THE DIKE COMPLEX OF KOOLAU VOLCANO, OAHU: INTERNAL STRUCTURE OF A HAWAIIAN RIFT ZONE

By George P.L. Walker[1]

ABSTRACT

The Koolau dike complex in the deeply eroded lava shield of Koolau Volcano on Oahu is extraordinarily intense and where widest contains an estimated 7,400 subparallel dikes totaling 3–5 km in width. Quantitative study involving measurement of 3,550 dikes reveals that the complex has a non-Gaussian intensity distribution. Dikes generally constitute 50–70 percent of the total rock and form an intensity plateau across the complex, decreasing very rapidly to <5 percent at the edges. A proposed model for formation of the complex envisages the highly mobile tholeiitic magma as being tightly constrained by the zonation of bulk-rock density in the volcanic edifice. This model, applied to the active Hawaiian volcanoes, explains well the marked propensity of magma to stay underground in what is evidently a gravitationally very stable situation. Flow lineations on Koolau dike margins indicate that the magma generally rose obliquely, from two distinct magma supply centers situated 5 km apart and 2–3 km deep. The dikes are systematically nonvertical and form two complementary sets dipping at 65° to 85° in opposite directions, like normal faults in an extensional setting. Predominance of one dip direction over a wide area may indicate an early tendency to seaward creep of the volcano in that area. Stages in the buildup of the complex are marked by increasing proportions of dikes entering multiple clusters, these clusters having the characteristics of a sheeted dike complex. The Koolau Volcano has a wide caldera of downsag type, with probable conventional calderas in the middle. The strong inward decrease in dike concentration is interpreted to mean a general inward increase in subsidence rate, subsidence in the central area exceeding the rate of upward growth of the dike complex. This leads to the concept that subsidence of Hawaiian calderas is caused by the weight of intrusions in an area of lithospheric weakness above a hot spot.

INTRODUCTION

Many dikes are exposed where denudation has cut deeply into the older basaltic shield volcanoes of the Hawaiian Islands, and in some volcanoes they are concentrated into well-defined dike complexes. These complexes have long been regarded as the subsurface expression of rift zones such as those in which eruptions on Kilauea and Mauna Loa Volcanoes are concentrated.

A full understanding of active rift zones requires a knowledge of dike complexes, just as surely as understanding the dike complexes depends on knowing how active rift zones develop. The general distribution patterns and characteristics of the dike complexes are well established, but very little detailed information about them is available, and the present study is aimed at documenting one complex more fully than has been attempted before.

Another reason for documenting one of these complexes is that they are very similar to the sheeted dike complexes of the ophiolite suite. This suite is interpreted to form by oceanic crustal spreading along globally extensive spreading zones, whereas the dike complexes of denuded Hawaiian lava shields occur in an intraplate tectonic setting and extend high into the individual volcanic edifices. It is important to have a basis by which they can be compared with sheeted complexes.

One of the most intense and accessible of the Hawaiian dike complexes is that exposed in the core of the Koolau shield volcano on Oahu. Lava of this shield gives K-Ar ages of 2.67–1.83 Ma (McDougall and Aziz-ur-Rahman, 1972; Doell and Dalrymple, 1973). The Koolau Volcano is strongly elongate on a northwest-southeast axis and has a subaerial length of 57 km. The shield surface is well preserved on the lower parts of the interfluves along the southwestern or leeward side, and the shield form may be reconstructed (fig. 41.1) by drawing generalized contours that neglect all the lesser topographic features.

The position of the long axis of the Koolau shield is apparent from curvature of the generalized contours around the northwestern end, and this coincides with the antiform on the two sides of which the lava dips outward in opposite directions. The position is less clear at the southeast end, but the antiform lies between the Mokulua Islands and Makapuu Head, and its approximate position is shown in figure 41.1.

Erosion of the Koolau shield has been concentrated on the northeastern or windward side; between Waikane and Waimanalo, deep embayments cut right across the long axis, and more than half of the original shield has there disappeared. I agree with Moore (1964) in regarding much of the loss as having been accomplished by great landslides. An impressive cliff (the pali), which faces northeast and is as high as 900 m (3,000 ft), marks the headwall of the series of landslide scars.

A strip of low-lying ground 4–8 km wide extends from Waikane to Waimanalo and between the pali and the coast consists mostly of alluvium and reef deposits, but it is transected by

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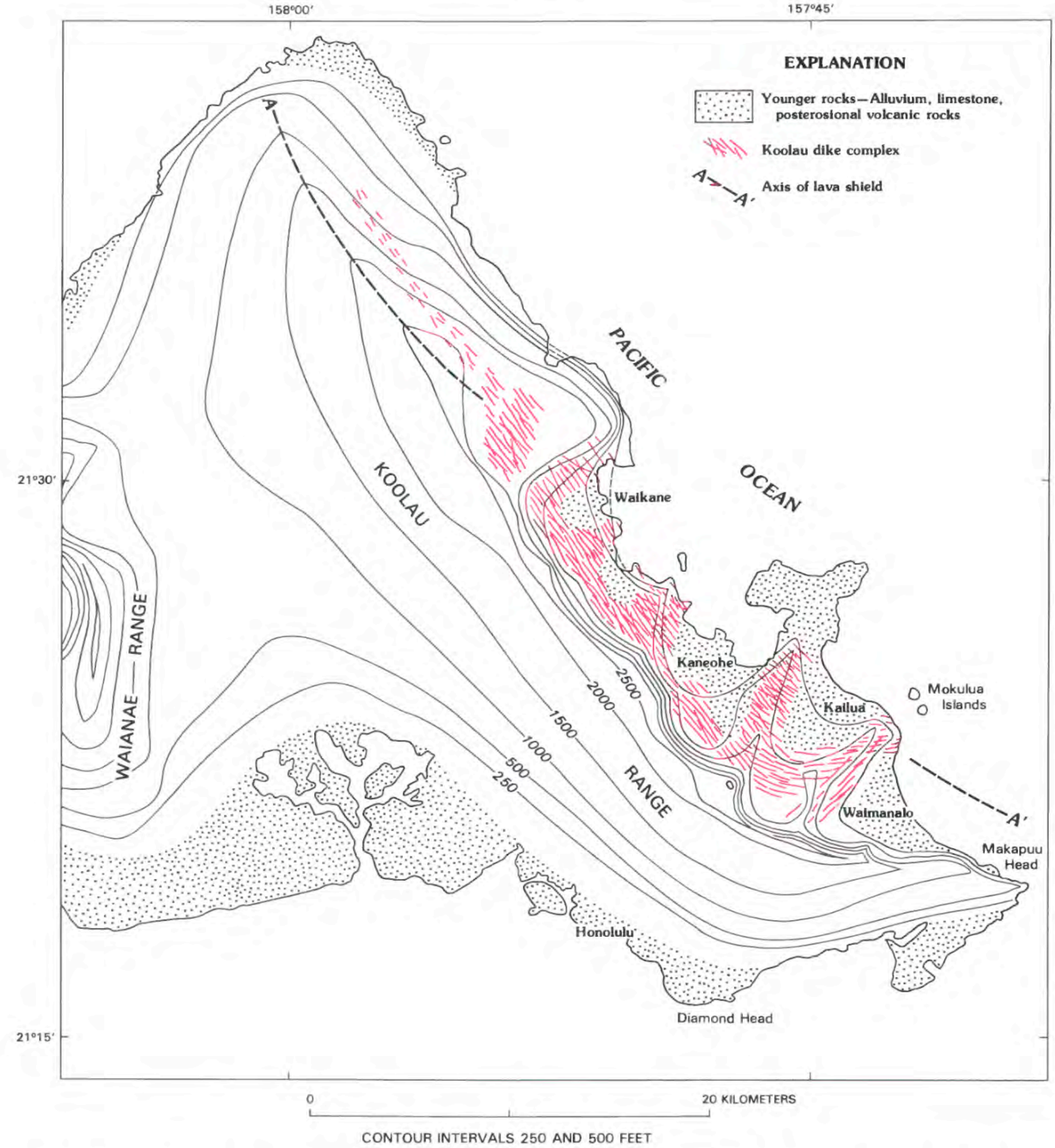


FIGURE 41.1.—Setting of Koolau dike complex on Island of Oahu. Distribution of complex (modified from Stearns, 1939) shown in relation to Koolau lava-shield volcano, form of which is portrayed by generalized topographic contours. Volcano is very strongly elongate northwest-southeast and position of axis is based on generalized contours and opposing dip directions of shield lava.

northeast-trending ridges—possibly these are septa between the landslide scars—where most exposures of the Koolau dike complex are found. Natural exposures tend to be difficult of access and unfavorable for quantitative studies. A notable exception is the two small Mokulua Islands, on which are found the finest known outcrops.

The present study has relied much on artificial exposures. Noteworthy among these are roadcuts in the unfinished H3 Highway, the two large Kapaa quarries, and cuts in new housing subdivisions in the Keolu Hills. The available artificial and natural exposures are thought to be just adequate to reveal the principal features of the Koolau dike complex.

ACKNOWLEDGMENTS

This research was not funded and was undertaken as a part-time activity to satisfy scientific curiosity, contribute to the geological understanding of Hawaii's volcanism, and complement the fine research done on active volcanoes of Hawaii by personnel of the Hawaiian Volcano Observatory. It was made possible by my employment at the University of Hawaii. I thank Kevin Kennedy for introducing me to the Mokulua Islands, the Manager of Kapaa Quarry for permission to visit, and the U.S. Air Force for permission to visit Bellows Air Force Base. I also acknowledge useful comments by reviewers Paul Delaney, Mary M. Donata and Tom L. Wright, and my wife for her help and forebearance. This paper is Hawaii Institute of Geophysics contribution number 1706.

