; PKR—Puakukui Reservoir; HTZ—Hanamaulu Town.

*Fe_2O_3 = total iron.

†N.A. = not applicable.

altered than breccia or alluvium, Koloa samples also have unusually low alkalis (particularly Na_2O) compared with other Hawaiian lavas, reflecting alteration (alkalis are preferentially mobilized in Hawaiian lavas during near-surface weathering [e.g., Clague and Frey, 1982]).

Koloa Volcanics. Most Lihue basin samples have compositions typical of the rejuvenated-stage lavas of the Koloa Volcanics (Macdonald et al., 1960; Feigenson, 1984; Clague and Dalrymple, 1988; Maaløe et al., 1992), with low SiO_2 and high MgO, P_2O_5, CaO, and alkalis (Fig. 4). Within lavas of the Koloa Volcanics there appears to be an overall increase in TiO_2 and P_2O_5, and decrease in SiO_2 and Al_2O_3/CaO, with stratigraphic height, in all of the drill holes (Fig. 4). Other major elements, including MgO, show no clear stratigraphic-compositional trends.

TABLE 2. ISOTOPIC COMPOSITIONS OF LIHUE BASIN AND WAIMEA CANYON BASALT SAMPLES

Sample locality	Sample name	Lithology/ formation	$^{87}Sr/^{86}Sr$	2σ	$^{143}Nd/^{144}Nd$	2σ	ε_{Nd}
HTZ drill hole	95HTZ265	Breccia (Palikea)	0.703709	8	0.512912	8	5.34
	95HTZ290	Breccia (Palikea)	0.703748	8	0.512929	13	5.67
	95HTZ315	Breccia (Palikea)	0.703792	8	0.512939	6	5.88
	95HTZ335	Breccia (Palikea)	0.703770	8	0.512921	9	5.52
Wiliwili Camp	94PRMK56	Tholeiite (Makaweli)	0.703699	8	0.512942	6	5.93
Puu Kee	94PRNP24	Tholeiite (Napali)	0.703710	8	0.512943	7	5.94
Nonou Ridge	94PRNP33	Tholeiite (Napali)	0.703826	8	0.512899	8	5.10
	94PRNP34	Tholeiite (Napali)	0.703890	8	0.512889	8	4.89
Haena dry cave	94PRNP17	Tholeiite (Napali)	0.703569	9	0.513001	7	7.08
Hanalei	94PRNP16	Tholeiite (Napali)	0.703623	8	0.512956	8	6.21

Notes: Isotopic analyses performed at University of Washington, using procedures described in Nelson (1995). Subsamples analyzed for isotopes were leached for 2 hr in 6.2 N HCl in an ultrasonic bath to avoid weathering effects on Sr- and Nd-isotope compositions. ε_{Nd} is deviation of $^{143}Nd/^{144}Nd$ from that of inferred bulk earth (0.512638): $\varepsilon_{Nd} = [(^{143}Nd/^{144}Nd)_{sample}/0.512638\text{-}1] \times 10^4$. Analytical error (2σ) of isotopic analyses is ± in last digit of ratio. Long-term reproducibility of Sr and Nd isotopic measurements are 41 ppm and 26 ppm (2σ), respectively. NBS 987 yields an average $^{87}Sr/^{86}Sr$ = 0.710266 (n = 85 over 2 yr) and La Jolla Nd averages $^{143}Nd/^{144}Nd$ = 0.511841 (n = 34 over 2 yr).

Breccia Layer. Between ~55 and 120 m depth, all drill holes contain an ~25–70-m-thick layer of matrix-supported breccia. Approximately 30% of the clasts have a fine- to medium-grained gabbroic texture. Analyzed breccia samples from the drill holes could not be separated according to clast or matrix lithology, and compositions probably represent average compositions of the breccia layer, containing matrix and a variety of clast lithologies. Compositions of samples from the breccia layer are substantially different from Koloa Volcanic lava compositions. Many of the bulk breccia samples have compositions similar to those of Kauai tholeiites (Fig. 3) (Macdonald et al., 1960; Macdonald and Katsura, 1964). Some of the more weathered samples (especially the breccia samples in the south Wailua and Puakukui Reservoir drill holes) have unusual compositions, with high Fe_2O_3, TiO_2, and P_2O_5, and low CaO and SiO_2. These compositions are unlike typical Hawaiian lavas, and probably reflect extensive alteration, also indicated by their deep red color and the presence of significant amounts of clay in some samples. Macroscopic lithologic descriptions from well logs indicate that these breccia layers extend from 62.5 to 134.1 m below the ground surface in the northeast Kilohana drill hole, 56.4 to 94.5 m in Puakukui Reservoir, 64.0 to 111.2 m in Hanamaulu Town, 53.3 to 77.7 m in south Wailua, and 70.1 to 99.1 m in northwest Kilohana. When integrated into a generalized composite stratigraphy for the basin (Fig. 5), these intervals appear to correlate with surface exposures of the Palikea Breccia Member in the Waiahi Stream and at Palikea Ridge, both in the western margin of the basin. Isotopic compositions of samples from this interval in the Hanamaulu Town drill hole are similar to isotopic compositions of tholeiites from eastern Kauai and distinct from those of tholeiites from western Kauai (Table 2, Fig. 6).

Waimea Canyon Basalt. Samples at or near the bottom of two drill holes (Puakukui Reservoir and northwest Kilohana) have compositions very similar to subaerial tholeiite, hawaiite, and mugearite on Kauai (Table 1, Fig. 3). We suggest that these drill holes penetrated through the Koloa Volcanics and into the underlying tholeiitic and postshield alkalic lavas of the Waimea Canyon Basalt (Fig. 5).

