INTRUSIVE ROCKS OF KILAUEA CALDERA

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ABSTRACT

Eighteen prehistoric dikes exposed in the west wall of Kilauea caldera have been mapped and analyzed for major, trace, and volatile elements. Twelve dikes occur along Uwekahuna Bluff and to the north and east; six dikes occur south of the bluff. Alignment of many dikes approximates the northeasterly trend common for several tectonic elements at Kilauea: the 6 southern dikes generally follow the N. 48° E. strike of the southwest rift zone, and 9 of 12 dikes in the north set strike roughly parallel to the linear western wall of the caldera (N. 40° E.). Chemical analyses of the dikes show that all are tholeiitic basalts, typical of Kilauea summit flows and similar to the lava flows making up the western caldera wall.

Five dikes of the north set occupy fractures cutting the entire section of flows in the caldera wall and therefore must be fairly young. Their age relative to the A.D. 1790 Keanakakoi Ash Member of the Puna Basalt is unknown, but we suggest that they formed just before or shortly after the explosive eruption and presumed caldera collapse responsible for the ash. Dikes of the south set show a close parallelism with recent prehistoric and historical fissures in the southwest rift zone. They are also young and may be closely related to recent activity in the upper southwest rift zone. The more northerly strike of the north set of dikes may reflect the combined influences of stresses caused by flexing of Kilauea's shallow summit magma reservoir and gravitational slumping of the volcano's south flank.

PURPOSE AND BACKGROUND

At Kilauea Volcano on the Island of Hawaii, much effort has been directed to identify and understand subsurface processes responsible for eruption-related seismicity and surface deformation (Eaton and Murata, 1960). Models invariably refer to the causative bodies as dikes (Ryan and others, 1981; Duffield and others, 1982; Epp and others, 1983; Pollard and others, 1983; Dvorak and others, 1986), and the shallow magma reservoir is usually envisioned as a plexus of dikes and sills (Fiske and Kinoshita, 1969; Fiske and Jackson, 1972; Ryan and others, 1983). Despite the many references to intrusive bodies, little effort has been spent in examining those exposed in Kilauea caldera.

Kilauea is one of the youngest of the Hawaiian volcanoes, and erosional dissection of the edifice has been insufficient to expose intrusive bodies. However, the walls of the 3 × 5 km summit caldera are as much as 140 m high and provide a window into the upper level of the Kilauea edifice. The western caldera wall comprises numerous lava flows, at least 18 dikes, the Uwekahuna laccolith (Murata and Richter, 1961), and 3 thin pyroclastic units (the lithic ash of 1924, the Keanakakoi Ash Member of the Puna Basalt, of about A.D. 1790; and the Uwekahuna Ash Member of the Puna Basalt, of about 2.1 ka).

In this paper, we describe the distribution, form, dimensions, and chemistry of intrusive bodies exposed in the western wall of the Kilauea summit caldera. From Uwekakuna Bluff to Steaming Bluff, this wall is an unbroken, nearly vertical cliff averaging 130 m high. The wall south of Uwekahuna Bluff is lower (15–40 m) and it has a stepped profile that has been attributed to normal faulting along the caldera rim (Dutton, 1884; Peterson, 1967; Holcomb, 1981; Saint Ours, 1982). We studied the intrusive bodies exposed in the caldera walls in order to compare them petrologically with the flows that they cut, to assess their volumetric importance, and to evaluate their relationship to the structural setting and state of stress in the summit region.

PREVIOUS STUDIES

KILAUEA INTRUSIVE BODIES

The largest intrusive body exposed at Kilauea is the Uwekahuna laccolith, which Daly (1911) first described and inferred to have an intrusive origin. Powers (1916) mapped this laccolith and noted that "about 20 dikes also occur in the [caldera] walls at various points, but especially at the northeast end of the sink." Washington (1923) published two chemical analyses of a dike (11N of this report) from the wall below Steaming Bluff. Murata and Richter (1961) and Aramaki (1968) studied the petrology of the Uwekahuna laccolith, accepted its intrusive origin, and concluded that its compositional variation could be explained by gravity settling of olivine followed by filter-pressing of the residual liquid.

Walker (1969) mapped several dikes in the Hilina system of normal faults on the south flank of Kilauea, about 12 km from the summit caldera and far from any known eruptive vent. He interpreted those dikes as fillings of deep ground cracks by surface lava flows. Easton and Lockwood (1983) presented data on the volatile contents of those dikes to support that interpretation.

MECHANISMS OF INTRUSION

Several mechanisms have been proposed to explain the origin of intrusive bodies at Kilauea. One is the intrusion of magma from a deep source; in this mechanism, magmatic pressure and increasing buoyancy owing to exsolution of volatiles combine to overcome effects of gravity and lithostatic load, forcing magma upward or laterally into country rock (Ryan and others, 1981).

A second mechanism is the lateral injection of degassed lava from a ponded lava lake. Daly (1911) and Murata and Richter (1961) proposed such an origin for the Uwekahuna laccolith, and Swanson and Peterson (1973) hypothesized a similar mechanism during the filling of Alae lava lake. The driving force for such lateral injection is limited to the weight of the lava column in the lake.

A third mechanism is the filling of fractures by lava flows. Deep vertical ground cracks are common both at the summit and along the rift zones of Kilauea (de Saint Ours, 1982), and lava flows have frequently been observed cascading into these cracks (Duffield and others, 1982). Solidification of the crack filling would form a tabular body of rock indistinguishable in most respects from upwardly or laterally fed dikes. Walker (1969) and Easton and Lockwood (1983) support such an origin for the dikes in the Hilina fault system. The low volatile contents that characterize lava flows some distance from their vents (Swanson and Fabbi, 1973) aid in distinguishing such surface-fed bodies from dikes intruded from depth (Easton and Lockwood, 1983).

ACKNOWLEDGMENTS

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METHODS

Our work included field mapping and description, petrographic study, and chemical analysis. Most field work was done in 1979–1980 and focused on the west wall of the caldera for reasons of easy access and good exposure. We briefly examined sections of the wall near Keanakakoi, in the Byron Ledge-Waldron Ledge area, and north of Steaming Bluff (fig. 14.1), but found no dikes. Sections of these walls are covered by vegetation, talus, or young lava flows, however, so that small intrusive bodies might be obscured.

FIELD CRITERIA FOR RECOGNIZING INTRUSIONS

The Uwekahuna laccolith (fig. 14.2*A*) has a dense, blocky texture that gives it a light color and smooth, massive surface appearance. Similar light-colored, smooth-surfaced rock lenses occur throughout the western caldera wall; many have prismatic jointing similar to that in the laccolith. Based on these similarities we originally suspected that many of these bodies might be sills or laccoliths. To distinguish between surface flows and sills we focused attention on contact relations, particularly evidence for cross-cutting relations, deformation of wall rocks, and textures of the top and bottom surfaces of a unit. Textures such as pahoehoe ropes, evidence for collapsed pahoehoe shells, and the rubbly surfaces of aa flows indicate a surface flow. Internal features such as visible mineralogy and vesicle abundance and distribution were of secondary importance in mapping flow units. When these criteria were applied to the suspected sills, contact relations invariably revealed an extrusive origin. In particular, the contacts between the dikes and their wall rocks often showed signs of rapid cooling, including fine grain size and glassy margins.

Vesicles of various sizes and shapes are abundant in most flows at Uwekahuna Bluff; flows below the Uwekahuna Ash Member are generally less vesicular than those above (Casadevall and Dzurisin, chapter 13). In contrast, vesicles are rare in dikes and in the Uwekahuna laccolith. Vesicles in dike interiors are typically small (1–10 mm) and spherical. The paucity of vesicles in the dikes and laccolith suggests either that confining pressure was too large to permit formation of an extensive separate gas phase or that the intruding magma was largely degassed. Additional details of the petrography and volatile content of the intrusions are discussed later.

RESULTS

DISTRIBUTION AND DESCRIPTION OF INTRUSIVE BODIES

About 20 intrusive bodies are exposed in the western wall of the caldera. The largest and most conspicuous is the Uwekahuna laccolith (fig. 14.2*A*), which consists of two bodies having a total outcrop length of about 300 m and a maximum thickness of about 30 m. The dense, light-colored laccolith contains 15–40 percent olivine phenocrysts concentrated in its central and lower parts by gravitational settling (Murata and Richter, 1961). Similar patterns of olivine concentration occur in the thicker picritic flows of the Uwekahuna Bluff section (Casadevall and Dzurisin, chapter 13). The laccolith is the only body in the western caldera wall that visibly deformed its host rocks, except for the obvious extensions caused by dikes: 10–15 m of the overlying picritic lavas are deformed (fig. 14.2*A*).

A possible sill or low-angle dike is exposed in the western wall about 1 km north of the laccolith, but is not easily accessible from the caldera floor (fig. 14.2*B*). This massive body, which we refer to as the manta ray because of its shape, has two limbs extending outward and upward and appearing to cut across adjacent flows. We tentatively conclude that the body is an intrusion, but it could also be a flow that filled a small surface depression. The major lenticular bodies of rock in the Uwekahuna Bluff section are thick subaerial lava flows, as judged from contact relations (Casadevall and Dzurisin, chapter 13).