PREVIOUS WORK

The distribution of the dike complex and the positions and trends of isolated dikes elsewhere, were clearly shown on the 1:63,360-scale map of Stearns (1939) and described by Stearns and Vaksvik (1935). They distinguished two dike complexes lying alongside one another and having a parallel trend. The former cuts volcanic rocks of the Kailua Volcanic Series (now Kailua Member of the Koolau Basalt) which they interpreted to have accumulated under or close by the caldera of the Koolau shield volcano, whereas the latter cuts shield-building lava of the Koolau Volcanic Series (now Koolau Basalt). Takasaki and others (1969, 1982) accepted the distinction between caldera infill and shield-building lava but regarded the complex as one, and I follow this usage.

Wentworth (1951) applied the term "dike complex" to areas where there are 100 or more dikes per mile, and Takasaki and others (1969) applied it to areas where dikes constitute more than 5 percent of the rock. The latter authors called the zone adjacent to the dike complex, characterized by scattered dikes that constitute less than 1 percent of the rock, the marginal dike swarm, and pointed out (p. 14) that "although the strike of dikes is generally the same in both zones, the dike complex and the marginal dike zone are distinct, and no transition zone intervenes." Dike complex is a useful term for an intense swarm in which the dikes are so narrow, numerous and intertwined that it is not feasible to map individual members.

The important influence of the Koolau dikes on ground-water storage in the Koolau Range led to studies of them by Takasaki and others (1969), Takasaki (1981), and Takasaki and Mink (1982). These authors mapped the dike complex and marginal zone and measured the dike trend and intensity in six water-supply tunnels west of Waikane.

The maps of Stearns (1939), Takasaki and others (1969), and Takasaki and Mink (1982) show clearly the predominant northwest-southeast trend of the dikes, parallel with the longitudinal axis of the Koolau shield. They also show dikes trending in a southwesterly direction from Kailua into the leeward side of the Koolau Range towards Diamond Head; these have been identified as a secondary swarm (the Kaau or southwest rift zone) analogous with the minor rift zones that occur on some active Hawaiian volcanoes.

Few studies have hitherto been made of the dike structures, apart from that by Wentworth and Jones (1940) on jointing and the distribution of amygdules. Among recent workers, Ryan and others (1983) most clearly recognized how important it is to study the dike swarms when seeking to understand rift zones. Walker and Kennedy (in preparation) describe aspects of the dike complex exposed on the Mokulua Islands, and Walker (1986) discussed the origin of the complex in an earlier report on the present study.

DIKE DISTRIBUTION

The present quantitative study of the Koolau dike complex is based on measurements made at 55 localities in windward Oahu, distributed as shown in figure 41.2 and listed in table 41.1. At each locality the width, trend, and dip of each dike was measured; the dike widths in a measured traverse were also totaled so as to yield the dike intensity, expressed as the percentage of rock composed of dikes, as shown in figure 41.3. Intensity is alternatively expressed as the calculated number of dikes per 100 m of traverse in a direction at right angles to the predominant dike trend, as shown in figure 41.4. The measured traverses totaled 7.4 km in length and contained 3,550 dikes aggregating to 2.6 km in width. Data from these 55 localities are supplemented by data from six water-supply tunnels (Takasaki and others, 1969; Takasaki, 1981).

The dikes very commonly occur in multiple clusters as wide as about 20 m, in which successive subparallel members were injected either along the margins of, or inside, preceding dikes; dikes constitute 100 percent of the width of such a cluster. Screens of country rock occur between clusters. A valid value for the dike intensity is obtained only if the measured traverse includes at least several dike clusters and their intervening screens.

The highest intensity (80–85 percent) occurs on the coast at Heeia (locality 41) and on the Mokulua Islands (localities 19 and 20); a measured 185-m traverse most of the way across the northwestern island recorded 240 dikes totaling 145 m thick. The dike intensity is high, exceeding 40 percent, in a belt of country 3–6 km wide extending northwest from Kailua, but it is not uniformly high over the entire length or width of this belt; in particular it drops to 2 percent in the Kailua caldera, which interrupts the continuity of the complex. The calculated number of dikes per 100 m (fig. 41.4)

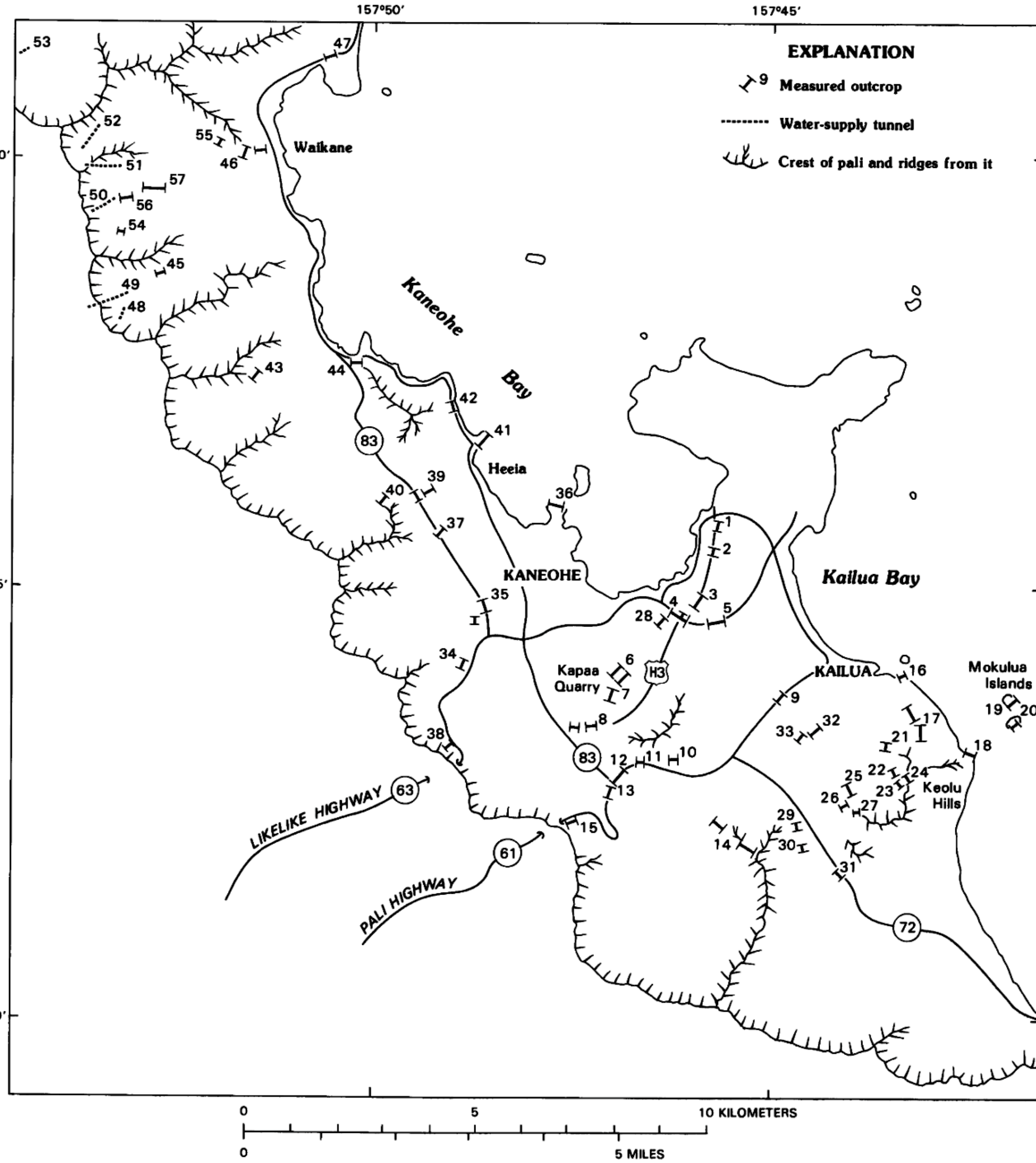


FIGURE 41.2.—Windward side of Oahu showing location of outcrops at which dike complex was studied. Numbers identify outcrops listed in table 41.1. All but outcrops 14, 15, and 38 are less than 240 m (800 ft) above sea level, and most are less than 120 m (400 ft) above sea level.

TABLE 41.1.—*Localities in the Koolau dike complex used for the present study*

[W, deeply weathered outcrop]