Palikea Ridge

The Palikea Breccia Member at Palikea Ridge is a massive, unsorted, matrix-supported breccia at least 213 m thick, with clast sizes ranging from less than 1 cm to more than 3 m in diameter. Large clasts (> 0.5 m) are typically fresh, hard, and fine grained, with a trachytic texture (Fig. 7). They have a large modal proportion (>75%) of elongate, highly lineated lath-shaped plagioclase crystals and rare microcrysts of pyroxene and opaque phases. Smaller clasts (< 0.5 m) are either porphyritic lavas or fine- to medium-grained gabbros (Fig. 7). Porphyritic clasts contain abundant large plagioclase crystals in a groundmass of plagioclase, pyroxene, and opaque phases. Fine- to medium-grained gabbro clasts contain plagioclase, pyroxene, opaque phases, and rare olivine crystals, with very little or no groundmass. Many of the gabbro clasts have a miarolitic structure, as described by Macdonald et al. (1960, p. 101). Major element compositions of breccia from Palikea Ridge indicate that the matrix has a composition similar to tholeiitic basalt; a fine-grained clast has a hawaiite composition, and a fine-grained gabbro clast has the composition of a low-MgO alkalic basalt (Fig. 3).

Subaerial Napali Member Lavas

Isotopic compositions of subaerial samples from east Kauai (Puu Kee and Nonou Ridge) have higher $^{87}Sr/^{86}Sr$ and lower ε_{Nd} than samples from the northwestern (Haena dry cave) and north-central (Hanalei) parts of the island (Table 2, Fig. 6), supporting earlier isotopic work indicating that tholeiites from the eastern side of the island are isotopically distinct from those on the west side (Holcomb et al., 1995, 1997). A single sample of tholeiitic basalt from near the base of the Makaweli Member in Waimea Canyon (Table 2, Fig. 6) has an isotopic composition intermediate between those of the east and west sides of the island.

DISCUSSION

The variety of lithologies recovered from the Lihue basin drill holes and adjacent areas provides new stratigraphic and petrologic constraints on the origin of the basin and the geologic history of Kauai. The following discussion focuses primarily on three aspects: (1) the compositions of Koloa Volcanics in the basin, (2) the stratigraphic relations of tholeiites and differentiated postshield alkalic lavas (hawaiites, mugearites and alkalic basalts) found deep in three of the drill holes, and (3) the thick layer of breccia found in all the drill holes and exposed on the western margin of the basin.

Stratigraphic-Geochemical Trends in the Koloa Volcanics

Previous studies have emphasized the absence of spatial or temporal patterns in lithologies of rejuvenated-stage volcanism on Hawaiian shields