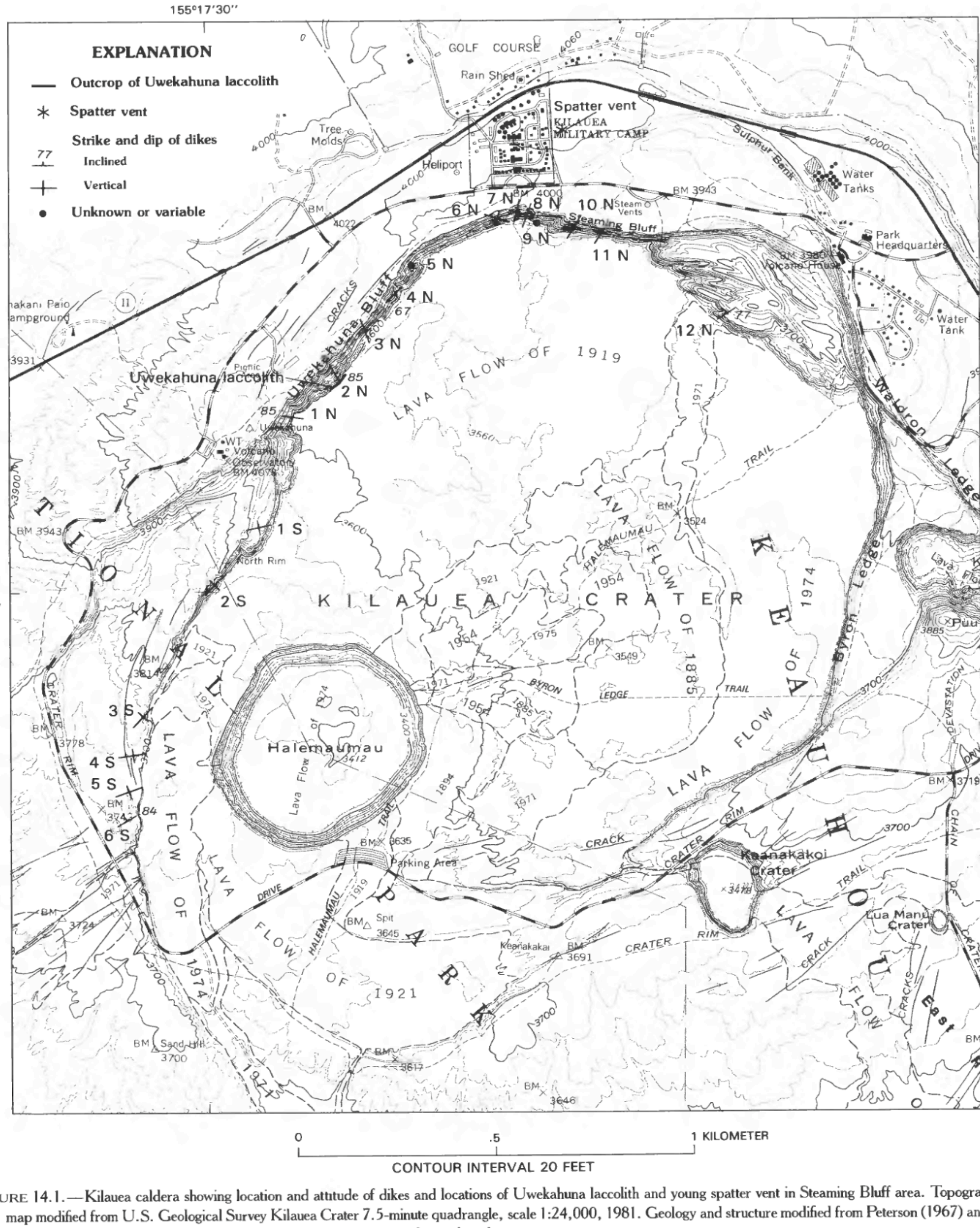
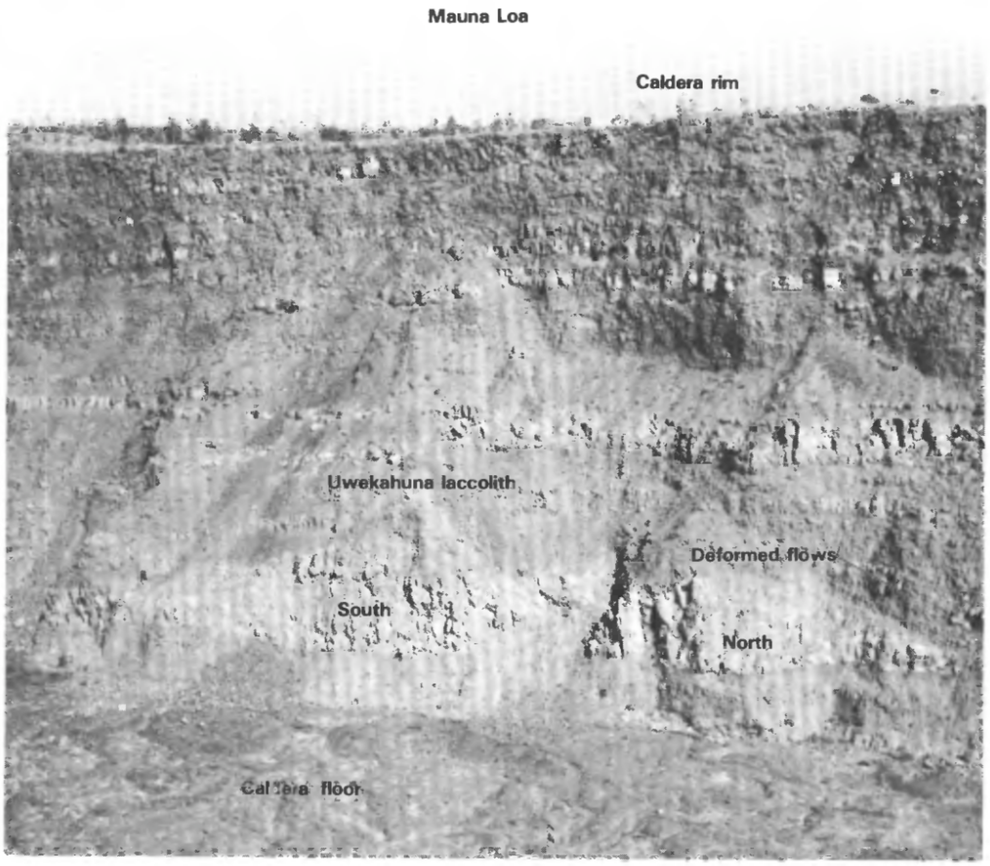
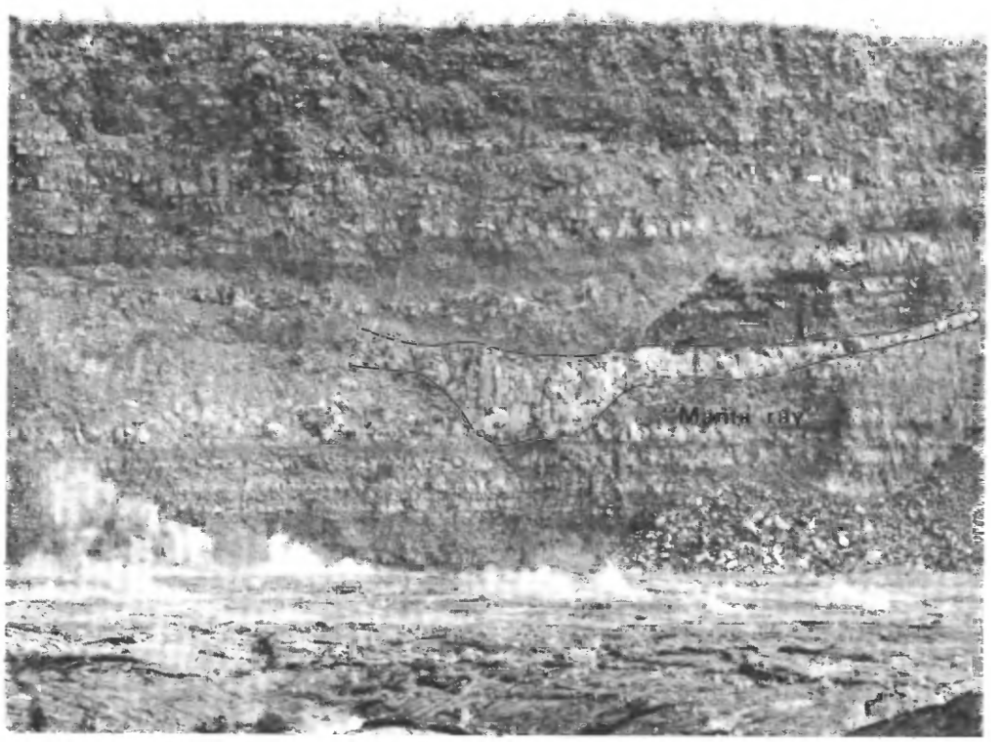


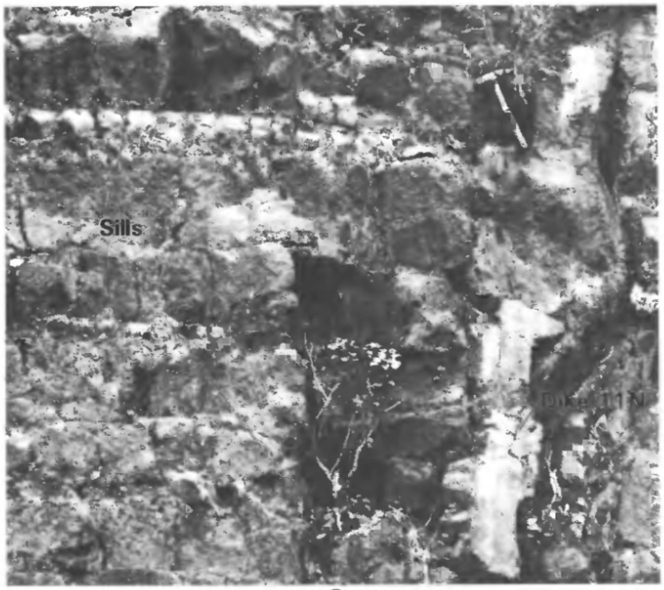
FIGURE 14.1.—Kilauea caldera showing location and attitude of dikes and locations of Uwekahuna laccolith and young spatter vent in Steaming Bluff area. Topographic map modified from U.S. Geological Survey Kilauea Crater 7.5-minute quadrangle, scale 1:24,000, 1981. Geology and structure modified from Peterson (1967) and de Saint Ours (1982). Dikes of north (N) and south (S) sets separately numbered.


Mauna Loa
Caldera rim
Uwekahuna laccolith
Deformed flows
South
North
Caldera floor

A



B



C

We identified 18 dikes in the western caldera wall that we subdivided into a north set (dikes 1N–12N) and a south set (dikes 1S–6S) based on their position relative to Uwekahuna Bluff (fig. 14.1). Most of the dikes trend northeasterly, roughly parallel to the strike of the southwest rift zone (N. 48° E.) and the linear segment of the western caldera wall (N. 40° E.; see fig. 14.6). Dike widths range from 5 cm to 2 m (table 14.1). The combined width of all dikes is only about 15 m, less than 1 percent of the length of the west wall.

DIKES OF THE NORTH SET

Dikes of the north set are oriented more northerly than those of the south set (fig. 14.1; table 14.1). Olivine-rich dikes 1N and 2N differ from other dikes of the north set in both composition and orientation (fig. 14.1); neither penetrates above the picritic lavas overlying the Uwekahuna Ash Member (Casadevall and Dzurisin, chapter 13). Dike 1N cuts the 2.1-ka Uwekahuna Ash Member and the lowermost flows of the picritic sequence at Uwekahuna

D

E

FIGURE 14.2.—Intrusive bodies in the west wall of Kilauea caldera. ***A***, Aerial view showing the two main parts (north and south) of the Uwekahuna laccolith; note tilted attitude of thin flows along northern edge of body. ***B***, Small manta ray-shaped body that is either an intrusion or formed by lava filling a surface depression. ***C***, Small sills coming off from main mass of dike 11N. ***D***, Detail of southwest caldera wall showing September 1971 eruptive fissure. ***E***, Dike 10N showing sets of prismatic joints perpendicular to dike walls.