Number	Location and description
1.	Northernmost deep cut in Highway H3.
2.	Middle cuts beside viewpoint on Highway H3.
3.	Southernmost deep cut in the Highway H3 north of the join with Mokapu Saddle Road.
4.	Cuts in Mokapu Saddle Road near the Highway H3 overpass and adjacent cuts.
5.	Cut in Mokapu Saddle Road near Kalaheo High School.
6.	Kapaa Quarry, northeastern of two.
7.	Kapaa Quarry, southwestern of two.
8.	Cuts in Highway H3 between Kapaa Quarry and Kamehameha Highway (W).
9.	Cut in Kailua Road south of its join with Kaelepulu Street.
10.	Cut behind Kailua Drive-in Theatre (W).
11.	Cut in Kalanianaole Road 0.8 km (0.5 mi) northeast of join with Kamehameha Highway (W).
12.	Cut in Kalanianaole Road just northeast from join with Kamehameha Highway (Castle Junction) (W).
13.	Cut in Kalanianaole Road just southwest from join with Kamehameha Highway.
14.	Northwest ridge of Olomana Peak.
15.	Cuts in Old Pali Highway, northeast from pass.
16.	Coast exposures and nearby road cuts, Alala Point.
17.	Northern part of Kaiwa Ridge.
18.	Coast exposures at Wailea Point.
19.	Coast exposures on northwestern Mokulua Island, northwestern of two.
20.	Coast exposures on Mokulua Islands.
21.	Hillside west of Kaiwa Ridge, above Kamahele Place.
22.	Cuts behind subdivision alongside Kuuna Place.
23.	Cuts at north end of Apokula Street.
24.	Cuts on hilltop east of Apokula Street.
25.	Cuts behind subdivision alongside Auwaiku Street.
26.	Cuts west of Auauki Street.
27.	Cuts near hilltop south of Aunauma Street.
28.	Cut in track off Kahinani Way.
29.	Northern section of Old Kalanianaole Road.
30.	Middle section of Old Kalanianaole Road.
31.	Southern end of Old Kalanianaole Road.
32.	Cuts north of Akiohala Place.
33.	Cuts north of Akiohala Street.
34.	Cut on southwest Kahekile Highway 0.8 km (0.5 mi) of join with Likelike Highway (W).
35.	Cuts in and near Kahekile Highway 0.8 km (0.5 mi) north of join with Likelike Highway (W).
36.	Coast exposures and nearby road cuts at Pohakea Point.
37.	Cut in Kahekile Highway 1 km (0.6 mi) northwest of join with Haiku Road (W) and behind subdivision east of Highway (W).
38.	Stream section at foot of Pali just north of Wilson Tunnel.
39.	Cut in Kahekile Highway just southeast of Temple Valley Shopping Center and in fields to east (W).
40.	Cuts in Valley of the Temples Memorial Garden (W).
41.	Coast exposures at Kealohi Point (Heeia State Park) (W in part).
42.	Coast exposures 0.8 km (0.5 mi) northwest of Kealohi Point.
43.	Pit at foot of southeastern spur of Kalahaku Ridge (W).
44.	Cuts in Lulani Street and at join of Kamahameha Highway with Kahekile Highway.
45.	Roadcuts west of Waiahole Camp (W).
46.	Badland and ridge exposures on southeastern side of Puu Pueo Ridge (W).
47.	Cuts in Kamahameha Highway west of Kualoa Park turnoff.
[1]48.	Intake tunnel A.
[1]49.	Main transmission tunnel R.
[1]50.	Uwau tunnel.
[1]51.	Waikane 2 tunnel.
[1]52.	Waikane 1 tunnel.
[1]53.	Kahana tunnel.
54.	Path cuts at head of Waianu Valley.
55.	Badland exposures at southwestern foot of Puu Pueo (W).
56.	Path cuts east of Uwau tunnel.
57.	Path cuts on southern side of interfluve between Waikeekee and Uwau Valleys.

[1]From Takasaki and others (1969).

is between 50 and 100 over most parts of the complex where the intensity exceeds 40 percent, and reaches 130 in the Mokulua Islands; it drops to less than 10 in the Kailua caldera.

The Koolau dike complex was shown by Stearns (1939) to extend at least 35 km from Kailua in a northwest direction. It is assumed to extend also southeast beyond Waimanalo; exposures deep in the volcano are absent there, however, and all that is seen is a few southwest-trending dikes cutting lavas near the original shield surface on and near Makapuu Head.

The dikes predominantly have a northwest-southeast strike parallel with the longitudinal axis of the Koolau shield (fig. 41.5) and show a high degree of parallelism. Dike swarms elsewhere tend to have a fascicular (that is, cornsheaf-like) or radial arrangement, with at least some degree of divergence away from the volcanic center to which the dikes are related; the Koolau complex is noteworthy for the lack of divergence.

A subsidiary dike complex, well defined but narrower and less intense, trends southwest across the Keolu Hills in the general direction of Diamond Head, and the generalized contours of figure 41.1 show that the volcano bulges out slightly in this direction. This subsidiary complex attains a maximum intensity of about 15 percent at locality 31. Southwest-trending dikes on its extension to the leeward side of the Koolau Range were mapped by Stearns (1939) and Wentworth and Jones (1940).

The center of the Koolau Volcano is considered to be situated in the general area of Kailua, and the two complexes are regarded as the subsurface expression of two rift zones, a main northwest one and a minor southwest one. Note, however, that the pattern is not a simple one of two intersecting orthogonal dike complexes: the western part of the main complex seen in localities 12 and 13 curves around toward the Keolu Hills, where it converges on the minor southwest one. The dike swarm intensity of 80 percent at locality 23 in the Keolu Hills is therefore not simply that of the southwest rift zone.

At localities 23 and 24, where both northwest- and southwest-trending dikes occur, crosscutting relationships indicate that the injection of northwest dikes alternated with that of southwest dikes (fig. 41.6*A*), and similar relationships are seen at locality 4 (fig. 41.6*B*) and elsewhere. This shows that the periods of injection in the two directions overlapped.

This time relationship was not expected: in the model of Fiske and Jackson (1972), dike orientation is controlled by the overall geometry of a Hawaiian volcano and tends to run parallel with the long axis of the edifice. It is difficult to see how the edifice effect by itself could generate dikes alternating in trend along two orthogonal axes.

DESCRIPTION OF THE DIKES

WIDTH

Widths were measured on 3,550 dikes of the Koolau complex and are recorded by the histogram, figure 41.7*A*. Dikes range in width from less than 5 cm to 670 cm, and the median width is 53 cm. The arithmetic average width is 73 cm; this is greater than the median because of the contribution made to the total width by the small number of very broad dikes. The dike widths can also be portrayed in a different way, as the percentage of total dike width contributed by each width class (fig. 41.7*B*); 50 percent of the dikes are 60 cm or less wide, but these narrow dikes account for only 20 percent of the total width, and the 20 percent of dikes that are more

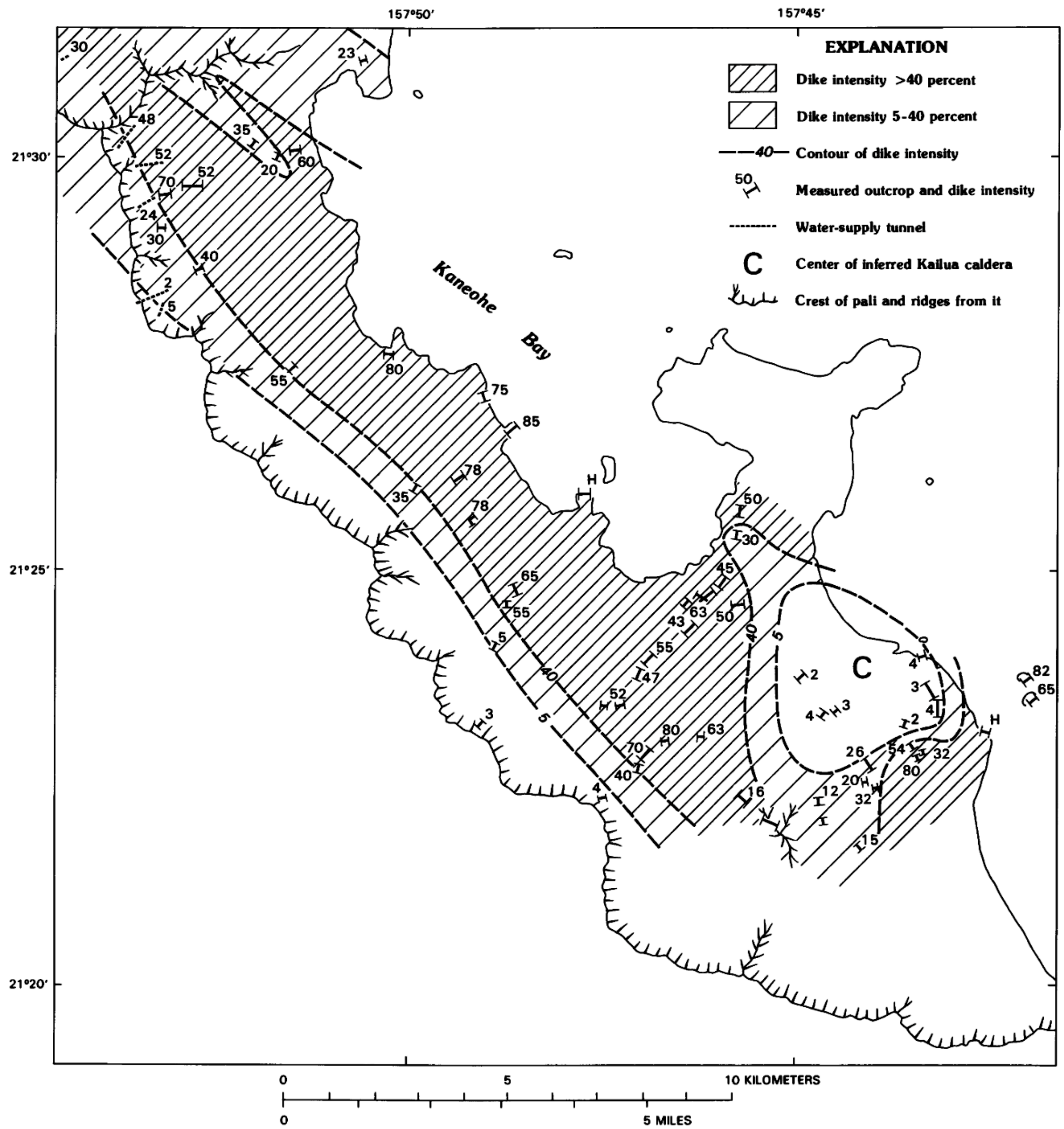


FIGURE 41.3.—Intensity of Koolau dike complex, expressed as percentage of outcrop width occupied by dikes. Close-shaded area is that in which dikes constitute 40 percent or more. Complex attains its maximum width of about 7 km in Kailua area, and narrows significantly toward northwest. The dike intensity is anomalously low in a large area centered on Kailua, interpreted to mark a caldera or caldera cluster. The intensity values at localities 3, 5, and 10 include 30 percent added for early brecciated dikes. H denotes a high intensity, but no measurement obtained.