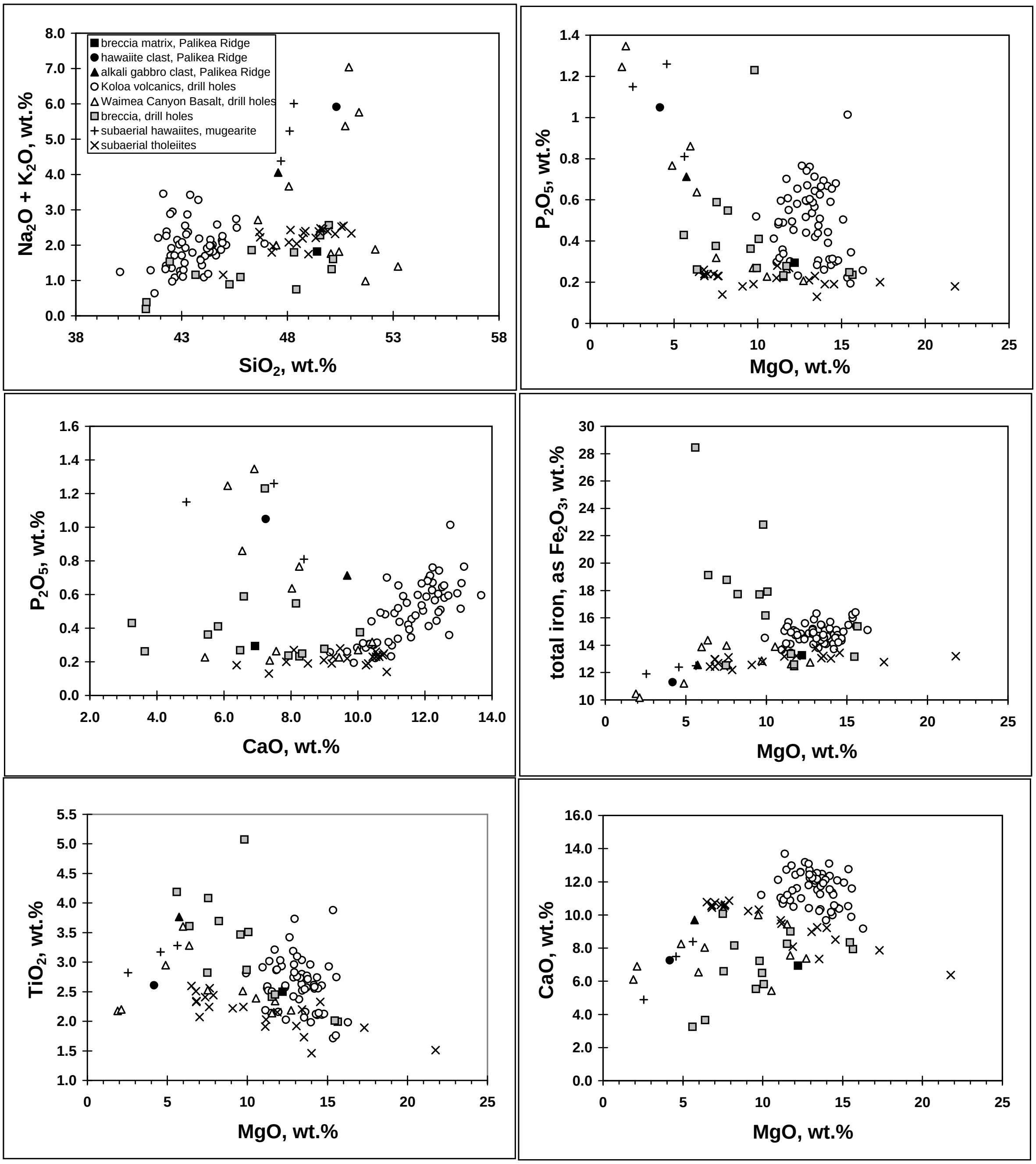

Figure 3. Major element compositions of samples from Palikea Ridge and the Lihue basin drill holes. Also shown are compositions of Kauai tholeiites, two hawaiites, and one mugearite from the literature (Clague and Dalrymple, 1988; Macdonald and Katsura, 1964; Macdonald et al., 1960). Samples from the Lihue basin drill holes of this study are subdivided into the Koloa Volcanics, Waimea Canyon Basalt (including tholeiites, hawaiites, differentiated alkali basalts, and mugearites), and the breccia layer (correlative with the Palikea Ridge breccia). Some of the breccia samples from the drill holes have unusual compositions (high Fe_2O_3, TiO_2, and low SiO_2, CaO) that reflect extensive weathering.

(Clague and Frey, 1982; Clague and Dalrymple, 1988). In contrast, detailed petrographic study of the Hanamaulu Town drill hole shows a stratigraphic trend from alkalic basalts to basanites, to nephelinites, from the older to younger lavas (Fig. 8) in the samples of Koloa Volcanics. Although we do not have detailed petrographic observations from all of the drill holes, it is likely that Koloa lavas in other drill holes also show this lithologic sequence, because stratigraphic-chemical trends among Koloa lavas from all of the drill holes are largely consistent (Fig. 4). In particular, the overall gradual increase in P_2O_5 and TiO_2, and decrease in SiO_2 and Al_2O_3/CaO, with stratigraphic height in Koloa lavas in the basin is similar in all of the drill holes. These stratigraphic-compositional trends cannot be due to fractional crystallization, as MgO only varies

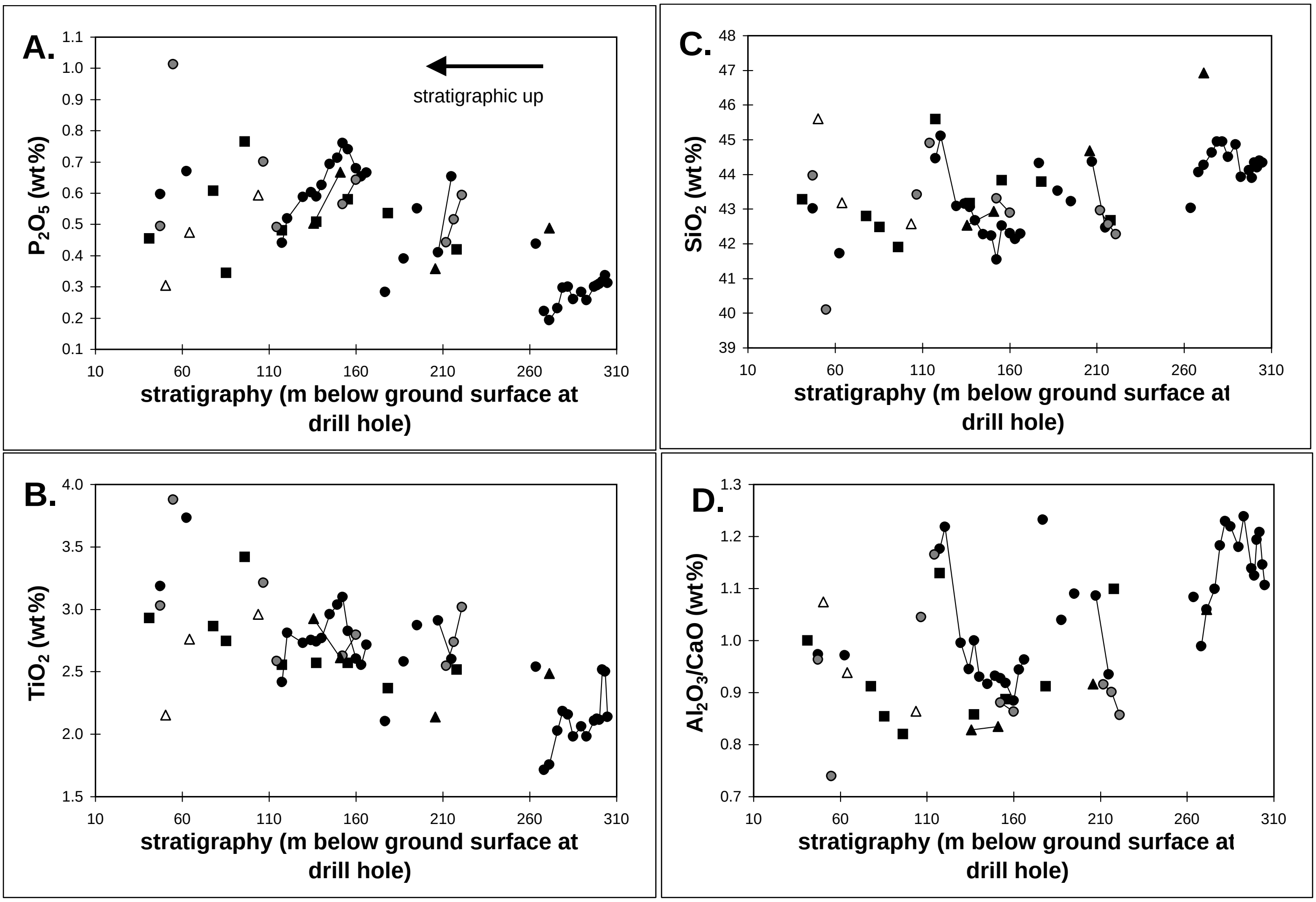

Figure 4. (A) P_2O_5, (B) TiO_2, (C) SiO_2, and (D) Al_2O_3/CaO vs. stratigraphic position (depth below ground surface in meters) for Koloa lavas from each drill hole. Symbols: black circles—Hanamaulu Town; black triangles—northeast Kilohana; gray circles—Puakukui Reservoir; black squares—south Wailua; white triangles—northwest Kilohana. Samples that appear to be from the same eruption (or sequence of eruptions closely spaced in time) without interbedded alluvium or sediments are joined by solid lines. There is an overall increase in P_2O_5 and TiO_2, and decrease in SiO_2 and Al_2O_3/CaO, in Koloa lavas in all of the drill-hole samples, from bottom to top of the basin, suggesting a gradual decrease in the extent of partial melting of the mantle source(s) that produced the rejuvenated-stage volcanic material with time in eastern Kauai.