TABLE 14.1.—*Thickness, orientation, MgO content, and brief description of dikes in the west wall of Kilauea caldera*

[n.d., not determined]

Dike	Thickness (cm)	Orientation		MgO content (weight percent)	Comments
		Strike	Dip		
				North set	
1N	40–60	N. 83° W.	85° N.	6.9 (margin) 14.3 (core)	Glass margin, picritic core.
2N	85–110	N. 33° W.	85° NE.	26.6	Margin of Uwekahuna laccolith.
3N	5–10	N. 10° W.–N. 30° W.	vertical	n.d.	Thin dikelets in section of thin picritic pahoehoe flows.
4N	80 (minimum)	N. 45° E.	67° SE.	n.d.	Tabular dike; east wall is missing.
5N	8–10	n.d.	n.d.	n.d.	Thin dikelet, top of talus cone against caldera wall.
6N	20–30	N. 73° W.	vertical	6.7	Complex of dikes and dikelets with glassy margins.
7N	50	N. 17° E.	vertical	7.3	
8N	65	N. 29° E.	vertical	7.8	Glassy margins.
9N	20–30	NE. (varies)	n.d.	7.2	Complex of dikes and sills; glassy margins.
10N	60	N. 34° E.	vertical	7.0	Portion of dike by caldera floor has open, vuggy interior; glassy margins. Fills fracture that cuts entire section; dike stops 15 m below rim.
11N	100–180	N. 38° E.	vertical	7.5	Widest dike within caldera wall.
12N	100–150	N. 64° E.	77° NW.	6.9	Cuts flows in bench above 1974 flow on crater floor; glassy margins.
				South set	
1S	8–12	N. 45° E.	vertical	6.7–7.7	Complex of dikelets and sills; glassy margins.
2S	75 (maximum)	N. 53° E.	vertical	6.6–7.5	Glassy margins.
3S	85–120	N. 42° E.–N. 53° E.	vertical	6.7–7.0	Above 1974 flows; glassy margins.
4S	35	N. 67° E.	vertical	7.0–7.2	Glassy margins.
5S	20–35	N. 85° E.	vertical	6.7–7.2 (margin) 20.1 (core)	Glassy margins.
6S	90 (maximum)	N. 60° E.	84° N.	n.d.	Glassy margins.

Bluff. Dike 2N occurs along the southern margin of the north part of the Uwekahuna laccolith, and it is olivine-rich throughout. It cuts several flows below the laccolith, but we did not find it above the laccolith.

The wider dikes display crude columnar jointing perpendicular to their margins. Dikes 10N and 11N have multiple cooling surfaces parallel to their walls that suggest more than one period of filling (fig. 14.2*E*). Small sills along flow contacts sprout from many dikes (fig. 14.2*C*); examples as much as 7 m long were observed.

Most samples for petrographic and chemical study were collected from the base of the exposure on the caldera floor. Along dike 10N, we rapelled from the caldera rim to collect samples and inspect the higher part of the dike about 15 m below the rim (fig. 14.3), where it terminates abruptly. This dike has fine-grained margins, 10–15 cm wide, which adhere to the walls of the fracture. The interior of the dike in its upper part is an open space about 80 cm wide, partly filled with soil and rock talus. We noted no spatter, drapery, or increased vesicularity of the dike rock to indicate eruption of the dike. The dike neither appeared to feed nor be fed from a surface flow. The host fracture, however, continued to the surface. Several factors, which we discuss later, may have prevented the magma from filling the fracture and reaching the surface, at least in the cross-section view we examined.

All but one of the 12 dikes in the north set occur in the unbroken part of the west caldera wall; dikes 6N–11N occupy fractures that cut through the entire sequence of flows in the wall (fig. 14.3). In the Steaming Flats area above these dikes, we found no evidence within several hundred meters of the rim that any dikes had vented. Where these fractures intersect the caldera rim, they are typically filled with vegetation, talus, and the Keanakakoi Ash Member. This cover obscures contact relations between the dikes and the ash.

Anecdotal evidence suggests that recent eruptive activity has occurred in the Steaming Flat area. Perret (1913, p. 615–616, fig. 6) noted that "miniature bombs or lava drops *** were discovered by the writer on the top, and surrounding the base, of several small, dome-topped cones of very scoriaceous lava situated on the northern rim of Kilauea near 'Kaniakolea', and therefore *outside* of the great pit crater, although within one of the surrounding areas of subsidence and not very far from Sulphur Banks*** ." H.A. Powers (oral commun., 1979) reported that following a large earthquake in the 1930's he found fresh spatter on the road at the western edge of Steaming Bluff, where Crater Rim Road ascends toward Kilauea Military Camp (fig. 14.1).

We did locate a spatter vent mapped by Macdonald and others (1983, fig. 19.19) (fig. 14.1). This feature is actually a series of echelon spatter ramparts that range in height from 2–8 m. They extend from the access road along the eastern boundary of Kilauea Military Camp to the northeast for approximately 150 m. The ramparts are mantled by the Keanakakoi Ash Member as much as 80 cm thick, indicating that they predate the 1790 eruption.

The area of Steaming Flats is currently aseismic (R.Y. Koyanagi, oral commun., 1979), and there is no local center of deformation in the area (A.T. Okamura, oral commun., 1984). However, nearby Sulfur Bank (fig. 14.1) is an area of active fumaroles (Casadevall and Hazlett, 1983), suggesting that a magmatic source of heat and gas is located at a shallow depth beneath the Steaming Flats area.

DIKES OF THE SOUTH SET

The six dikes south of Uwekahuna Bluff cut a thinner section of flows (15–40 m) than do the dikes north of Uwekahuna Bluff (120–140 m). Five of these southern dikes are fine grained and only

FIGURE 14.3.—Dike 10N in caldera wall below Steaming Bluff. Caldera floor at base of cliff just below bottom of view. Top of dike is about 15 m below caldera rim.

sparsely porphyritic, but dike 5S contains abundant olivine phenocrysts (tables 14.1, 14.2). Most of the dikes have open or rubble-filled interiors that resemble the 1971 eruptive fissure (Duffield and others, 1982) (fig. 14.2*D*). These dikes may have formed in a manner similar to that observed during the September 1971 eruption, in which the same fissure served first as a source of lava and later as a drain for surface flows.

The glassy margins of dikes 4S and 6S were dated by J. Halbig (written commun., 1985) using hydration-rind techniques. The hydration-rind ages have been calibrated elsewhere at Kilauea for lava flows dated by the radiocarbon method. The dikes have ages ranging from 0.55 to 0.45 ka. No ages are available for lava flows in this part of the caldera, so it is difficult to evaluate the accuracy of these ages. If, as we suspect, the flows cut by these dikes are equivalent to the upper flows exposed at Uwekahuna Bluff (suite A, 1.5–0.35 ka; see Casadevall and Dzurisin, chapter 13), the hydration-rind ages are reasonable.

PETROGRAPHY

We examined 28 thin sections from the dikes and identified three rock types on the basis of crystallinity and phenocryst content. The margins of most of the dikes and related thin sills consist of dark brown to olive glass with sparse microlites and scattered euhedral phenocrysts of olivine. The margins range from a few millimeters to several centimeters thick and pass gradually into the finely crystalline interiors of the dikes.

The cores of the thicker dikes are of two textural varieties, a porphyritic picrite (5S and 1N) with a fine- to medium-grained groundmass and an aphanitic basalt with sparse olivine phenocrysts in a groundmass of brown glass and plagioclase microlites. Olivine phenocrysts in the cores are generally corroded and resorbed, in contrast to their distinctly euhedral habit in the glassy margins. Dike 2N is medium to coarsely crystalline rock with only minor glass. It is distinct from all other dikes at Kilauea and closely resembles the Uwekahuna laccolith, which it appears to intrude and may have fed.

CHEMISTRY

MAJOR AND TRACE ELEMENTS

Fourteen dikes were analyzed for major and trace elements, including rare-earth elements, sulfur, and chlorine (table 14.2). The major-element data were determined using rapid-rock methods (Shapiro, 1975) and were supplemented by electron-microprobe analyses of glass from the margins of dikes. All analyses were recalculated on a dry-weight basis after converting iron to FeO_t ($FeO_t = FeO + 0.9Fe_2O_3$) to facilitate comparison of the data. Our objective in obtaining these data was to use chemistry, in conjunction with field occurrence and petrography, to characterize dikes or sets of dikes and to relate the dikes to the flows in the Uwekahuna Bluff section (Casadevall and Dzurisin, chapter 13). Water (H_2O^+), sulfur, and chlorine were measured to estimate the extent to which the dikes had degassed.

TABLE 14.2.—*Chemical analyses of samples from dikes in the west wall of Kilauea caldera*

[Values for oxides in weight percent; values for trace elements in parts per million. Symbols (numbers and letters) used to distinguish samples in fig. 14.4; INAA, neutron-activation analysis; AA, atomic absorption analysis; n.d., not determined; <, less than. Sources of data: for WASH-11, Washington (1923); for Uwekahuna laccolith, Murata and Richter (1961)]