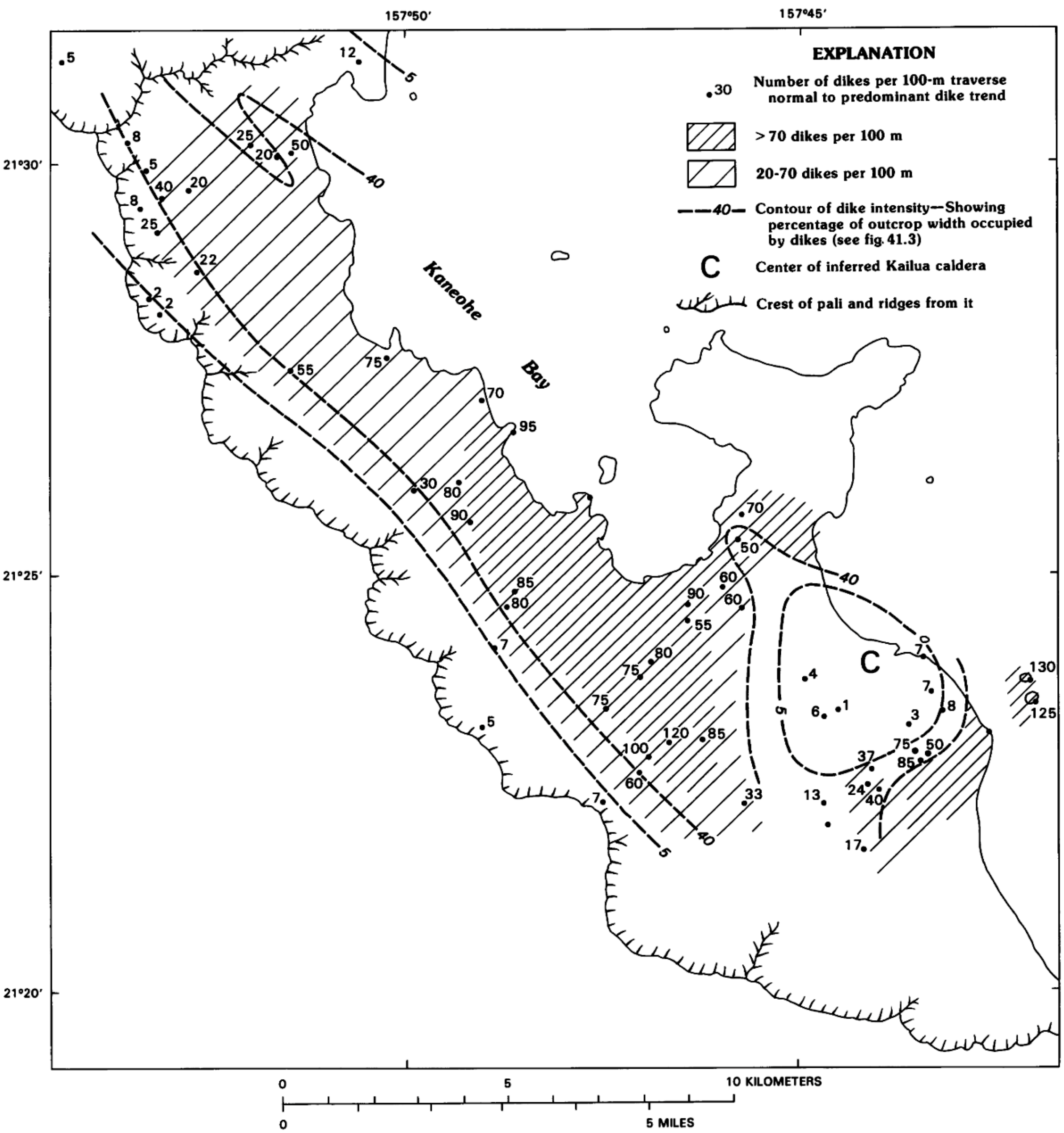


FIGURE 41.4.—Intensity of Koolau dike complex, expressed as number of dikes per 100-m traverse at right angles to predominant dike trend. Intensity contours from figure 41.3 also shown. Highest numbers of dikes (>100) occur where dikes form a high percentage of outcrop and also are narrow.

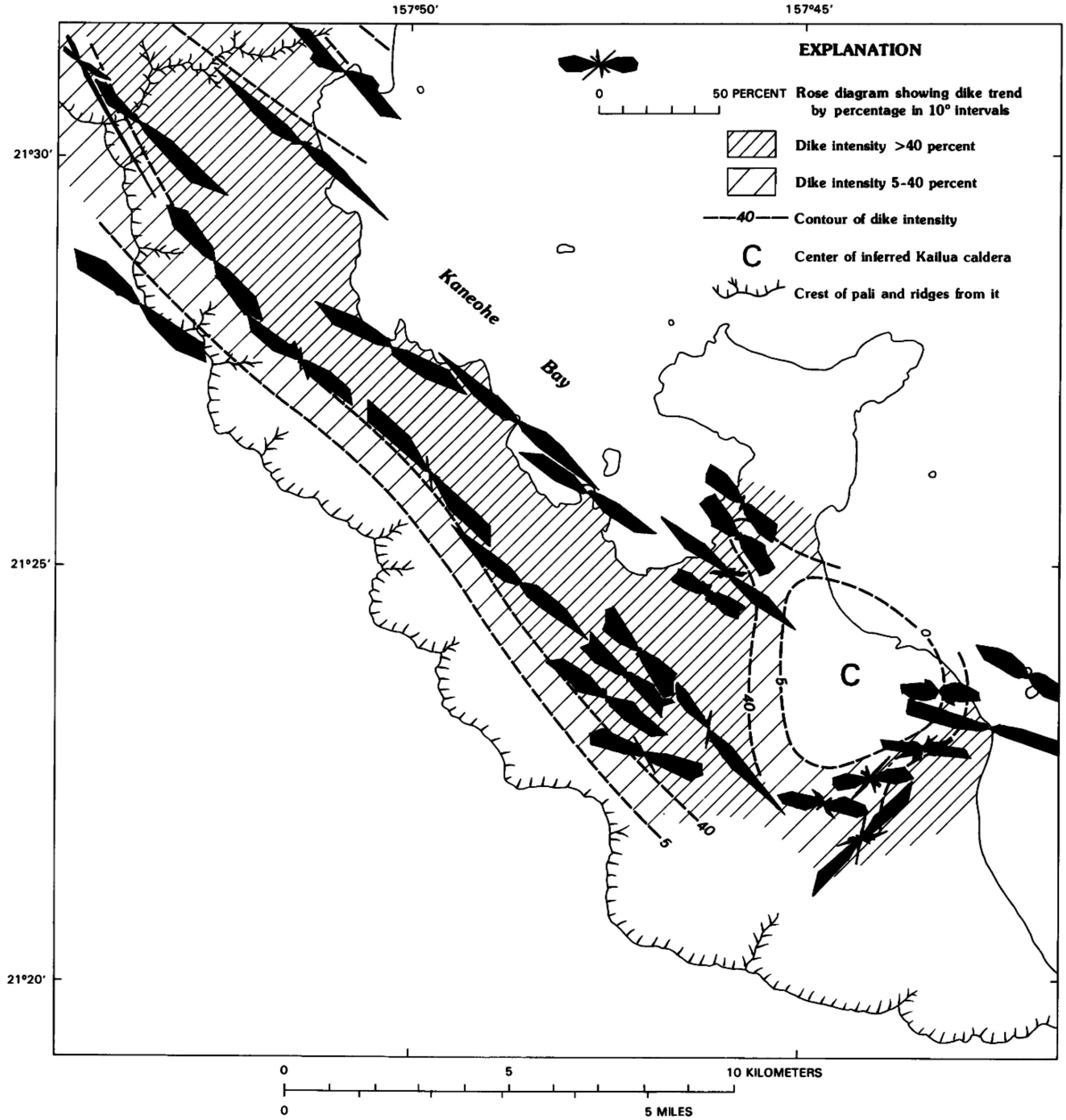


FIGURE 41.5.—Dike trends in Koolau dike complex. Rose diagrams constructed using 10° interval. Pattern is dominated by northwesterly trend: 70 percent of all measured dikes have a trend within 22.5° of N. 50° W. Subordinate but distinct southwest-trending complex occurs in south of area.