from 11 to 16 wt% and shows no trend with stratigraphy throughout the drill-hole sequences. Although postmagmatic, low-temperature alteration has probably affected alkali contents of the Koloa lavas (especially decreasing Na_2O), alkalis show no systematic trend though the sequences. Because these trends are observed for elements such as TiO_2 (and Zr in the Hanamaulu Town drill hole [Reiners and Nelson, 1998]) that are immobile during weathering, it is unlikely that low-temperature alteration is responsible for these stratigraphic-compositional trends. Other studies have found that increasing P_2O_5, TiO_2, and CaO, and decreasing SiO_2 and Al_2O_3 in Hawaiian rejuvenated-stage magmas represent a decreasing degree of mantle source melting (Clague and Frey, 1982; Clague and Dalrymple, 1988; Maaløe et al., 1992). These stratigraphic-compositional trends probably indicate a gradual decrease in the extent of partial melting of the mantle source(s) that generated the Koloa Volcanics through the rejuvenated volcanic stage. It is interesting to note, however, that sequences of samples without intercalated sediments (samples joined by lines in Fig. 4; most are from the Hanamaulu Town drill hole), which are interpreted as continuous eruption sequences, show the opposite stratigraphic-compositional trends. This probably reflects tapping of melts formed by progressively larger degrees of partial melting during individual eruptions. Similar trends were observed in shorter stratigraphic sections in the Koloa Volcanics on the south coast of Kauai by Maaløe et al. (1992), and in postshield alkalic flows in Haleakala crater by West and Leeman (1994).

Waimea Canyon Basalt Lavas near the Bottom of the Basin

Recovery of tholeiite, hawaiite, mugearite, and low-MgO alkalic basalt lavas from the lower parts of the northwest Kilohana, Puakukui Reservoir, and south Wailua drill holes (Table 1, Fig. 5) indicates that these drill holes penetrated through the Koloa Volcanics and into the underlying Waimea Canyon Basalt. The deepest lavas from the Puakukui Reservoir drill hole are tholeiitic, similar in composition to subaerial Napali Member lavas (Table 1, Figs. 3 and 5). Flows with compositions similar to subaerial hawaiites and mugearites of the Makaweli and Olokele Members overlie these tholeiites in the Puakukui Reservoir drill hole (and are the deepest lavas recovered in the northwest Kilohana drill hole).

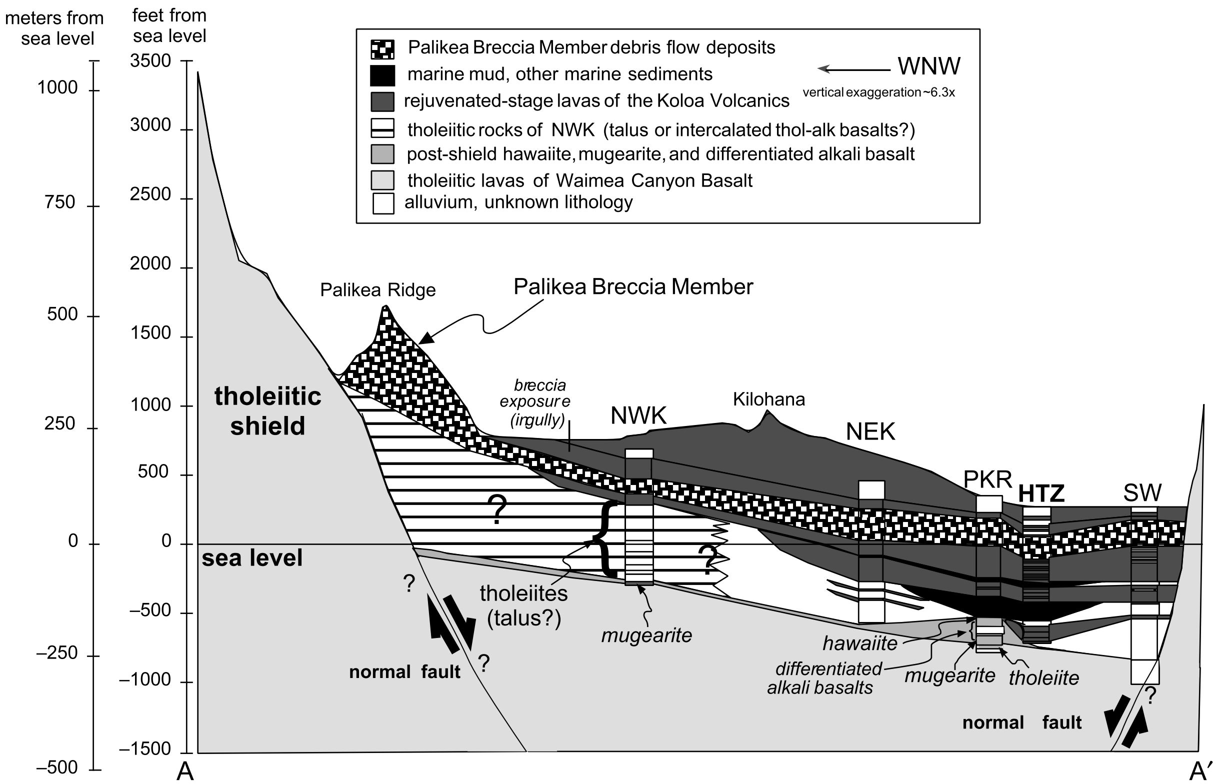

Figure 5. Generalized stratigraphic section of the Lihue basin, through the trace A–A′ in Figure 1, based on surface outcrops and drill-hole samples. See text for discussion. For abbreviations, see Table 1.