Dike Sample Symbol	1S 5614 1	1S W-211577 1	2S 5615 2	2S W-211567 2	3S 5616 3	3S 5617 3	3S W-211575 3	4S 5620 4	4S 5621 4	4S W-211574 4	5S 5618 5
SiO_2	51.84	50.2	51.75	49.7	50.64	50.78	50.2	50.96	51.65	50.0	51.62
Al_2O_3	13.96	13.7	14.06	13.5	13.99	13.91	13.4	13.58	13.70	13.7	13.95
Fe_2O_3	n.d.	1.9	n.d.	2.2	n.d.	n.d.	2.9	n.d.	n.d.	2.0	n.d.
FeO	10.75	9.1	10.94	9.3	11.09	11.10	8.9	11.18	11.16	9.5	11.05
MgO	6.71	7.7	6.63	7.4	6.84	6.77	7.0	7.24	7.10	7.0	6.76
CaO	10.88	10.9	10.96	10.9	11.03	11.09	11.4	11.33	11.22	11.2	10.95
Na_2O	2.43	2.3	2.39	2.2	2.22	2.30	2.1	2.31	2.25	2.2	2.12
K_2O	.47	.45	.41	.40	.39	.41	.41	.45	.44	.43	.34
H_2O	n.d.	.16	n.d.	.01	n.d.	n.d.	.13	n.d.	n.d.	.04	n.d.
TiO_2	2.71	2.5	2.48	2.3	2.50	2.58	2.4	2.38	2.48	2.4	2.35
P_2O_5	.27	.26	.23	.27	.23	.24	.27	.26	.25	.27	.20
MnO	n.d.	.16	n.d.	.15	n.d.	n.d.	.18	n.d.	n.d.	.17	n.d.
CO_2	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.
Cl	n.d.	.004	n.d.	.004	n.d.	n.d.	.005	n.d.	n.d.	.006	n.d.
F	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.
S	n.d.	.042	n.d.	.049	n.d.	n.d.	.066	n.d.	n.d.	.049	n.d.
Ba	n.d.	121	n.d.	117	n.d.	n.d.	109	n.d.	n.d.	139	n.d.
Co (INAA)	n.d.	44.3	n.d.	44.5	n.d.	n.d.	43.3	n.d.	n.d.	43.6	n.d.
Co (AA)	n.d.	45	n.d.	45	n.d.	n.d.	45	n.d.	n.d.	47	n.d.
Cr	n.d.	454	n.d.	408	n.d.	n.d.	315	n.d.	n.d.	309	n.d.
Ni	n.d.	190	n.d.	140	n.d.	n.d.	100	n.d.	n.d.	100	n.d.
Cu	n.d.	120	n.d.	120	n.d.	n.d.	110	n.d.	n.d.	120	n.d.
Hf	n.d.	3.87	n.d.	3.55	n.d.	n.d.	3.99	n.d.	n.d.	3.83	n.d.
Rb	n.d.	11	n.d.	14	n.d.	n.d.	13	n.d.	n.d.	13	n.d.
Ta	n.d.	.87	n.d.	.76	n.d.	n.d.	.99	n.d.	n.d.	1.08	n.d.
Th	n.d.	.86	n.d.	.7	n.d.	n.d.	.95	n.d.	n.d.	.96	n.d.
U	n.d.	<0.6	n.d.	<0.5	n.d.	n.d.	.34	n.d.	n.d.	.37	n.d.
Zn	n.d.	111	n.d.	108	n.d.	n.d.	108	n.d.	n.d.	114	n.d.
Zr	n.d.	119	n.d.	81	n.d.	n.d.	167	n.d.	n.d.	76	n.d.
Sc	n.d.	29.9	n.d.	30.6	n.d.	n.d.	31.7	n.d.	n.d.	31.6	n.d.
La	n.d.	12.8	n.d.	10.6	n.d.	n.d.	12.3	n.d.	n.d.	12.3	n.d.
Ce	n.d.	29.0	n.d.	25.3	n.d.	n.d.	27.8	n.d.	n.d.	28.9	n.d.
Nd	n.d.	21	n.d.	21	n.d.	n.d.	9	n.d.	n.d.	23	n.d.
Sm	n.d.	5.50	n.d.	5.2	n.d.	n.d.	5.35	n.d.	n.d.	5.39	n.d.
Eu	n.d.	1.92	n.d.	1.80	n.d.	n.d.	1.74	n.d.	n.d.	1.78	n.d.
Gd	n.d.	5.1	n.d.	4.7	n.d.	n.d.	3.3	n.d.	n.d.	4.2	n.d.
Tb	n.d.	.87	n.d.	.79	n.d.	n.d.	.80	n.d.	n.d.	.83	n.d.
Tm	n.d.	.27	n.d.	.23	n.d.	n.d.	.27	n.d.	n.d.	.22	n.d.
Yb	n.d.	2.05	n.d.	2.05	n.d.	n.d.	2.10	n.d.	n.d.	2.20	n.d.
Lu	n.d.	.286	n.d.	.310	n.d.	n.d.	.302	n.d.	n.d.	.301	n.d.
Dike Sample Symbol	**5S 5619 5**	**5S W-211407 5**	**5S W-211573 5**	**1N 5622 A**	**1N W-211408 A**	**2N W-211409 B**	**6N 5623 F**	**7N W-211410 G**	**8N W-211411 H**	**9N W-211415 I**	**10N W-211412 J**
SiO_2	51.06	46.6	50.3	51.38	48.7	44.8	51.63	50.5	50.6	51.3	51.0
Al_2O_3	13.61	9.5	13.9	14.18	11.3	6.9	13.9	12.7	13.1	13.7	13.9
Fe_2O_3	n.d.	1.5	2.1	n.d.	2.0	2.8	n.d.	2.3	2.1	2.2	2.5
FeO	11.00	10.7	9.4	9.96	9.6	10.8	10.87	9.9	9.4	9.1	8.8
MgO	7.17	20.2	7.2	6.94	14.3	26.8	6.78	7.3	7.8	7.2	7.0
CaO	11.23	7.7	10.9	11.47	9.3	5.9	11.10	10.4	11.0	10.6	10.9
Na_2O	2.23	1.6	2.4	2.36	1.9	.99	2.37	2.4	2.2	2.5	2.5
K_2O	.40	.33	.44	.47	.37	.19	.41	.50	.45	.41	.44
H_2O	n.d.	.35	.33	n.d.	.13	.31	n.d.	.25	.13	.22	.16
TiO_2	2.45	1.7	2.3	2.65	2.1	1.0	2.39	2.9	2.5	2.4	2.4
P_2O_5	.19	.21	.27	.23	.25	.13	.23	.35	.28	.30	.28
MnO	n.d.	.19	.17	n.d.	.18	.20	n.d.	.20	.18	.19	.18
CO_2	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.
Cl	n.d.	.004	.005	n.d.	.004	.004	n.d.	.005	.006	.004	.004
F	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.
S	n.d.	.024	.045	n.d.	.027	.015	n.d.	.063	.068	.048	.025
Ba	n.d.	101	121	n.d.	<200	66	n.d.	148	130	103	<200
Co (INAA)	n.d.	87.9	40.5	n.d.	65.1	110	n.d.	44.6	46	42.4	41.7
Co (AA)	n.d.	89	45	n.d.	66	110	n.d.	50	52	48	48
Cr	n.d.	1220	328	n.d.	934	1620	n.d.	289	355	331	347
Ni	n.d.	980	90	n.d.	600	1400	n.d.	97	110	85	82
Cu	n.d.	68	120	n.d.	99	49	n.d.	140	120	120	100
Hf	n.d.	2.48	3.54	n.d.	3.21	1.50	n.d.	4.52	3.7	3.6	3.57
Rb	n.d.	<30	19	n.d.	<30	<30	n.d.	<30	16	<30	<30
Ta	n.d.	.66	.82	n.d.	.81	.39	n.d.	1.13	.91	.77	.77
Th	n.d.	.47	.84	n.d.	.65	<.4	n.d.	.87	.90	.68	.69
U	n.d.	.33	<.4	n.d.	.29	<.5	n.d.	.43	<.6	.31	<.6
Zn	n.d.	104	103	n.d.	106	105	n.d.	119	111	110	110
Zr	n.d.	89	168	n.d.	<100	<200	n.d.	185	157	118	<200
Sc	n.d.	20.9	29.5	n.d.	26.5	19.2	n.d.	31.9	31.2	30.1	30.5
La	n.d.	8.9	10.8	n.d.	10.2	4.6	n.d.	14.9	11.5	10.9	11.1
Ce	n.d.	21.3	25.0	n.d.	24.8	12.6	n.d.	35.5	29.0	25.8	26.0
Nd	n.d.	15	16	n.d.	18	9	n.d.	25	19	17	19
Sm	n.d.	3.92	5.22	n.d.	4.65	2.30	n.d.	6.64	5.49	5.39	5.4
Eu	n.d.	1.26	1.68	n.d.	1.54	.748	n.d.	2.17	1.78	1.81	1.72
Gd	n.d.	4.8	3.8	n.d.	5.4	3.0	n.d.	8.1	6.4	6.4	6.4
Tb	n.d.	.56	.74	n.d.	.70	.46	n.d.	1.01	.84	.86	1.05
Tm	n.d.	.17	.26	n.d.	.26	.10	n.d.	.40	.24	.34	.27
Yb	n.d.	1.40	2.15	n.d.	1.70	.91	n.d.	2.45	2.03	2.18	2.03
Lu	n.d.	.196	.298	n.d.	.253	.132	n.d.	.35	.30	.30	.29

TABLE 14.2.—*Chemical analyses of samples from dikes in the west wall of Kilauea caldera*—Continued

Dike Sample Symbol	10N W-211416 J	11N W-211414 K	12N W-211413 L	11N WASH-11 K	11N WASH-11 K	LAC UWEMR-1 U	LAC UWEMR-2 U	LAC UWEMR-3 U	LAC UWEMR-4 U	LAC UWEMR-5 U	LAC UWEMR-6 U	LAC UWEMR-7 U
SiO_2	51.2	50.9	51.7	51.77	50.53	48.37	48.25	46.59	46.32	48.56	49.50	52.04
Al_2O_3	14.3	13.4	13.7	13.54	13.61	11.19	10.72	7.69	8.58	11.62	12.67	13.20
Fe_2O_3	1.8	2.1	2.0	.75	1.69	3.08	2.14	2.20	1.58	2.9	4.89	2.86
FeO	9.2	9.3	9.2	9.63	9.30	8.65	9.50	10.46	10.98	8.56	6.36	8.55
MgO	7.0	7.5	6.9	7.33	7.01	15.26	16.45	21.79	21.98	14.65	11.55	5.84
CaO	10.6	10.6	10.6	10.57	10.75	8.94	8.79	7.41	7.11	9.36	10.05	8.83
Na_2O	2.3	2.4	2.4	2.18	2.16	1.76	1.61	1.33	1.28	1.74	1.99	2.79
K_2O	.43	.41	.42	.45	.35	.28	.25	.28	.21	.26	.32	.83
H_2O	.29	.10	.30	n.d.	n.d.	.13	.11	.41	.15	.17	.14	.41
TiO_2	2.4	2.4	2.3	4.01	3.68	1.88	1.75	1.83	1.44	1.92	2.14	4.16
P_2O_5	.30	.29	.30	.26	.20	.16	.16	.11	.11	.14	.18	.49
MnO	.18	.19	.17	.15	.13	.17	.17	.18	.17	.16	.16	.16
CO_2	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.
Cl	.005	.004	.005	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.
F	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.
S	.034	.027	.065	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.
Ba	112	99	105	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.
Co (INAA)	37.9	45	41.5	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.
Co (AA)	45	48	48	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.
Cr	309	370	318	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.
Ni	97	120	94	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.
Cu	120	100	120	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.
Hf	3.30	3.6	3.6	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.
Rb	<20	<30	<30	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.
Ta	.68	.79	.75	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.
Th	.68	.83	.76	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.
U	<.3	<.6	<.6	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.
Zn	98	120	115	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.
Zr	88	113	141	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.
Sc	27.5	31.0	30.1	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.
La	10.8	10.7	10.7	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.
Ce	24.1	24.9	25.5	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.
Nd	18	19	17	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.
Sm	5.34	5.24	5.24	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.
Eu	1.61	1.71	1.77	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.
Gd	6.6	6..1	5.7	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.
Tb	.85	.86	.83	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.
Tm	.23	.25	.33	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.
Yb	2.07	2.15	2.32	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.
Lu	.28	.318	.321	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.

The dikes are tholeiitic basalt and have compositions similar to those of typical Kilauea summit flows (Macdonald, 1949; Wright, 1971; Casadevall and Dzurisin, chapter 13), for which the main control on composition is the gain or loss of olivine (Powers, 1955; Murata and Richter, 1966a, b; Wright, 1971). Dikes of the north set and those of the south set are chemically similar. MgO variation diagrams show no obvious linear trends because most analyses cluster between 6.6 and 7.8 weight percent MgO (fig. 14.4A). The cores of the three picrite dikes (5S, 1N, and 2N) have MgO in excess of 14 weight percent; dikes 5N and 1S have glassy margins with MgO contents near 7.0 weight percent. The olivine-control lines for these two dikes are similar to those for lava flows of Uwekahuna Bluff (fig. 14.4; table 14.3; Casadevall and Dzurisin, chapter 13).