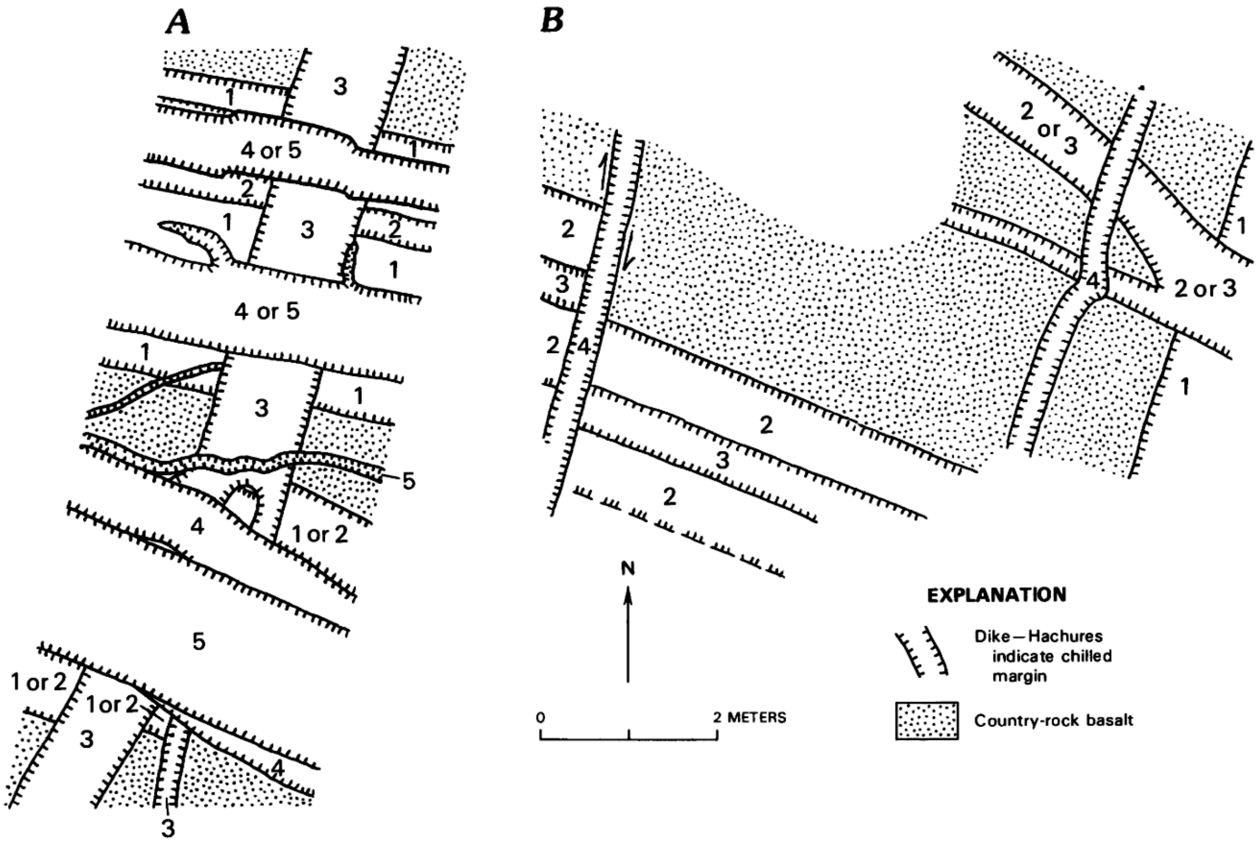


FIGURE 41.6.—Examples of age relationships at outcrops in Koolau dike complex where orthogonal dike intersections occur, shown somewhat schematically. ***A***, At locality 24. West-northwest-trending dikes (1 and 2) are cut by north-northeast-trending dike (3) that is cut by west-northwest-trending dikes (4 and 5). ***B***, Locality 4. North-northeast-trending dike (1) is cut by west-northwest-trending dikes 2 and 3, which are in turn cut by north-northeast trending dike (4). Note that significant fault movement occurred on one of the dikes (4).

than 110 cm wide account for 50 percent of the total width. The distribution in figure 41.7*B* closely approximates a lognormal distribution.

The dike widths of the Koolau complex are compared in figure 41.8 with those of Tertiary basaltic dike swarms in Iceland (Walker, 1959; Gudmundsson, 1984), which occur in the tectonic setting of an oceanic spreading center. The Koolau dikes are on the whole much narrower. This may reflect a generally lower viscosity of the Koolau magma but is at least partly attributable to the close proximity of most of the measured Koolau dikes to their volcanic center. Most of the measured Koolau sections lie within 15 km of the Kailua center, whereas the Icelandic dikes were mostly measured farther than 15 km from the respective volcanic centers to which they are related.

The width of dikes varies in different parts of the Koolau complex; it trebles from the Kailua volcanic center to the Waikane area (figs. 41.9, 41.10). The most obvious reason for this increase in width is that the lateral distance a dike travels from its source is related to its width: broader dikes are more far-ranging, and therefore far from the source the dikes tend all to be wide ones. As discussed in a later section, the trebling of average dike width is accompanied by a decrease to less than one third of the number of dikes present in transects across the complex.

LITHOLOGY

The Koolau dikes are basalts and diabases and are generally aphyric or have only a small content of phenocrysts. Phenocrysts are of olivine, augite, and plagioclase and are mostly less than 4 mm in size. Some dikes are highly porphyritic; the most common type, several examples of which are seen at localities 1 and 3, has aphyric margins and a central part containing abundant olivine phenocrysts. The abrupt juxtaposition of aphyric and porphyritic rocks is suggestive of the injection of two successive magma fractions. One porphyritic dike at locality 4 contains about 50 percent of platy plagioclase crystals, many exceeding 1 cm in size, decreasing in abundance toward the margins.

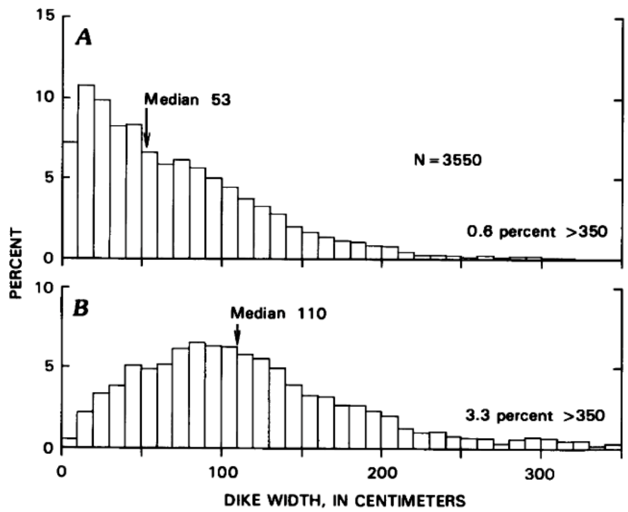


FIGURE 41.7.—Distribution of dike width in Koolau dike complex. N, total number of dikes. ***A***, Histogram of dike widths. Median width is 53 cm, arithmetic average 73 cm. About 90 percent of the dikes are less than 150 cm wide. ***B***, Percentage of total dike width contributed by each width category.

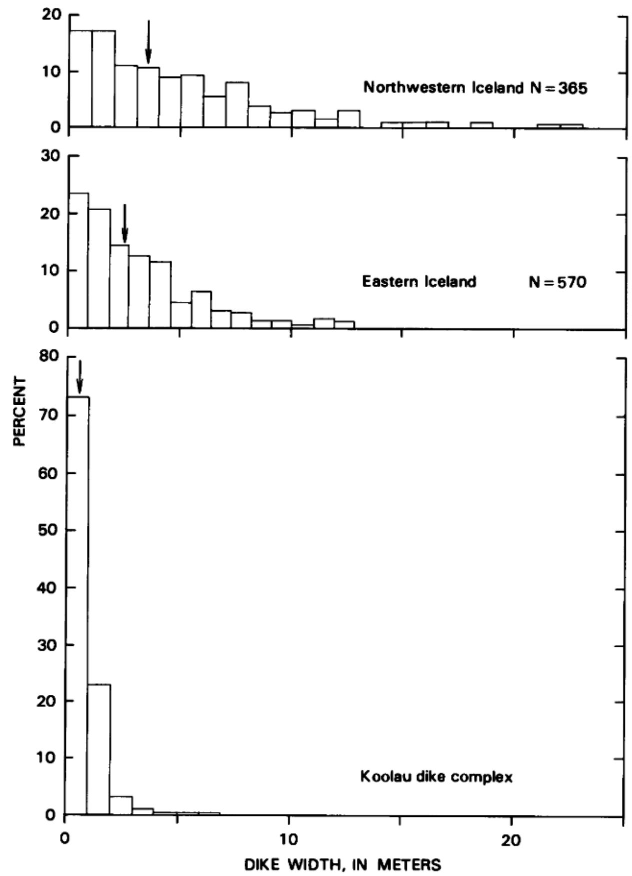


FIGURE 41.8.—Dike widths in Koolau complex compared with Tertiary basaltic dike swarms in eastern Iceland (Walker, 1959) and northwestern Iceland (Gudmundsson, 1984). Arrows indicate median width. Dikes in the Icelandic swarms are significantly wider than those in Koolau complex (median width 5–6 times greater). N, total number of dikes.

The dikes typically have glassy chilled margins and show a gradual steady increase in grain size inward from rim to center. The inner part of the glassy selvage is generally altered to orange palagonite, and this makes the dike margins easy to see. The width of the layer of glassy rock averages about 1 cm but varies from less than 1 cm to about 5 cm. One dike on the shore at locality 41 has glassy margins about 10 cm wide; the glass has varioles scattered through it or concentrated in narrow bands, and the banding is locally folded.

The three main roadcuts in the completed section of Highway H3 (localities 1–3 in figure 41.2 and table 41.1) provide fine exposures of the Koolau dike complex, and close examination of localities 1 and 3 reveals that the complex actually consists of two complexes, as follows: (1) An older complex consisting of highly irregular sheetlike intrusions, many of them amygdaloidal, which lack their own individual sets of cooling joints and have been affected at locality 3 by a pervasive propylitic alteration; and (2) a younger complex consisting of nearly planar dikes, which mostly have a low content of amygdules, possess their own individual sets of prismatic or sheetlike cooling joints normal to their margins, and are less altered.

An outstanding feature of the older dikes is that they are highly irregular, often curved and with outwardly convex protuberances, suggesting that they were intruded into a loose and yielding environment. The best explanation is that these dikes were injected into thin and strongly disjointed lava flows near the land surface of their day and sent off many sheetlike and irregular apophyses into these flows. Near-surface lava in Hawaii is typically transected by a great many cooling joints, vesicle partings, flow-unit boundaries, rubble layers and other planes of weakness, and dikes cutting them are highly irregular. Good examples are seen in the walls of Kilauea caldera and in roadcuts near Makapuu Head in Oahu.

The older dikes are amygdaloidal, often conspicuously so, and this is consistent with their intrusion near the surface. Amygdules tend to increase in size toward the dike center (fig. 41.11*C*), and attain a greater size (commonly exceeding 1 cm) in the wider dikes than in the narrower ones (fig. 41.11*A*). They tend to be concentrated in layers parallel with the dike margins. The amygdules contain zeolites (notably laumontite) and other secondary minerals.

A few older dikes contain pipe amygdules in a zone near the margin. The pipes on either side of a dike form parallel sets, the orientations of which combine growth of the pipes inward from the dike margin and their alignment in the magma flow direction.