This is consistent with the subaerial stratigraphy of Waimea Canyon Basalt, in which hawaiite and mugearite lavas overlie tholeiites in the Makaweli and Olokele Members. These observations suggest that Waimea Canyon Basalt flows in the Lihue basin are ~200 m below sea level in the vicinity of the Puakukui Reservoir drill hole.

The observed stratigraphy of samples with tholeiitic compositions below lavas of the Koloa Volcanics and above hawaiite lava in the lower part of the northwest Kilohana drill hole (Fig. 5) is unexpected, and has at least two possible explanations. First, these tholeiitic samples could be lava flows in a section of intercalated alkalic and tholeiitic lavas of a postshield volcanic stage. Other Hawaiian shields have erupted both tholeiitic and alkalic magmas during their postshield, or alkalic-cap, stages of growth (Chen and Frey, 1985; Presley et al., 1997). Other drill holes in the Lihue basin, however, do not contain sections of intercalated tholeiitic and (postshield, non-Koloa) alkalic lavas, and no such subaerial sections have described. The other possibility is that these tholeiitic samples represent a very thick layer of breccia or talus that accumulated at the margin of the basin, and was capped by Koloa lavas. The proximity of this drill hole to the steep cliffs on the western margin of the basin is consistent with thick talus accumulations in this part of the basin.

The presence of hawaiitic and mugearitic lavas deep beneath the surface in the Lihue basin provides an important constraint on the origin of the basin, which has been attributed to either erosion by fluvial processes or structural collapse (Macdonald et al., 1960). Nearly flat-lying stratified rocks are present in the steep cliffs as much as 1200 m above and to the west of the Lihue basin. If formed by fluvial erosion, removal of more than 1 km of vertical thickness from the top of the shield would be required to form the Lihue basin. Given typical eruption and growth rates for Hawaiian shield volcanoes (Bargar and Jackson, 1974; Shaw et al., 1980), it is unlikely that fluvial erosion rates could exceed lava accumulation rates to generate 1 km of relief during the shield-building stage. Available radiometric age dates from Kauai indicate that hawaiites and mugearites were erupted ca. 3.92–3.95 Ma, and the youngest dated tholeiitic lavas were erupted ca. 4.00 Ma (Clague and Dalrymple, 1988; McDougall, 1979). It is unlikely that fluvial erosion of the extent necessary to remove 1 km of the shield could have occurred within the few tens to a hundred thousands years between tholeiitic and postshield alkalic eruptions. Therefore, if erosion produced the Lihue basin, it must have occurred after the postshield alkalic stage of volcanism. However, if the hawaiite postshield lavas sampled from beneath the Koloa Volcanics deep in the Lihue basin are remnants of fluvial erosion and alkalic-tholeiitic intercalation is not uniquely invoked for this single part of the island, it would imply a postshield alkalic sequence greater than 1 km thick in this area. This is unlikely given the thicknesses of postshield alkalic sequences on other Hawaiian volcanoes (e.g., West and Leeman, 1994), as well as the thin cap of hawaiitic flows in other areas of Kauai (only three known flows). It would also imply that erosion coincidentally removed all but a few to tens of meters of postshield alkalic hawaiitic lavas now found at the bottom of the Lihue basin. We prefer the interpretation that the postshield alkalic-stage lavas at the bottom of the basin represent the old top of the shield that was structurally downdropped more than 1 km to its present elevation. This could have occurred either before or after the postshield alkalic stage of volcanism. In any case, the presence of the postshield alkalic lavas at the bottom of the Lihue basin precludes an origin by fluvial erosion for the basin, and strongly suggests a structural cause.

The exact nature of the structural feature (i.e., whether the Lihue basin represents a caldera collapse or giant landslide or slump-like feature) is more difficult to address. The roughly semicircular form of the basin and the curvilinear ridges on the east side suggest a caldera-like morphology, but the large contrast in elevations of the bounding central highlands on the west side (1600 m) and ridges on the east side (300 m) are not consistent with an expected symmetrical caldera shape. It is possible that the basin instead formed by a large-scale, east-directed landslide or slump. Alternatively, it could have formed by a combination of caldera-collapse and giant mass-wasting events. Large-scale, east-directed slumping or landsliding may have followed (and exploited earlier faults created by) earlier caldera collapse. The Lualualei Basin on Waianae (Presley et al., 1997) and semicircular topographic depressions on Réunion and the Canary Islands (Gillot et al., 1994; Carracedo, 1994, 1996; Duffield et al., 1982; Lénat et al., 1989; Holcomb and Searle, 1991; Gillot and Nativel, 1989; Watts and Masson, 1995) may result from similar processes.