Thirteen dikes were analyzed for a suite of 24 trace elements using a combination of instrumental neutron activation (Baedecker, 1979), atomic absorption, and X-ray fluorescence methods (table 14.2). Most of the trace elements correlate negatively with MgO content (fig. 14.4*B*) but dilution by settled olivine causes Ni, Co, and Cr to show positive correlations (fig. 14.4*B*) for reasons discussed in Casadevall and Dzurisin (chapter 13). The rare-earth-element (REE) abundances and the shapes and slopes of chondrite-normalized REE plots for the dike samples (fig. 14.5) closely resemble those for Kilauea lava flows (Leeman and others, 1977, 1980; Basaltic Volcanism Study Project, 1981), including those from Uwekahuna Bluff (Casadevall and Dzurisin, chapter 13).

VOLATILE CONSTITUENTS

The dikes contain concentrations of water, sulfur, and chlorine that are higher than in typical surface-degassed lava, but lower than in primitive basaltic magma (table 14.4). Water content for glassy margins of most of the dikes is in the range of 0.13–0.35 weight percent; in dikes 2S and 4S it is considerably lower (0.01 and 0.04 weight percent, respectively). Sulfur content of glassy margins of the dikes ranges from 0.042 to 0.068 weight percent, and that of chlorine from 0.004 to 0.006 weight percent. Interiors of the dikes generally have less H_2O, S, and Cl than do their glassy margins. This difference probably reflects the fact that glassy margins quench in higher volatile contents compared to the more crystalline interior portions of the dikes. The concentrations in the glassy margins are low compared to the postulated abundances for parental Hawaiian basaltic magma (table 14.4): 0.30–0.45 weight percent H_2O; 0.10–0.15 weight percent S, and 0.008–0.011 weight percent Cl (Harris and Anderson, 1983; Gerlach and Graeber, 1985; Greenland and others, 1985; L.P. Greenland, written commun., 1985).

Gerlach and Graeber (1985) and Greenland and others (1985) have demonstrated that Hawaiian magma loses volatiles on the way to the surface as well as during eruption. Loss of carbon dioxide probably begins soon after the magma leaves the upper mantle. Significant loss of water and sulfur, on the other hand, occurs when the magma is at a confining pressure equivalent to several tens of meters of lithostatic load (Moore, 1970; Moore and Fabbi, 1971), although some is lost while the magma temporarily resides in the shallow summit reservoir (Gerlach and Graeber, 1985; Greenland and others, 1985).

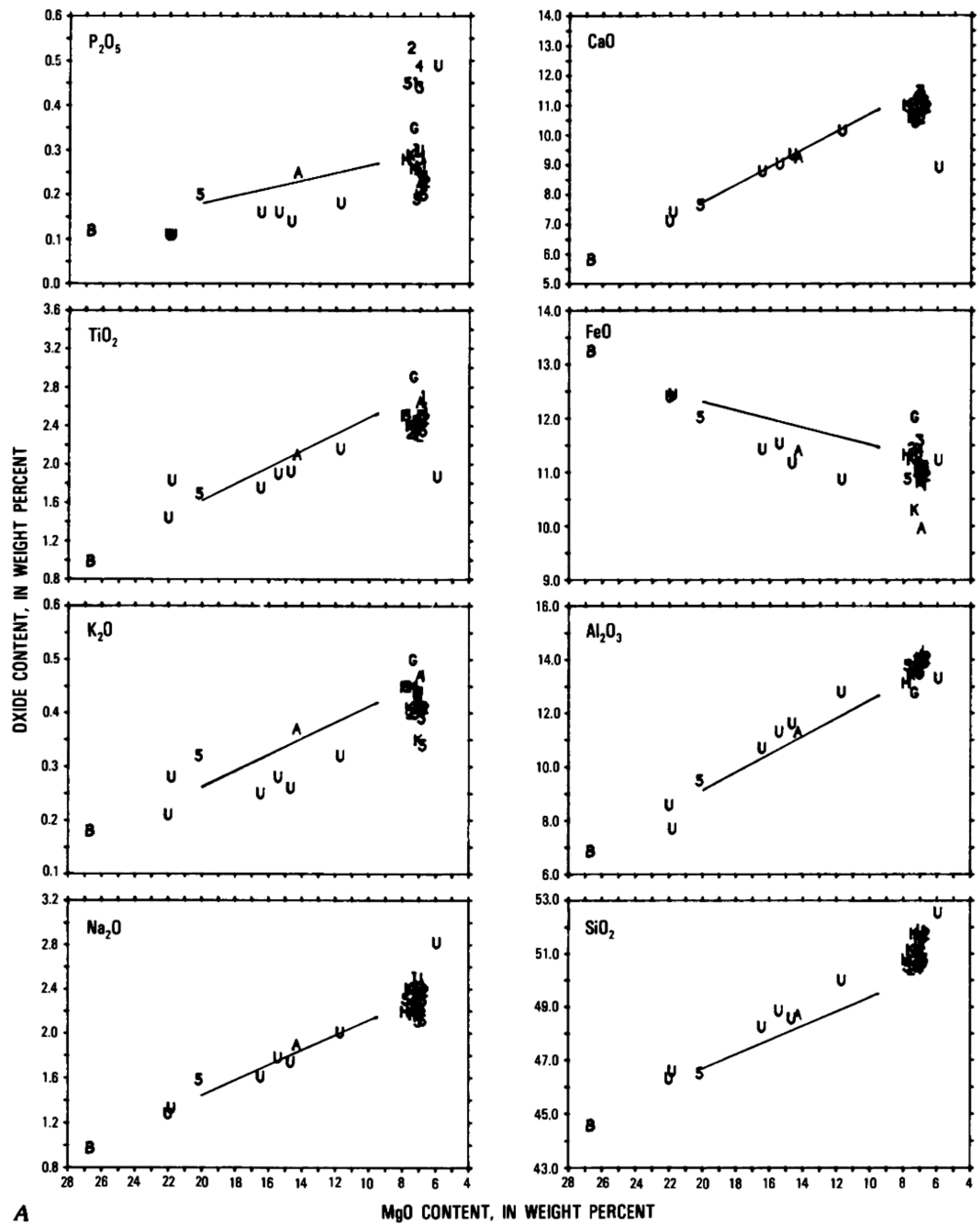


FIGURE 14.4.—MgO variation diagrams for intrusive rocks of Kilauea caldera. A, dike 1N; J, dike 10N; K, dike 11N; L, dike 12N; O, dike 10N; U, Uwekahuna laccolith. Also plotted are olivine-control lines for the picritic suite C lava flows at Uwekahuna Bluff (Casadevall and Dzurisin, chapter 13); these lines are not derived from the plotted data but instead provide a comparison between the caldera intrusions and the lava flows they intruded. Data for Uwekahuna laccolith from Murata and Richter (1961). Other number and letter symbols refer to samples listed in table 14.2. ***A***, Major-element abundances. ***B***, Trace-element abundances. ***C***, Rare-earth-element abundances.

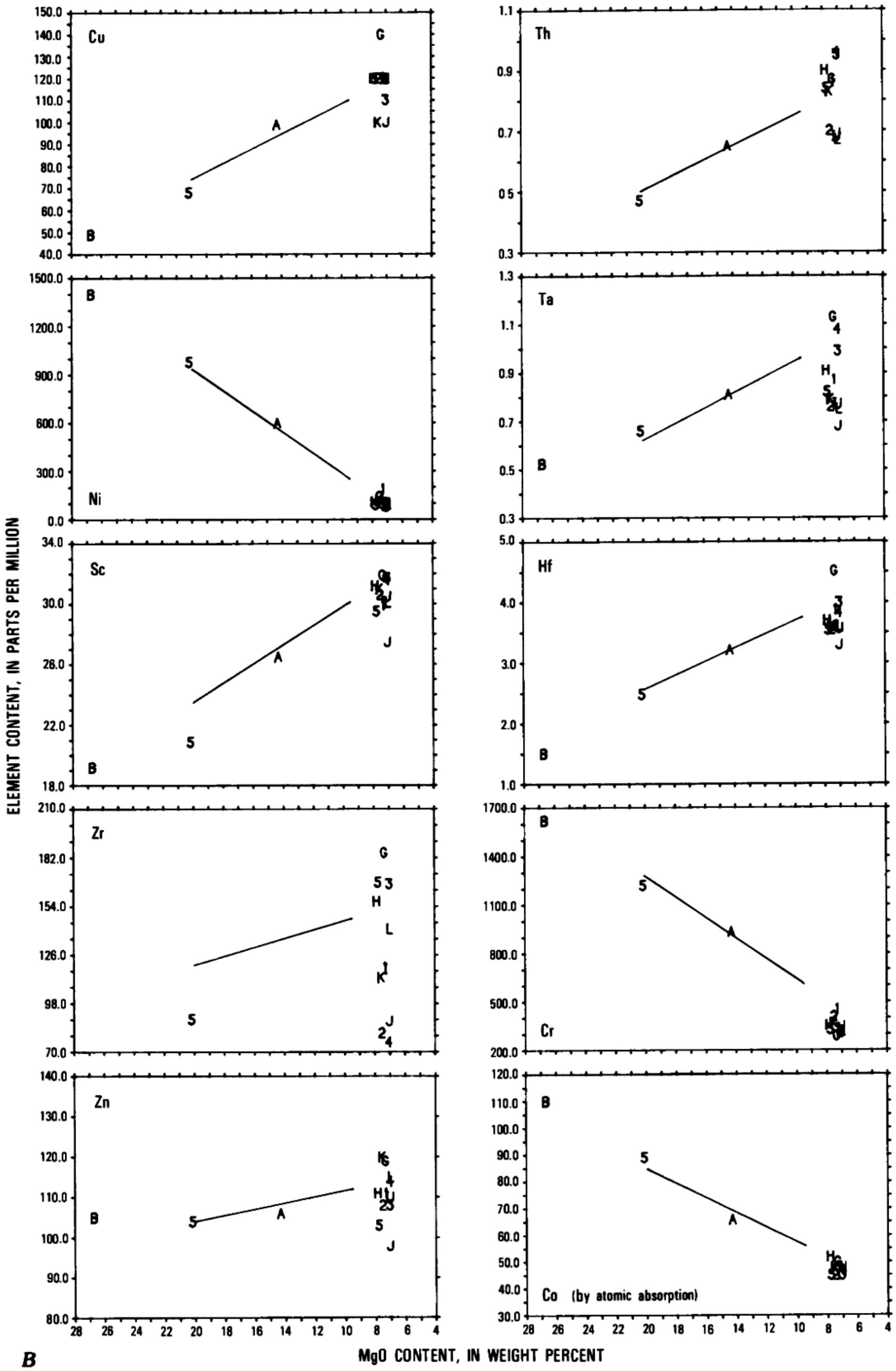


FIGURE 14.4.—Continued.