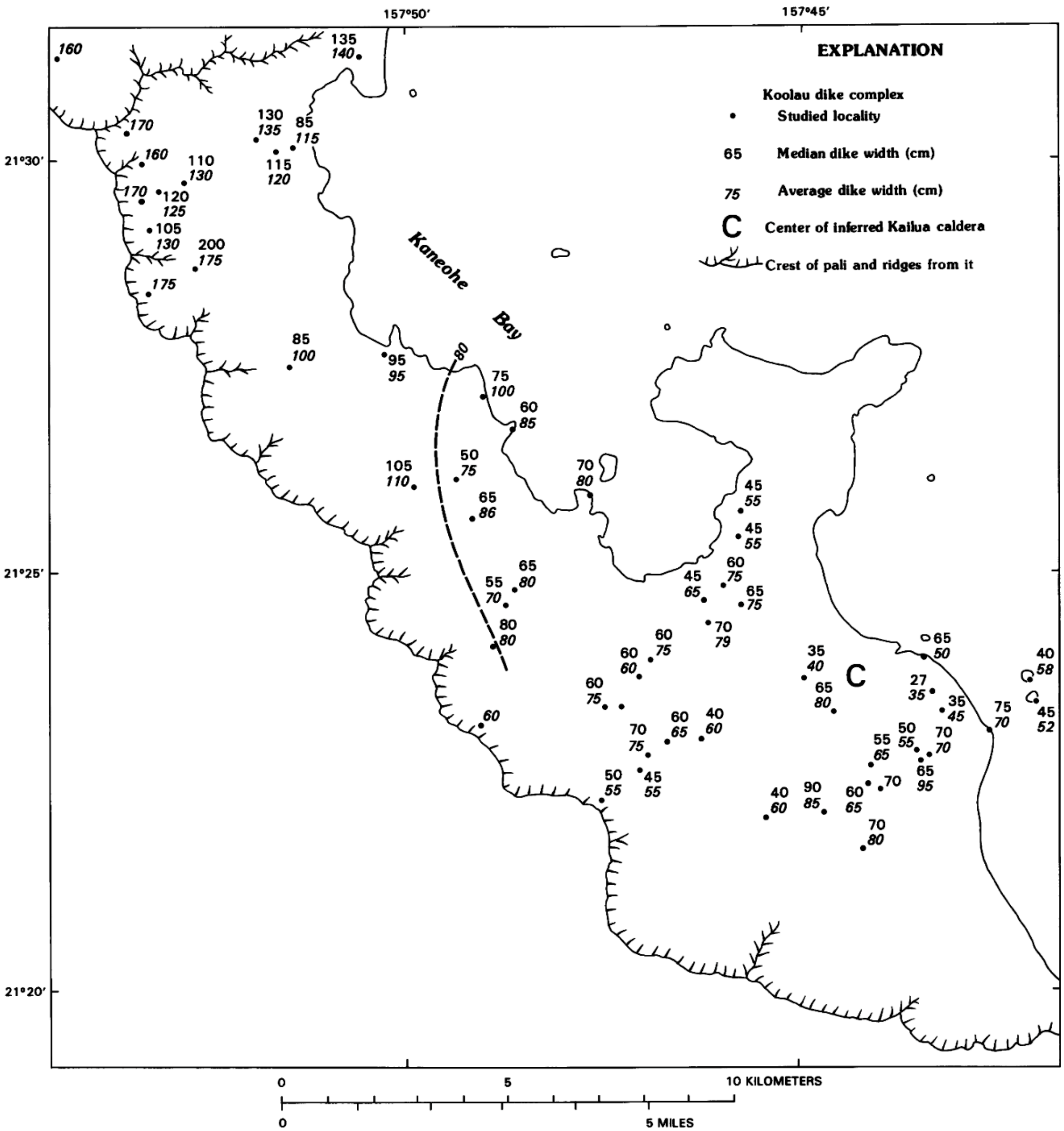


FIGURE 41.9.—Geographic variation of dike width in Koolau complex. Figures give width in centimeters. Arithmetic average width is generally larger than median. Note that lowest values occur in Kailua area, where center of Koolau Volcano was situated, and values tend to increase with increasing distance from center.

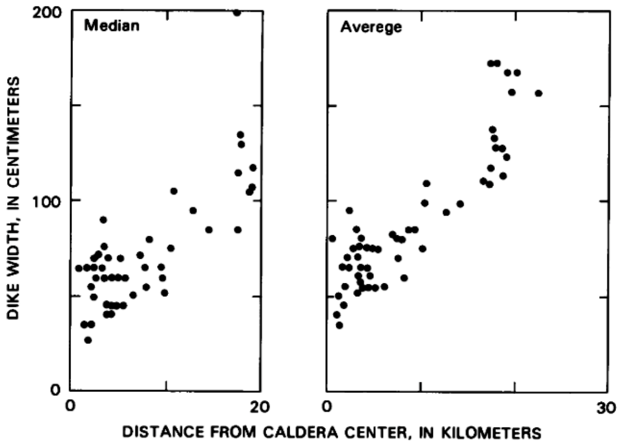


FIGURE 41.10.—Variation in median and average dike widths in Koolau complex with distance from presumed center of Kailua caldera (see figure 41.9 for location). Both median and average widths show a clear tendency to increase with increasing distance.

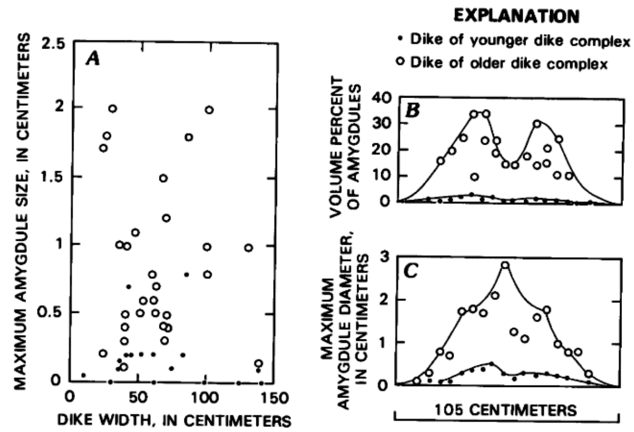


FIGURE 41.11.—Variation of amygdule size and content in dikes of Koolau dike complex. ***A***, Maximum amygdule size versus dike widths for 49 dikes at localities 2, 3, and 4, showing tendency for amygdule size to increase with dike width. ***B***, Profiles showing amygdule content across two dikes at locality 3, a typical member from each of older and younger complexes; each dike is 105 cm wide. ***C***, Profiles showing maximum amygdule size across same two dikes as in ***B***.

Another important feature of the older dikes is the presence on them of conspicuous pale green rims 1–2 cm and occasionally as much as 5 cm wide, interpreted to consist of altered glass of a thickness suggestive of quenching in water. The loose and yielding lava pile into which they are interpreted to have been intruded may have contained abundant ground water.

The younger dikes in the roadcuts on Highway H3 tend to possess their own joint sets instead of imposed joint systems such as cut the older dikes. Close-spaced cooling joints normal to the margins are particularly well developed in marginal parts of many dikes. The nearly planar form of the dikes indicates that they were intruded into rigid rocks. The general scarcity and small size of amygdules indicates that the younger dikes were probably intruded under a thick cover.

The observed relations among the dikes in localities 1 and 3 are consistent with the view that the earlier members were intruded in a very shallow setting, near the land surface of their time, into an assemblage of thin and mechanically very weak lava flows with a high water table; the younger members on the other hand were intruded at a much deeper level after a considerable thickness of lava had been added to the Koolau shield volcano. The differences are similar to those that Wentworth and Jones (1940) inferred to be related to different depths of intrusion; at localities 1 and 3, however, dikes intruded thus at different depths are now found side by side at the same level, instead of (as Wentworth and Jones found) at different levels in the shield.

FLOW LINEATIONS

The chilled edges of many dikes carry a lineation that appears to have been produced by magma flowage through the dike fissure. The flow lines of this lineation generally consist of millimeter-high wrinkles projecting out from the glassy surface of the dike or from planes within the glass selvage. Streaky coloration often also occurs in the outermost few millimeters of glass. Slickensidelike grooves are occasionally seen on a sheet joint a few centimeters inside the dike margin. Pipe vesicles in marginal parts of a few dikes have a parallel orientation neither vertical nor normal to the dike margins but in the flow direction. Spindle-shaped vesicles are also rarely found in the dike margins elongate in the flow direction.

The attitude of the flow lineation has been systematically measured to investigate its utility. Such mapping has rarely been attempted since attention to its potential was drawn by Harker (1904). Flow lineations are common on the Koolau dikes but have been measured on fewer than 10 percent of the dikes examined because they are seen only where a sufficiently broad dike surface is bared and is not so weathered that the outermost few millimeters have been stripped off.

The lineation plunges at an angle that, within a few meters, typically varies over a range of about 50°, as illustrated by figure 41.12. Some of this variation is clearly related to local irregularities in the dike surface as where the flow lines curve around surface bulges.

Wherever possible, measurements of the plunge were made at different points on the same dike, avoiding places where the lineation was strongly curved. The median plunge angle was then determined. In all, measurements were made and the median angle determined on more than 100 dikes.