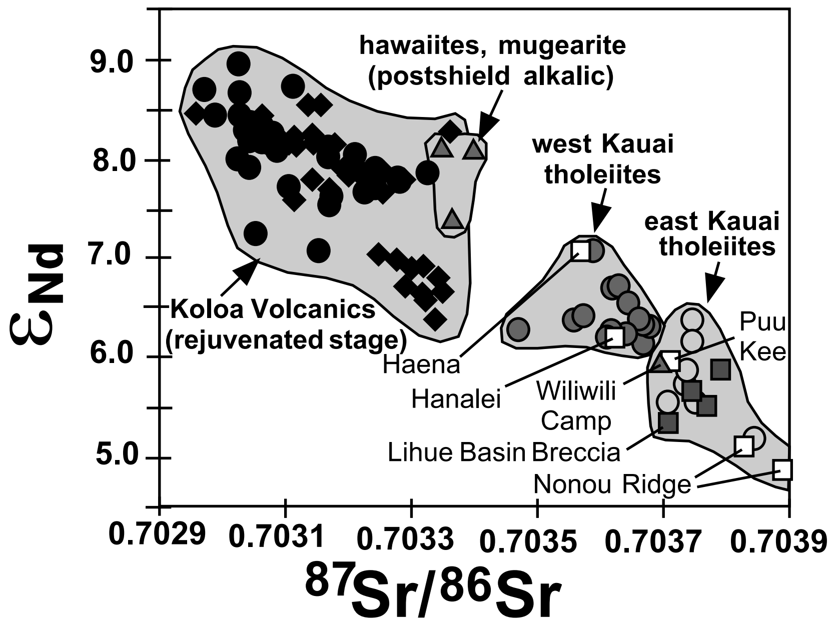

Figure 6. Sr- and Nd-isotope compositions of Kauai lavas. The Koloa Volcanics field includes data from the literature (black circles) (Park, 1990; Maaløe et al., 1992; Clague and Dalrymple, 1988; Feigenson, 1984) and from the Koloa Volcanics lavas of the Hanamaulu Town drill hole (black diamonds) (Reiners and Nelson, 1998). Hawaiite and mugearite data (gray triangles) are from the three flows identified and analyzed by Clague and Dalrymple (1988) and Park (1990) in the upper Olokele and Makaweli Members. West Kauai (dark gray circles) and east Kauai (light gray circles) tholeiite data are from the literature (Holcomb et al., 1995, 1997; Park, 1990; Feigenson, 1984 [with reinterpretations of Clague and Dalrymple, 1988]; Stille et al., 1986; White and Hoffman, 1982). Tholeiitic lavas from the north and west sides of Kauai (Haena and Hanalei) plot in the west Kauai field. Samples from the east side of Kauai (Puu Kee and Nonou ridge) plot in the east Kauai field. The tholeiite from the lower Makaweli Member, collected at Wiliwili camp in Waimea Canyon, has isotopic compositions intermediate between the west and east Kauai fields. Bulk breccia samples (gray squares) from the Hanamaulu Town drill-hole plot in the east Kauai field, suggesting that the source of the breccia contained lavas with isotopic compositions similar to east, not west, Kauai.

Provenance of the Breccia Layer

The presence of a 25–70-m-thick breccia between about 55 and 120 m below ground surface in each drill hole indicates that the breccia is laterally continuous throughout at least the central and southern parts of the Lihue basin. Samples of the breccia are matrix supported and contain clasts with both fine-grained and gabbroic textures. Although many of the breccia samples recovered from the drill holes are substantially altered, and drill-hole sampling did not permit analyses of individual clasts, compositions of the least-altered average (bulk) breccia samples are similar to those of subaerial tholeiites (Table 1, Fig. 3). Isotopic compositions of the least-altered samples are similar to those of tholeiites of east Kauai (Table 2, Fig. 6). The breccia layer in the Lihue basin appears to be correlative between drill holes based on consistent dip and thickness, and is also correlative with surface exposures of a thick breccia layer found along the western margin of the basin, most notably in the Waiahi River gorge and Palikea Ridge (Figs. 2 and 5). The Palikea Ridge breccia is also matrix supported and contains both fine-grained hawaiite clasts and fine- to medium-grained alkali gabbros. The petrographic and compositional similarities between the drill-hole breccia layer and the Palikea Ridge breccia, as well as the apparent stratigraphic correlation between the two (Fig. 5), are strong evidence that they are the same unit and that it is continuous within the Lihue basin.

The massive, unsorted character and great thickness of the breccia at the Palikea Ridge, the matrix-supported texture of the breccia both at Palikea Ridge and in the drill holes throughout the basin, the lateral continuity of the breccia throughout the basin, and the major element and isotopic composition of both the matrix and clasts within the breccia indicate that this unit represents one or more contemporaneous debris flows derived from the steep cliffs and highlands west of the Lihue basin. Assuming that the debris flows covered the entire Lihue basin (about 110 km^2 if the Kalepa and Nonou Ridges form the eastern boundary), and an average thickness of 42 m (from the average thickness in the drill holes and neglecting the Palikea Ridge section of at least 213 m), then the debris layer would have an approximate volume of 4.6 km^3. Assuming that it covered only the area delimited by the drill holes, about one-third to one-half of the basin, the estimated volume would be 1.5 to 2.3 km^3. If the deposit is much thicker in the western part of the basin, as suggested by the minimum thickness of 213 m at Palikea Ridge, then this volume could be much larger.

Isotopic analyses of bulk breccia samples indicate that its source region in the cliffs or highlands to the west contains lavas with isotopic compositions similar to those of east Kauai tholeiites, and distinct from those of west Kauai tholeiites (Fig. 6). Approximately 70% of the clasts in the breccia at Palikea Ridge are hawaiite. Assuming that this is true for all of the Palikea breccia in the Lihue basin (assumed to be 4.6 km^3 in volume), and that clasts represent 50% of the breccia volume, this yields a volume of hawaiite of about 1.6 km^3 in the breccia. This means that in the cliffs and highlands to the west of the Lihue