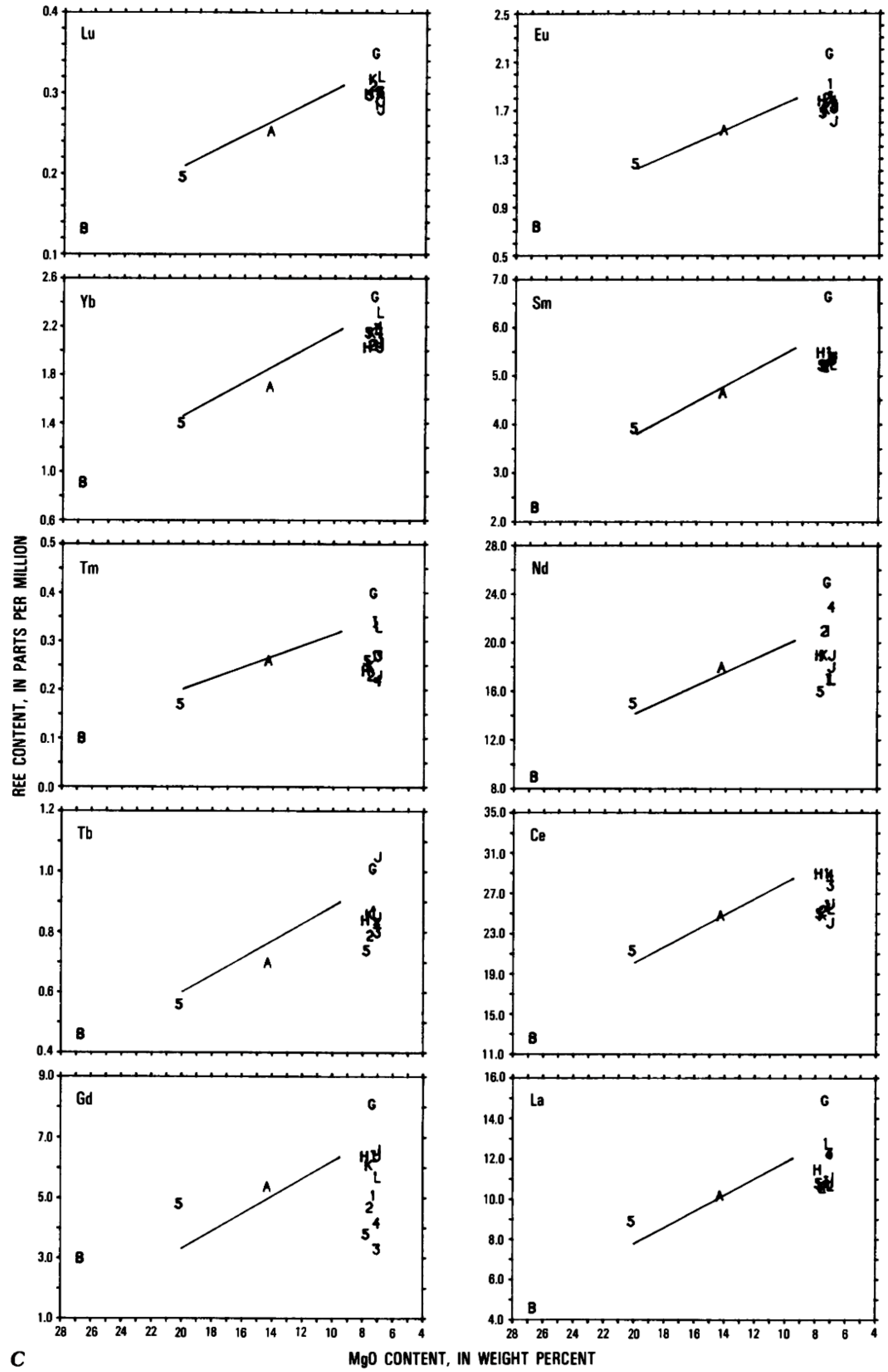


FIGURE 14.4.—Continued.

TABLE 14.3.—*Coefficients of olivine control lines (equations of the form $y = ax + b$) for Kilauea intrusive rocks and lava flows*

[y is the major oxide or element, x is the MgO content, a is the slope, and b is the y intercept value at MgO = 0 weight percent. Values for oxides in weight percent; values for trace elements in parts per million. Data sources: Dikes, this paper; Uwekahuna laccolith, Murata and Richter (1961); Uwekahuna Bluff suite C flows, Casadevall and Dzurisin (chapter 13); prehistoric pahoehoe picrite complex (PPPC) flows and prehistoric Kilauea caldera and Hilina (PHKILCAL) flows, Wright (1971). FeO_t, total iron oxide = FeO + 0.9 Fe_2O_3; n.d., not determined]

Element/oxide	Slope (a)	Uncertainty	Intercept (b)
Dike 5S			
SiO_2	−0.356	±0.047	53.651
Al_2O_3	−.332	±.024	16.181
FeO	.808	±.016	10.404
CaO	−.262	±.025	12.931
Na_2O	−.048	±.015	2.563
K_2O	−.005	±.007	.435
TiO_2	−.057	±.014	2.845
P_2O_5	−.005	±.019	.314
MnO	.002	n.d.	.148
Dike 1N			
SiO_2	−0.363	n.d.	53.898
Al_2O_2	−.391	n.d.	16.896
FeO	.196	n.d.	8.602
CaO	−.300	n.d.	13.554
Na_2O	−.063	n.d.	2.794
K_2O	−.014	n.d.	.564
TiO_2	−.075	n.d.	3.169
P_2O_5	.003	n.d.	.211
MnO	n.d.	n.d.	n.d.
Uwekahuna laccolith			
SiO_2	−0.307	±0.017	53.394
Al_2O_3	−.455	±.056	18.202
FeO	.160	±.013	8.935
CaO	−.275	±.019	13.342
Na_2O	−.066	±.005	2.744
K_2O	−.006	±.005	.367
TiO_2	−.045	±.023	2.603
P_2O_5	−.006	±.002	.253
MnO	.001	±.001	.144
Uwekahuna Bluff suite C flows			
SiO_2	−0.248	±0.064	51.828
Al_2O_3	−.336	±.025	15.852
FeO	.071	±.037	10.811
CaO	−.306	±.056	13.797
Na_2O	−.070	±.008	2.822
K_2O	−.015	±.003	.556
TiO_2	−.086	±.015	3.348
P_2O_5	−.008	±.003	.348
MnO	−.002	±.002	.183
Ba	.565	±2.649	100.346
Co (INAA)	3.297	±.253	19.006
Uwekahuna Bluff suite C flows—Continued			
Co (AA)	2.772	±.353	29.385
Cr	63.771	±6.067	2.147
Ni	65.268	±5.240	−368.050
Cu	−3.969	±1.398	151.439
Hf	−.113	±.025	4.831
Rb	−.289	±.345	16.829
Ta	−.032	±.009	1.272
Th	−.025	±.005	1.001
U	−.005	±.012	.369
Zn	−.700	±.600	118.175
Zr	−3.137	±2.066	171.211
Sc	−.635	±.074	36.140
La	−.409	±.079	15.931
Ce	−.800	±.162	36.090
Nd	−.578	±.267	25.673
Sm	−.170	±.033	7.194
Gd	−.291	±.070	9.128
Tb	−.029	±.008	1.186
Tm	−.011	±.004	.432
Yb	−.068	±.012	2.822
Lu	−.009	±.002	0.392
Prehistoric pahoehoe picrite complex (PPPC) flows			
SiO_2	−0.289	±0.023	52.894
Al_2O_3	−.357	±.010	16.643
FeO	.068	±.017	10.480
CaO	−.288	±.017	13.184
Na_2O	−.053	±.007	2.691
K_2O	−.014	±.003	.561
TiO_2	−.065	±.006	2.906
P_2O_5	−.006	±.001	.266
MnO	.000	n.d.	.164
Cr_2O_3	.008	.001	−.009
Prehistoric Kilauea caldera and Hilina flows (PHKILCAL)			
SiO_2	−0.317	±0.021	53.327
Al_2O_3	−.354	±.029	10.585
FeO	.081	±.030	10.260
CaO	−.266	±.016	13.044
Na_2O	−.065	±.005	2.753
K_2O	−.012	±.003	.497
TiO_2	−.057	±.012	2.843
P_2O_5	−.005	±.001	.259
MnO	n.d.	n.d.	n.d.

Lava flows from Kilauea and Mauna Loa that have traveled several kilometers from their feeding vents have low water contents of 0.01–0.10 weight percent, low total sulfur (0.004–0.007 weight percent), and chloride contents of 0.005–0.006 weight percent (Swanson and Fabbi, 1973; L.P. Greenland, written commun., 1985). These volatile contents are similar to those of surface-fed fracture fillings at Hilina Pali (Easton and Lockwood, 1983; table 14.4), but lower than most dikes in the west caldera wall. Surface flows within a few hundred meters of a vent may have higher volatile contents (0.01 weight percent S; 0.009 weight percent Cl) (Swanson and Fabbi, 1973).

DISCUSSION OF CHEMISTRY

The major- and trace-element chemistry of the dikes and Uwekahuna laccolith is similar to that of lava flows at Uwekahuna Bluff. In a companion paper (Casadevall and Dzurisin, chapter 13), we compare the composition of lava flows at Uwekahuna Bluff at a constant MgO content of 7.0 weight percent, by addition or subtraction of olivine from the bulk composition. We apply the same approach here to the intrusions. We used the olivine composition for the Uwekahuna laccolith determined by Murata and Richter (1961) and recalculated the composition for each analysis to 7.0 weight percent MgO. We then averaged the normalized magma compositions for dikes of the south set and the north set (table 14.5). The major-element and trace-element compositions of the intrusive bodies strongly resemble those of the succession of flows at Uwekahuna Bluff.

Olivine-control lines for dikes 5S and 1N, as well as for the Uwekahuna laccolith, have slopes similar to those for prehistoric Kilauea summit flows and the regional prehistoric pahoehoe picrite complex (PPPC) of the summit region (Wright, 1971), and the picritic flows (suite C) of the Uwekahuna Bluff section (table 14.3; fig. 14.4*A*; Casadevall and Dzurisin, chapter 13). These similarities indicate that the magma of the picritic dikes and the laccolith is chemically similar to other magmas of the Kilauea summit region.