At some localities, the lineations in most dikes plunge in the same direction, though the angle varies from dike to dike over about 50°, as illustrated by figure 41.13*A*. At such localities the median plunge angle was determined and is plotted on figure 41.14. At other localities the dikes fall into two groups having opposing plunge

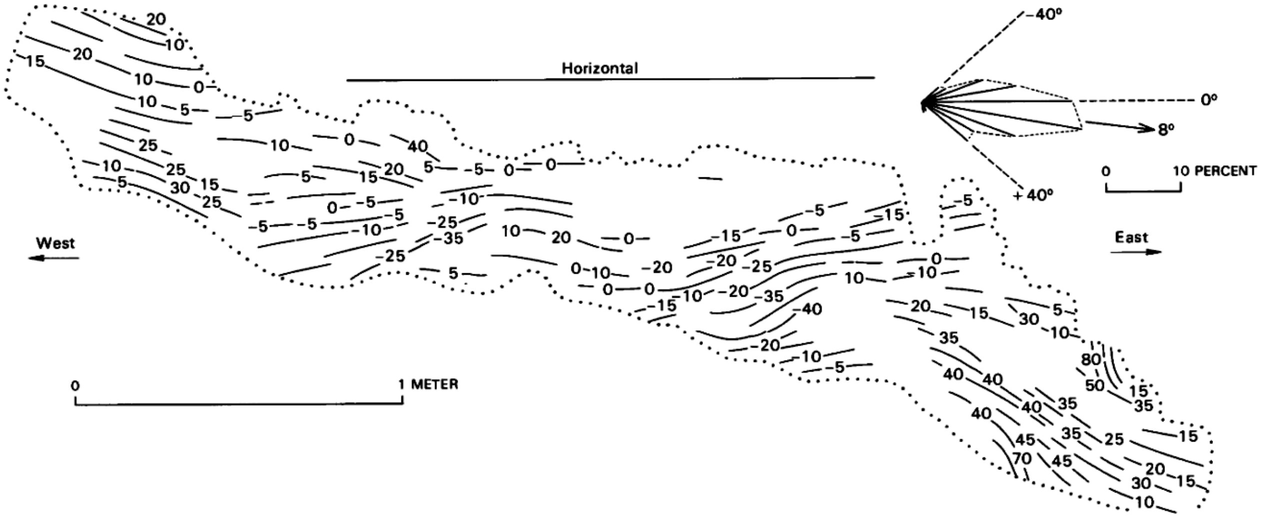


FIGURE 41.12.—Flow lineations on steeply dipping dike surface (area 1.8 m^2) in Koolau dike complex (loc. 4). Numbers give measured plunge in degrees measured from horizontal. Inset at upper right: rose diagram showing variation in plunge angle, based on 89 measured values. Median plunge angle is 8° to east; 75 percent of measured values are within about 25° of this angle.

directions, as illustrated by figure 41.13*B*; at these localities the median plunge angle for each group was determined, and both angles were plotted on figure 41.14.

The arrows on figure 41.14 record the predominant directions of the flow lineation at each locality, and the numbers give the median plunge angle. Most of the arrows point toward Kailua or to an area southwest of Kailua, but many point toward Kaneohe Bay.

In interpreting these data it is assumed that the magma rose through each dike fissure, and the arrows that record the predominant plunge directions on figure 41.14 thus point back towards the source regions from which the dike magma came. At least two source regions are indicated, one below Kailua caldera and the other below Kaneohe Bay. The depth at which the plunge lines would intersect is about 2–3 km below sea level.

DIKE SIDESTEPS

Dike sidesteps are commonly observed in which a dike tapers out and then resumes on a parallel course as much as several meters to one side. In some examples the two sidestep segments are joined by a narrow stringer; in others a connection is presumed to have existed above or to exist below the present erosion surface. Sidesteps are observed on both vertical and horizontal surfaces, but outcrops in the Koolau complex are less favorable for studying the latter. Attention is therefore concentrated on the features of sidesteps seen in vertical sections.

At a sidestep in a dike having the dominant northwesterly trend, the upper segment may step either to the southwest or the northeast side; these are referred to as southwest and northeast sidesteps, respectively. A study was made at several sites to determine if one sidestep direction is particularly favored and whether dike sidesteps have utility in structural studies. Curry and Ferguson (1970) considered the origin of offsets, and Pollard and others (1975) and Delaney and Pollard (1981) investigated the position of offset segments in sheet intrusions relative to the propagation direction. Few studies, however, have attempted to relate dike sidesteps to the overall structure of a rift zone (see Duffield and Nakamura, 1973).

Eight good examples of sidesteps were identified among the younger dikes in locality 3 (fig. 41.15), and it is seen that southwest and northeast sidesteps are roughly equal in number. This is also true at other localities, and thus the sense of sidesteps is probably not determined by any regional pattern.

Closer examination of the dike sidesteps at locality 3 reveals that about half occur where the sidestep dike cuts across an earlier dike and steps across from one to another plane of structural weakness.

I conclude that the dike sidesteps form mostly where the course of a dike trends obliquely across the preexisting grain (the trend of earlier intruded dikes) of a dike complex.

DIKE INCLINATION

The dikes of the Koolau complex are predominantly steeply dipping (generally 65°–85°) but not vertical. The measured dips are plotted on the histograms of figure 41.16. The reason for this departure from verticality is one of the most intriguing of the problems posed by the complex.

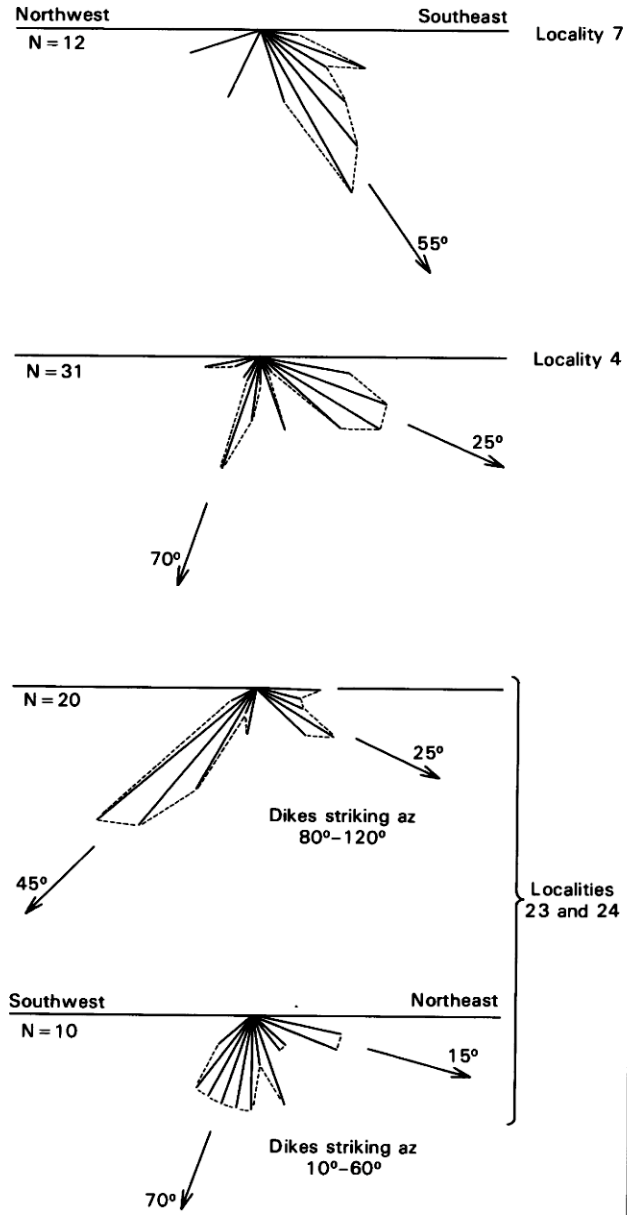


FIGURE 41.13.—Rose diagrams of average plunge of flow lineation measured on dikes at localities 4, 7, 23, and 24. At least one source is deduced for locality 7 and two sources for locality 4; arrows give predominant plunge. N, number of measured dikes.

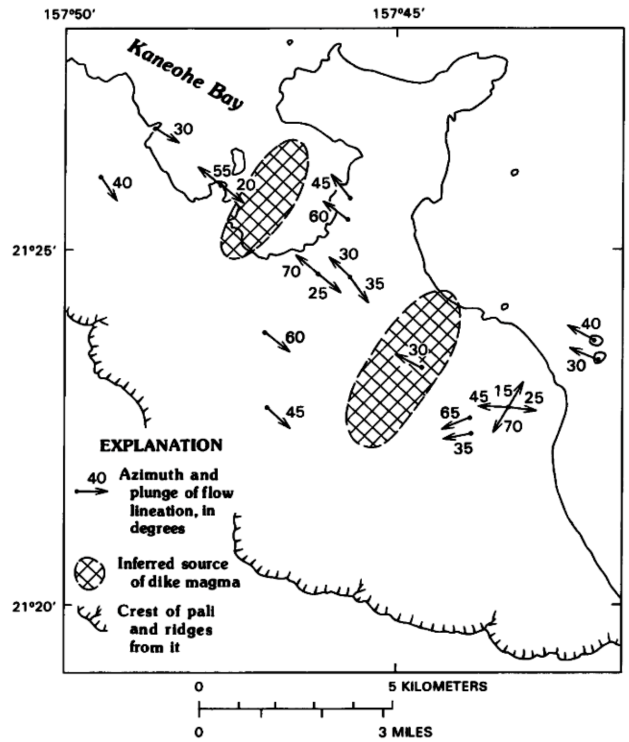


FIGURE 41.14.—Predominant plunge of flow lineation on dikes in Koolau complex. On the assumption that arrows point back to sources from which dike magma came, two sources are inferred, one near Kailua and the other under Kaneohe Bay.

The most common relationship is that the dikes in part of an exposure mostly dip in the same direction and at about the same angle, whereas farther along in the same exposure the dikes mostly dip in the opposite direction. This is clearly shown at locality 12, where the predominant dip direction changes from southwest to northeast several times along the 350-m length of the outcrop. The frequent change in the dip direction is well shown on the Mokulua Islands (localities 19 and 20): there the same cluster of dikes that in one place dips predominantly in one direction may be found to swing over and dip in the opposite direction a short distance along strike or higher up on the same cliff section. There are also many places at locality 12 and on the Mokulua Islands where, though the dikes predominantly dip in one direction, a significant number dip in the opposite direction and intersect to produce a braided pattern.

Individual dikes commonly vary in dip over several tens of degrees in the same outcrop, and it is often difficult to know what to measure. An attempt was generally made to measure the dip of a plane joining the points on each dike at top and bottom of the outcrop. This value for the dip obviously has a different validity depending on whether the outcrop is 1 m or 10 m high. Although the individual dip readings are of varied validity, the collective readings from many dikes at the same locality should define significant trends.