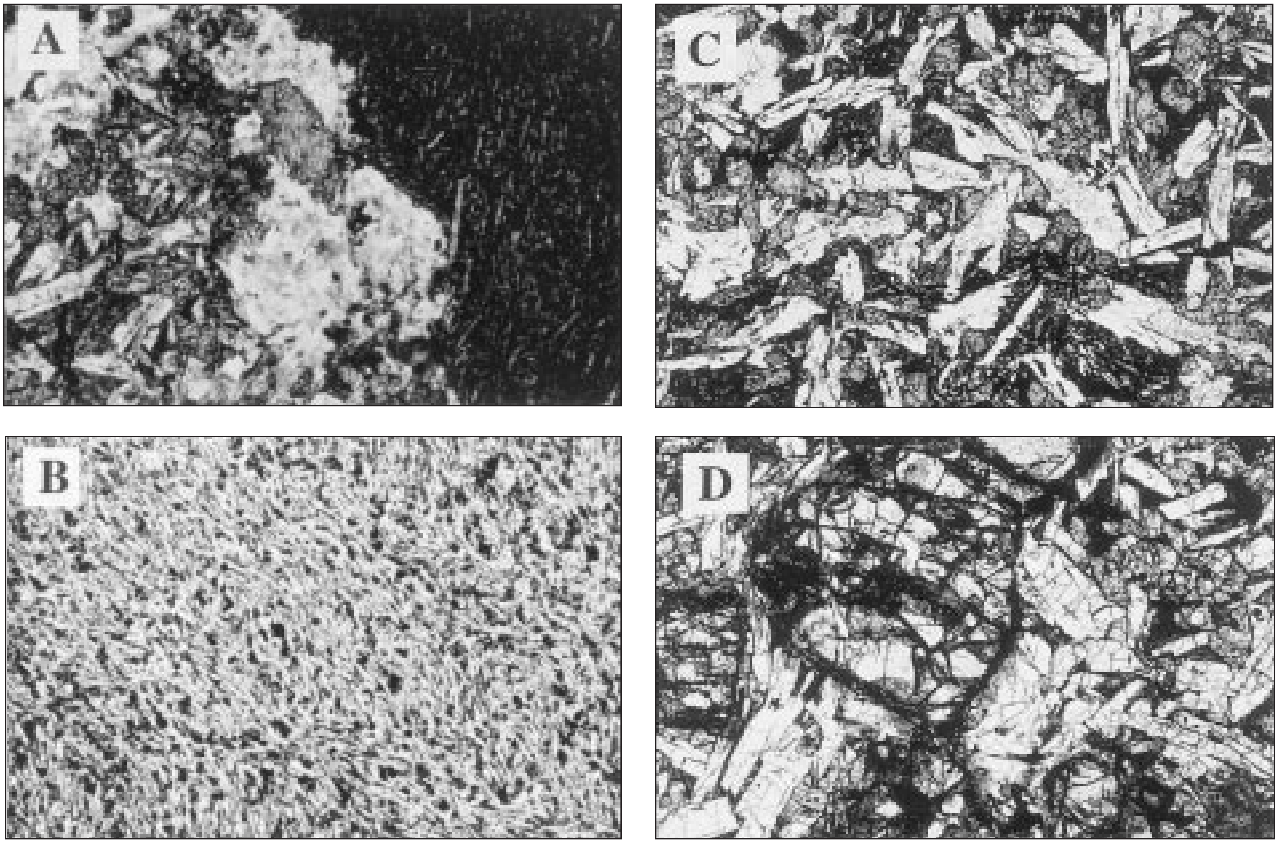

Figure 7. Photomicrographs of breccia from the Lihue basin and Palikea Ridge. Horizontal field of view in all images is 4 mm. (A) Matrix and clasts within breccia sample from Palikea Ridge. Light-colored matrix is in center of image, consisting of very fine-grained clasts and clay minerals. Fine-grained gabbroic clast is on left side of image; phases are plagioclase, clinopyroxene, olivine, and oxides. Fine-grained clast with trachytic texture is on right side, consisting of lineated plagioclase crystals in a very fine-grained matrix. Analyses of larger clasts from the Palikea breccia with textures similar to these smaller clasts indicate that the gabbroic clast is probably alkali gabbro and the trachytic-textured clast is hawaiite. (B) Hawaiite clast (sample 97PRQKP6, Table 1) from Palikea Ridge. Note excellent alignment of lathe-shaped plagioclase feldspars. Phases are plagioclase, clinopyroxene, and oxides. (C) Alkali gabbro clast from Palikea Ridge. Note lack of fine-grained matrix. Phases are plagioclase, clinopyroxene, and oxides. (D) Gabbroic clast from Hanamaulu Town drill hole. Phases are plagioclase, olivine, clinopyroxene, and oxides.

basin there is (or was) a fairly large volume of hawaiitic lava that has not been recognized.

The clasts of alkali gabbro in the breccia also suggest a somewhat unusual source region. Approximately 30% of the clasts in the breccia layer in the basin and in the Palikea Ridge are doleritic or gabbroic (Fig. 7). Many have miarolitic structures. These textures are not typical of Hawaiian lava flows. Macdonald et al. (1960) reported that pebbles of fine-grained gabbro are common in several stream beds on Kauai, but that few corresponding intrusive bodies have been found. Most gabbros described by Macdonald et al. (1960) are petrographically similar to those in the Lihue basin breccia, with miarolitic textures, and contain phases typical of alkalic volcanics, consisting predominantly of plagioclase (labradorite to andesine), clinopyroxene, magnetite, ilmenite, and rare olivine and alkali feldspar.

Several small intrusive bodies of alkali gabbro near Puu Lua, on the west rim of Waimea Canyon, provide a possible analogue for the source region of the gabbroic clasts of the breccia. Gabbro samples from these plugs are similar to the alkali gabbro clasts within the Lihue basin breccia. They are gray, fine- to medium-grained granular gabbros with miarolitic textures, consisting chiefly of plagioclase and clinopyroxene, with lesser amounts of opaque phases and alkali feldspar. One or more intrusive bodies of alkali gabbro, similar to those at Puu Lua, in the cliffs or central massif west of the Lihue basin could be a source of the alkali gabbro clasts in the Lihue basin breccia. The abundance of fine-grained hawaiite clasts in association with the alkali gabbros also indicates that the source region(s) of the clasts (but probably not the matrix) consisted of lavas and intrusives of the postshield alkalic stage of the Waimea Canyon Basalt. The textures of the alkali gabbros resemble textures of magmas that cooled slowly in lava lakes (e.g., Helz et al., 1989). Instead of, or in addition to, intrusive bodies, the source region for the hawaiite and alkali gabbro clasts may be one or more calderas or pit craters filled with postshield stage alkalic lavas in the steep cliffs and highlands west of the Lihue basin.