TABLE 14.4.—*Volatile contents of samples from Kilauea caldera dikes and other Hawaiian intrusive and extrusive rocks*

[All values in weight percent. For Kilauea dikes, H_2O^+ content by modified Penfield method, analyses by CHN water analyzer (uncertainty ±3–5 percent of reported value); total sulfur analyses by Leco sulfur analyzer with infrared detector (uncertainty±0.005 weight percent); total chlorine analyses using separation by Conway cell method, measured by selective ion electrode (uncertainty ±0.002 weight percent). Other samples: 1–9, Easton and Lockwood (1983), Swanson and Fabbi (1973); 10–12, L.P. Greenland, written commun. (1984); data for primitive Hawaiian magma from Greenland (in press), Greenland and others (1985), and Gerlach and Graeber (1985), also includes 0.65 weight percent CO_2]

Sample	Laboratory number	H_2O^+	Sulfur	Chloride	Total volatiles	Comments
Kilauea caldera dikes, south set						
1S	W-211577	0.16	0.042	0.004	0.206	Glass margin.
2S	W-211576	.01	.049	.004	.064	Glass margin.
3S	W-211575	.13	.066	.005	.201	Glass margin.
4S	W-211574	.04	.049	.006	.095	Glass margin.
5S	W-211573	.33	.045	.005	.380	Glass margin.
5S	W-211407	.35	.024	.004	.378	Picrite interior.
Kilauea caldera dikes, north set						
1N	W-211408	.13	.027	.004	.161	Picrite interior.
2N	W-211409	.31	.015	.004	.329	Cuts laccolith.
7N	W-211410	.25	.063	.005	.318	Glass margin.
8N	W-211411	.13	.068	.006	.204	Glass margin.
9N	W-211415	.22	.048	.004	.272	Glass margin.
10N	W-211412	.16	.025	.004	.189	Interior.
10N	W-211416	.29	.034	.005	.329	15 m below rim.
11N	W-211414	.10	.027	.004	.131	Margin.
12N	W-211413	.30	.065	.005	.370	Glass margin.
Other samples						
Field number		H_2O^+	Sulfur	Chloride	Total volatiles	Comments
(1) L-78-6B		---	0.09	0.04	0.2	0.33 Mauna Loa dike.
(2) L-78-7		.13	.05	.004	.184	Mauna Loa dike.
(3) L-78-8		.15	.03	<.05	<.23	Mauna Loa dike.
(4) L-78-9		.13	.05	.1	.28	Mauna Loa dike.
(5) L-77-35B		.05	.011	.006	.067	Hilina dike.
(6) L-77-35C		.06	.011	.007	.078	Hilina dike.
(7) --------		.09	.005	.007	.102	Uwekahuna laccolith.
(8) DAS71-1213-136		.04	.02	.009	.069	Kilauea surface flow.
(9) DAS71-1213-137		.04	.02	.009	.069	Kilauea surface flow.
(10) K 71		.13	.016	.008	.154	Puu Oo, April 1984.
(11) K 72		.16	.008	.008	.176	Puu Oo, April 1984.
(12) ML 117		.10	.016	.006	.122	Mauna Loa, April 1984.
Primitive Hawaiian magma (undegassed)						
		.30–.45	.10–.15	.008–.011	.41–.65	

The lava flows deformed by the laccolith are picritic, and we have interpreted them as ponded in an ancient caldera (Casadevall and Dzurisin, chapter 13).

The chilled margin of the Uwekahuna laccolith has a low total volatile content (table 14.4) that Easton and Lockwood (1983) attributed to degassing in a surface lake before intrusion. The picritic nature and low sulfur contents of dikes 1N (0.027 weight percent S) and 2N (0.015 weight percent S) indicate an origin similar to that of the laccolith. We concur with the interpretation of Murata and Richter (1961, p.433) that the laccolith was derived from "lateral injection during a prehistoric period of refilling of the caldera." We further suggest that dikes 1N and 2N formed by lateral injection from a picritic lava lake, since destroyed by collapse of the caldera. This lake may have been produced by eruption of the picritic lava of suite C. The intrusives may have derived from the lake and invaded its earlier overflows.

Dike 5S, on the other hand, cuts flows that are younger than the picritic flows of suite C, and therefore cannot be considered contemporaneous with either dikes 1N and 2N or with the laccolith. This dike cuts several tens of meters of lava flows in the southwest caldera wall; it may have fed a nearby olivine-rich lava flow exposed along Crater Rim Drive. That flow forms part of the regional prehistoric pahoehoe picritic complex (PPPC) of Wright (1971), as mapped by Walker (1969). R.T. Holcomb (oral commun., 1985), suggests that the PPPC probably represents a series of overflows from the summit region, a suggestion consistent with the possibility that dike 5S fed at least part of the PPPC.

The water, sulfur, and chlorine contents of the Kilauea intrusive rocks (table 14.4) indicate that about half of the parental abundance of these constituents was lost before the dikes solidified. Easton and Lockwood (1983) suggested that low total volatile content for the chilled margin of an intrusive body indicates that the body was fed by a surface flow draining into an existing fissure or by lateral injection from a surface lake, and not by intrusion from depth. The combined water, sulfur, and chlorine contents for Kilauea summit dikes (table 14.4) are high compared to those of degassed surface flows that have traveled some distance from their vent (Swanson and Fabbi, 1973) and to those of Hilina Pali crack fillings (Easton and Lockwood, 1983). However, we have no data on the volatile abundances in summit lava, which contains a higher initial volatile

TABLE 14.5.—*Chemical composition of intrusive and extrusive rocks from Uwekahuna Bluff, Kilauea compared with averages for Kilauea and Mauna Loa Volcanoes*

[Analyses recalculated to 100 percent dry weight after converting all iron to FeO_{total} and normalized to 7.0 weight percent MgO by subtracting or adding olivine of Uwekahuna laccolith composition (Murata and Richter, 1961, analysis 10). Sources of data: Kilauea caldera dike sets, this paper; Uwekahuna laccolith, Murata and Richter (1961); Uwekahuna Bluff flow suites, Casadevall and Dzurisin (chapter 13); Kilauea (1911–24 summit lavas) and Mauna Loa (historical eruptions) averages, Basaltic Volcanism Study Project (1981). n.d., not determined]

	Kilauea caldera dikes		Uwekahuna laccolith	Uwekahuna Bluff flow suites				Kilauea	Mauna Loa
	North set	South set		A	B	C	D		
SiO_2	51.31±0.44	51.14±0.50	51.20±0.17	51.10±0.23	50.90±0.39	50.60±0.78	50.23±0.25	50.70±0.31	52.45±0.31
Al_2O_3	13.8 ±0.4	13.9 ±0.2	14.0 ±0.8	13.7 ±0.2	13.6 ±0.2	13.6 ±0.3	13.7 ±0.2	13.57±0.12	13.94±0.10
FeO	11.1 ±0.6	11.2 ±0.2	10.8 ±0.4	11.7 ±0.3	11.8 ±0.3	11.3 ±0.5	11.4 ±0.3	11.03±0.20	10.62±0.49
MgO	7.0	7.0	7.0	7.0	7.0	7.0	7.0	7.0	7.0
CaO	11.0 ±0.4	11.2 ±0.2	11.6 ±0.2	10.6 ±0.2	10.9 ±0.3	11.7 ±0.7	11.7 ±0.4	11.65±0.33	10.73±0.15
Na_2O	2.3 ±0.1	2.3 ±0.1	2.2 ±0.1	2.4 ±0.1	2.3 ±0.1	2.3 ±0.1	2.3 ±0.1	2.32±0.04	2.36±0.06
K_2O	.43±0.04	.43±0.04	.37±0.05	.44±0.02	.43±0.03	.44±0.04	.48±0.03	.53±0.04	.39±0.03
TiO_2	2.68±0.58	2.45±0.12	2.46±0.24	2.51±0.08	2.49±0.12	2.62±0.21	2.68±0.04	2.73±0.11	2.10±0.04
P_2O_5	.28±0.04	.33±0.12	.19±0.02	.30±0.01	.29±0.01	.28±0.04	.30±0.01	.29±0.01	.24±0.02
MnO	.18±0.02	.17±0.01	.17±0.01	.17±0.02	.17±0.01	.16±0.02	.19±0.01	.17±0.01	.17±0.01
Ba	121 ±20	128 ±17	n.d.	118 ±19	118 ±23	127 ±29	136 ±11	138 ±18	84 ±14
Cu	117 ±13	117 ±7	n.d.	122 ±16	116 ±12	119 ±17	91 ±22	n.d.	n.d.
Hf	3.70±0.41	3.80±0.16	n.d.	3.91±0.14	3.83±0.16	4.02±0.30	3.99±0.08	4.58±0.17	3.59±0.11
Rb	16, n.d.	14 ±3	n.d.	12 ±3	13 ±1	16 ±3	14, n.d.	11 ±3	6 ±1
Ta	.86±0.15	.93±0.12	n.d.	.88±0.06	.88±0.11	1.02±0.10	1.12±0.02	n.d.	n.d.
Th	.77±0.10	.85±0.11	n.d.	.86±0.07	.81±0.10	.80±0.06	.97±0.02	1.28±0.22	.55±0.03
Zn	127 ±36	118 ±21	n.d.	111 ±3	111 ±3	132 ±14	113 ±5	n.d.	n.d.
Zr	135 ±35	126 ±41	n.d.	153 ±17	145 ±15	156 ±25	172 ±41	159 ±20	130 ±5
Sc	32.0 ±3.5	31.2 ±0.9	n.d.	31.4 ±0.9	32.8 ±0.7	33.5 ±1.4	31.8 ±0.4	33.0 ±2.0	31.0 ±1.2
La	11.5 ±1.6	12.2 ±1.1	n.d.	11.8 ±0.8	11.6 ±1.2	12.7 ±1.0	13.7 ±0.3	15.1 ±1.7	8.9 ±0.6
Ce	27.8 ±3.7	28.4 ±2.7	n.d.	28.9 ±1.6	28.3 ±2.0	30.7 ±1.9	32.7 ±0.5	37.5 ±3.2	23.9 ±1.4
Nd	20 ±3	19 ±5	n.d.	20 ±3	21 ±3	22 ±3	23 ±2	n.d.	n.d.
Sm	5.5 ±0.5	5.5 ±0.3	n.d.	5.7 ±0.1	5.7 ±0.3	6.0 ±0.4	5.9 ±0.1	6.2 ±0.2	5.0 ±0.2
Eu	1.78±0.19	1.83±0.09	n.d.	1.89±0.05	1.84±0.06	1.92±0.10	1.93±0.03	2.00±0.07	1.69±0.04
Gd	6.6 ±0.7	4.8 ±1.4	n.d.	6.1 ±1.4	6.2 ±0.9	6.4 ±1.0	6.7 ±0.7	n.d.	n.d.
Th	.91±0.08	.82±0.04	n.d.	.96±0.04	.96±0.04	.97±0.10	.93±0.03	.96±0.03	.86±0.04
Tm	.29±0.06	.25±0.02	n.d.	.33±0.06	.34±0.04	.34±0.05	.31±0.02	n.d.	n.d.
Yb	2.16±0.17	2.14±0.06	n.d.	2.25±0.11	2.20±0.13	2.31±0.14	2.17±0.06	2.05±0.03	2.10±0.04
Lu	.31	.30	n.d.	.31	.31	.33	.32	.26	.31

content than rift-zone lava (Gerlach and Graeber, 1985) or on those of any flow close to its vent. This makes it difficult to use volatile content as an indicator of origin for the dikes.

We interpret the major-, trace-, and volatile-element data for the dikes to indicate that they are composed of Kilauea magma that had an origin and evolution similar to that of the prehistoric flows of Uwekahuna Bluff. On the basis of contact relations and the higher volatile-element abundances in the dike rocks than in surface flows, we tentatively conclude that most or all of the dikes were injected from depth or laterally, not fed by surface flows.

ORIGIN OF THE DIKES

Igneous dikes are classically interpreted (Anderson, 1938) to form by forceful injection, in which magma pressure exceeds the least compressive stress acting across a potential dike plane. The extent to which existing fractures and regional structural fabric influence the propagation of dikes varies from one tectonic setting to another (Delaney and others, 1986). Most dikes in Kilauea caldera trend northeasterly, roughly parallel to major structural elements such as the southwest and east rift zones, the Hilina and Koae fault systems, and the linear west wall of the caldera. These elements were created by seaward migration of the south flank of the volcano (Fiske and Jackson, 1972; Swanson and others, 1976).

STRUCTURAL SETTING

The dikes in the summit region are confined to the west wall (fig. 14.1). Most have a northeast orientation, similar to that of surface fractures around the west rim of the caldera and to the strike of the southwest rift zone (N. 48° E.; fig. 14.6). Ground cracks extend southwestward into the southwest rift zone and northeastward only to the Steaming Flats area (de Saint Ours, 1982).

The pattern of dikes and other structural elements suggests that the dikes formed in a stress field reflecting the combined influences of the summit magma reservoir (radial) and a linear zone of weakness related to the contact between the edifices of Kilauea and Mauna Loa (N. 40° E.). That contact might be a zone of reduced compression if gravity pulls the unbuttressed Kilauea edifice seaward away from Mauna Loa (Fiske and Jackson, 1972; Swanson and others, 1976). We postulate that this zone offers a preferred path to the surface for magma in fractures in the volcano's summit region. According to this model, the southwest rift zone, the caldera rim at Uwekahuna Bluff, and the northeasterly dikes all reflect control by a structural element related to the contact between Mauna Loa and Kilauea.

SHALLOW DIKE EMPLACEMENT AT KILAUEA

The northeasterly orientation of many of the modern eruptive fissures within the Kilauea summit region (those of 1954, 1971, 1974, 1975, 1982) indicates that the northeasterly trend is still the favored orientation for fissure-fed eruptions. These fissures are typically discontinuous and in places show echelon offsets along their strike (Pollard and others, 1983). They often propagate in the form of slowly migrating surface cracks as an eruption develops (Duffield and others, 1982); seldom do these ground cracks and fissures erupt along their entire length (Pollard and others, 1983). Intrusions of magma into the summit region and rift zones, some of which cause surface deformation and ground breakage, account for about 65 percent of the magma supplied from Kilauea's shallow magma reservoir; only about 35 percent is erupted (Dzurisin and others, 1984). Most of these intrusions probably form dikes (Swanson and others, 1976; Pollard and others, 1982; Dvorak and others, 1986) that reach shallow depths without erupting.

A number of the dikes in Kilauea caldera occupy fractures that continue to the caldera rim (fig. 14.3) but provide no evidence of having vented. We tentatively conclude that many of the dikes reached or started from very shallow depths but simply did not vent, at least not on the surface directly overlying their present host fractures in the caldera wall. We reason that the driving force of vesiculation, which increases as the dike nears the surface, is opposed by the weight of the magma, which also increases as the dike nears the surface. Partly for this reason, many shallow dikes move laterally more than vertically and vent only when their paths intersect the volcano's sloping flanks along a rift zone. Intrusions into Kilauea's rift zones commonly cause surface deformation and fractures, indicating that magma reached within a few tens to hundreds of meters of the surface without venting (Pollard and others, 1983; Dvorak and others, 1986). Once the top of a dike is shallow enough to cause ground fractures, loss of magmatic volatiles through those fractures may cause the dike's movement to stall without venting. Even if a dike succeeds in reaching the surface somewhere along its length, field observations during eruptions at Kilauea show that vents are typically separated by cracked or deformed areas that do not vent; in other words, the dike does not vent along much of its length.

We therefore conclude that (1) many shallow dikes at Kilauea do not vent; (2) dikes can stall at almost any depth because of loss of volatiles or increasing potential energy; and (3) dikes that do vent usually do so along only a part of their total length. If these inferences are correct, the lack of identifiable vent deposits above

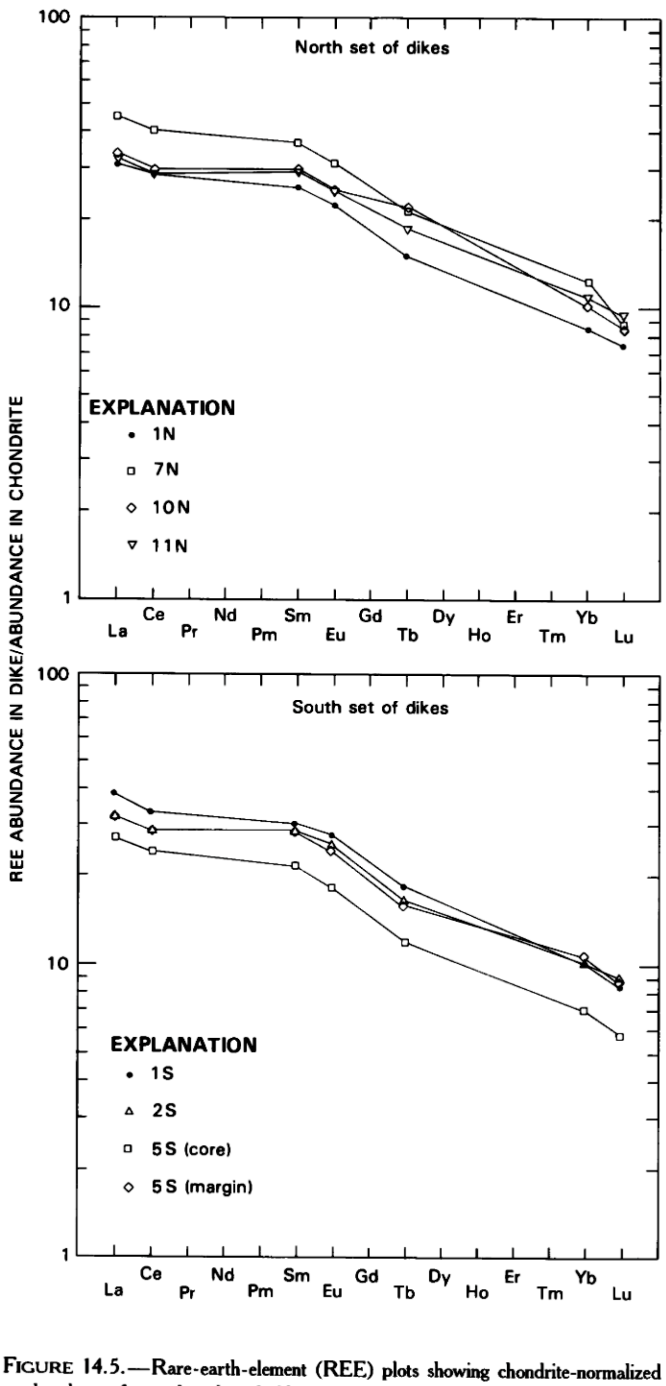


FIGURE 14.5.—Rare-earth-element (REE) plots showing chondrite-normalized abundances for north and south dike sets. Abundances are normalized to chondrite values (Haskin and others, 1968). Analytical precision for Nd, Gd, and Tm is poor (greater than ±6 percent of reported value in table 14.2), and these elements are not plotted.

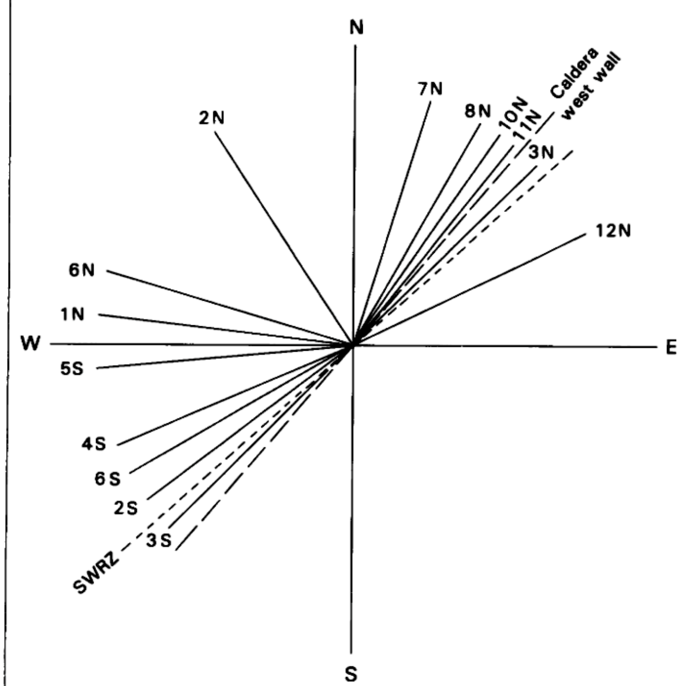


FIGURE 14.6.—Rose diagram showing orientation of dikes, west wall of Kilauea caldera. Also plotted are the orientations of the southwest rift zone (SWRZ) and the western wall of the caldera at N. 48° E. and N. 40° E., respectively.

many dikes at Kilauea caldera does not preclude an origin by forceful injection, either laterally or from below.

CONCLUSIONS

The main results of our study are the following:

(1) The Uwekahuna laccolith is the largest intrusive mass exposed in the west wall of the caldera. Contact relations indicate that most or all of the other dense lenses of rock in the wall are thick subaerial lava flows.

(2) Eighteen dikes occur in the western wall of Kilauea caldera, 12 north of and in Uwekahuna Bluff and 6 south of the bluff. The combined width of these dikes is only about 15 m and accounts for less than 1 percent of the length of the west wall.

(3) Of the 12 dikes in the north set, 5 occupy fractures cutting through the entire section of flows making up the west wall. Thus, these dikes were emplaced after all the flows had been extruded, but before the current caldera had formed.

(4) The composition of all dikes is remarkably uniform after the effects of olivine control are removed. The dikes are chemically similar to the undifferentiated summit lavas exposed at Uwekahuna Bluff and elsewhere in the Kilauea summit region.

(5) Contact relations and the volatile abundances of the dikes imply that most formed through injection, either laterally or from depth. Dikes 1N and 2N have low volatile contents and are chemically similar to the Uwekahuna laccolith and to the picritic lava flows of Uwekahuna Bluff; they may have formed by lateral injection of magma from a lava lake into a ponded sequence of picritic flows.

(6) The orientations of 15 dikes are similar to the structural grain formed by the western half of Kilauea caldera, the southwest rift zone, and the east rift zone. We conclude that the dikes formed under the combined influences of stresses caused by flexing of the summit magma reservoir and gravitational separation of Kilauea and Mauna Loa.

(7) The dikes of Kilauea caldera's west wall cut a succession of lavas that accumulated after the eruption of the Uwekahuna Ash Member, possibly as early as 2.1 ka (Dzurisin and Casadevall, 1986; Lockwood and Rubin, 1986), but before the formation of the present caldera.

FUTURE STUDIES

Several ideas about the origin of intrusive bodies at Kilauea caldera could be tested through further study. The relative ages of the dikes and the Uwekahuna laccolith could be determined by systematic paleomagnetic study supplemented by hydration-rind dating of glass from the margins of the dikes. The possible influence of regional structural fabric on dike propagation could be investigated through careful measurements of structural features such as fractures and joint sets in the vicinity of each dike (Delaney and others, 1986). More careful examination of the tops of the dikes and a thorough search for possible vent deposits could provide additional clues to their origins. Finally, additional measurements of volatile content of summit flows are necessary if the abundance of volatiles, especially sulfur and chlorine, is to be rigorously used as an indicator of dike provenance.

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