CONCLUSIONS

Samples from drill holes within the Lihue basin and adjacent areas of eastern Kauai provide a variety of constraints on the distribution and evolution of late-stage postshield and rejuvenated-stage alkalic magmatism on Kauai, as well as the origin of the Lihue basin. Regional stratigraphic-geochemical trends within more than 300 m of rejuvenated-stage lavas of the Koloa Volcanics in the basin indicate a gradual decrease in the extent of partial melting of mantle sources during the rejuvenated stage. Several 25–70-m-thick breccia layers within the basin and a correlative breccia layer at least 213 m thick on the western margin of the basin represent large (~ 4–5 km^3) debris-flow deposits derived from the central massif of the island. Compositions and petrographic textures of samples from this breccia reflect the presence of significant volumes of postshield alkalic magmatic products, and one or more large intrusive bodies or calderas comprising alkali gabbro and associated hawaiite lava flows, within the massif west of the Lihue basin. Hawaiite, mugearite, and differentiated alkalic basalt lavas overlying tholeiites of the Napali Member in the bottom of the basin also indicate a more voluminous and widespread postshield alkalic stage of volcanism on Kauai than previously recognized. The presence of these lavas at the bottom of the basin indicates that structural collapse, possibly caldera formation followed by large-scale east-directed slumping, created the Lihue basin.

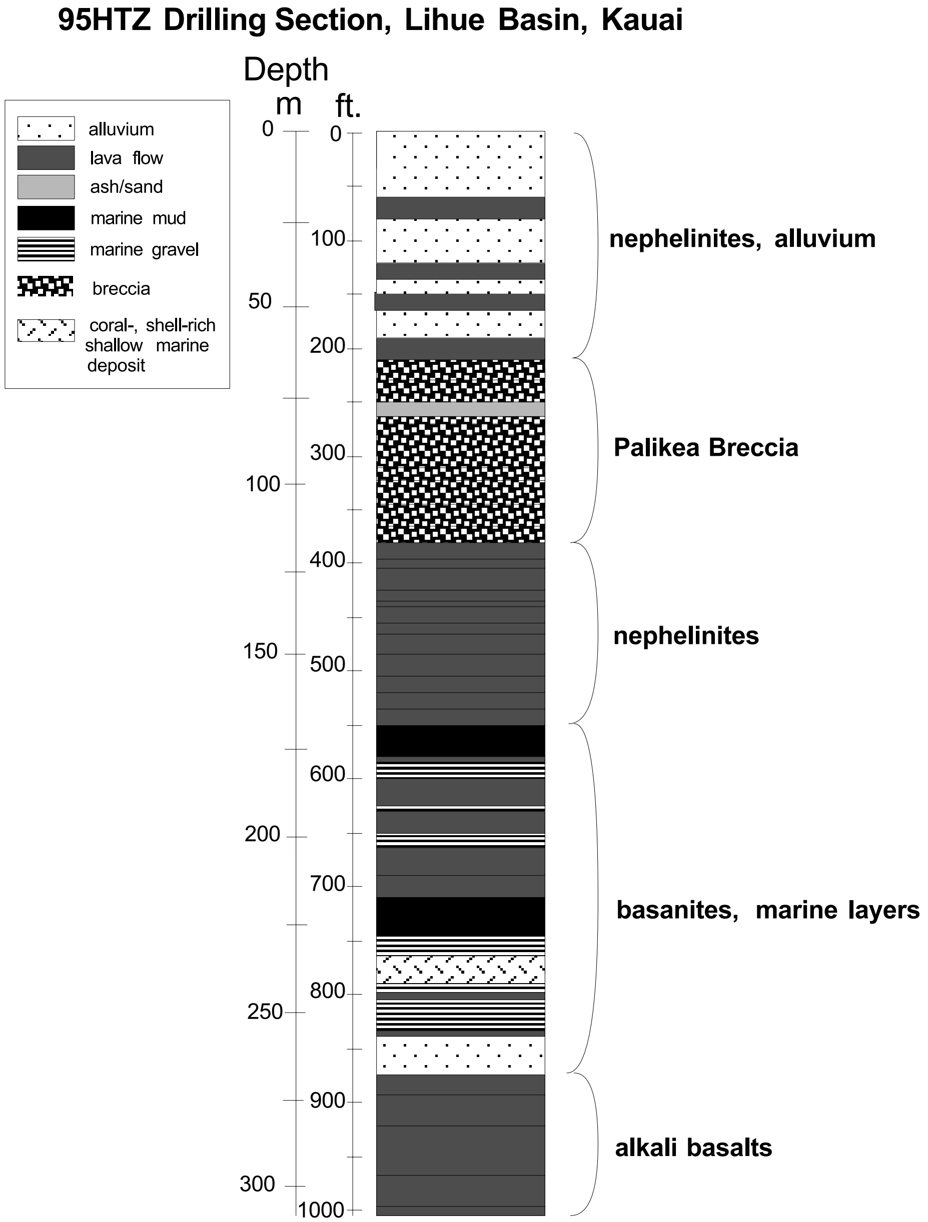

Figure 8. Detailed stratigraphy of the Hanamaulu Town drill hole in the Lihue basin. There is an overall trend in lithology of Koloa Volcanics, from bottom to top, of alkali basalts, basanites, to nephelinites. Other drill holes in the Lihue basin show the same major element stratigraphic trends as the Hanamaulu Town drill hole (see Fig. 4), suggesting that this lithologic sequence is probably present in other drill holes, and possibly throughout the basin.

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