On the whole the dikes dip predominantly outward on either side of the Koolau Volcano (fig. 41.17). This would be in accord with the anticipated dip of normal or listric faults on either side of a high-standing edifice. The axis separating mainly southwest-dipping from mainly northeast-dipping dikes, however, coincides with the axis of the volcano only near Waikane; elsewhere it is strongly

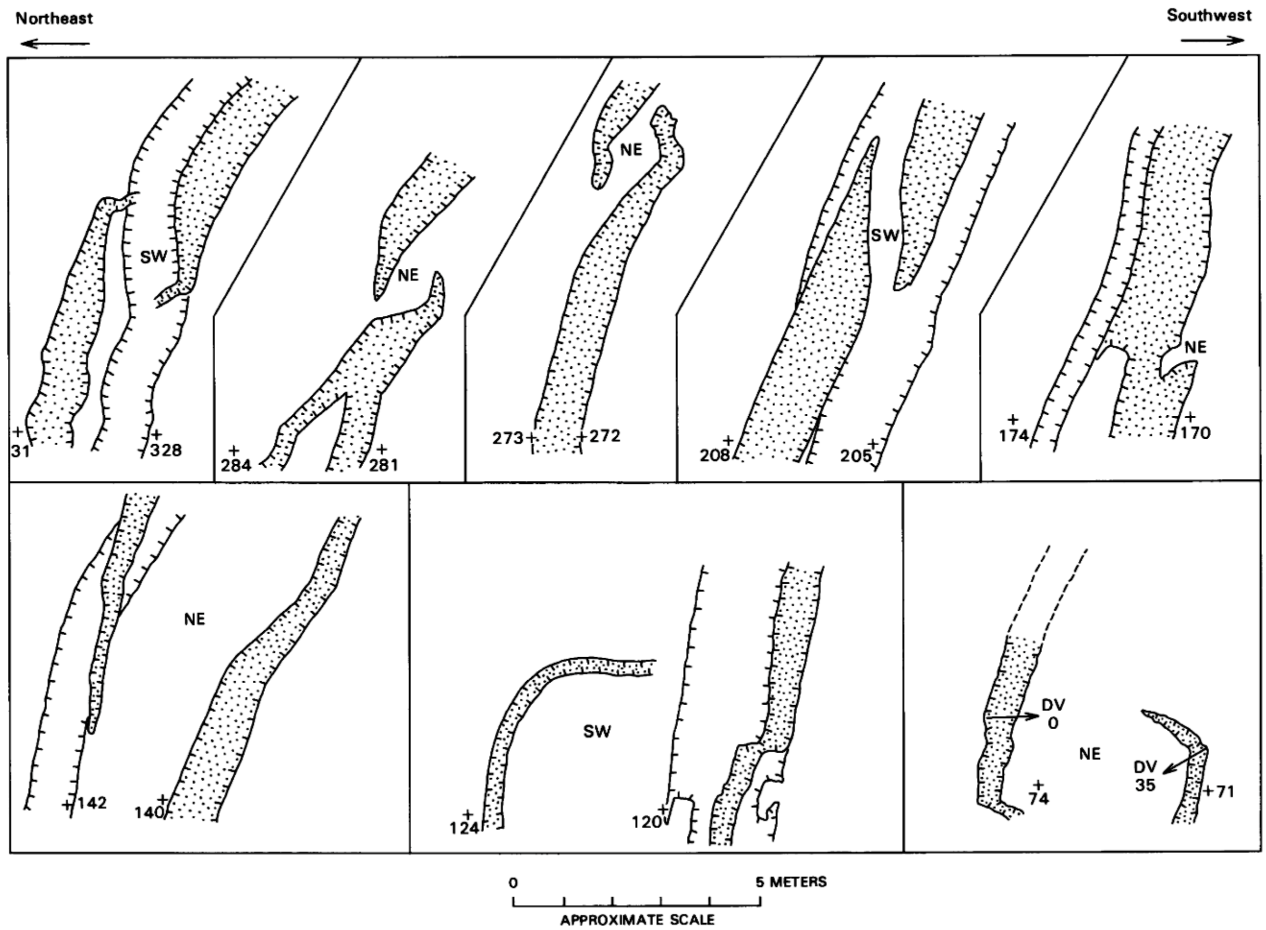


FIGURE 41.15.—Eight examples of dike sidesteps in Koolau complex of roadcut on Highway H3, locality 3. Where dike cuts dike, younger one is stippled. NE, SW, examples in which dike sidesteps upward to northeast and southwest, respectively. Numbers give distance in meters from south end of roadcut. DV, orientation and plunge angle of dilation vector, where known. Hachures indicate chilled margins.

displaced toward the southwest. In the area of locality 15 the part with northeast-dipping dikes embraces the entire width of the complex. This anomalous dip could indicate a weakness of the volcano and a tendency for it to creep northeastward toward the deep ocean in this area.

An older dike complex may be distinguished from a younger one at localities 1–7 as described earlier, and both dip predominantly in the same direction, showing that this weakness of the volcano was manifested early.

A late-manifested consequence of the weakness of the northeastern side of Koolau Volcano was the collapse by landsliding of much of that side (Moore, 1964). It is interesting to note that landsliding extended farthest across the volcano in the same area in which predominantly northeast-dipping dikes extend farthest. This may mean that both are manifestations of the same weakness. Alternatively, the predominance of northeast-dipping dikes in this area may have facilitated the landsliding.

The dip directions and angles of the dikes are apparently unrelated to the dip of the country rock lava; they are instead strikingly similar to those of normal faults developed in a tensional setting, which form complementary sets having opposing dips. The dikes of the Koolau complex may likewise form complementary sets oriented by a stress pattern similar to that which generates normal faults.

In many dike swarms elsewhere in the world the dikes are vertical or approximately so, as documented in Iceland by Gudmundsson (1983, 1984; fig. 41.16*D*). The problem is why the dikes of the Koolau complex systematically depart from verticality.

Dikes are conventionally interpreted to lie in the plane containing the maximum and intermediate principal stress axes and thus at right angles to the minimum principal stress axis (fig. 41.18). On the other hand, in an extensional tectonic setting in which horsts and grabens form, sets of normal faults form on planes oriented at about 20° on either side of the vertical plane that contains the maximum

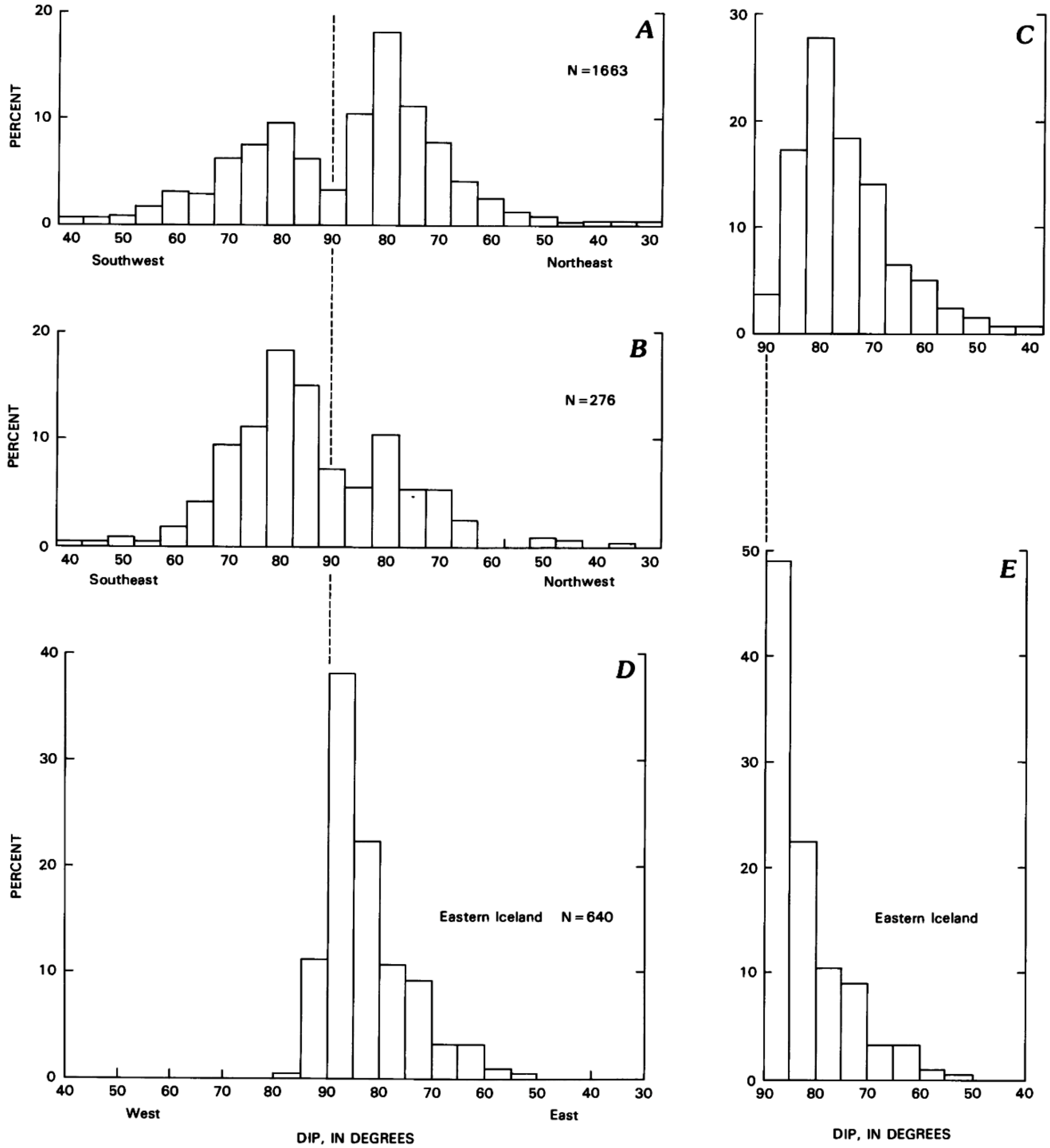


FIGURE 41.16.—Dip angles of dikes in Koolau dike complex and Tertiary dike swarm of eastern Iceland. N, number of dikes in each set. ***A***, Dips of northwest-trending dikes in Koolau dike complex. Note two peaks at 10°–20° on either side of vertical. ***B***, Dips of northeast-trending dikes in Koolau dike complex. Note similar peaks as for northwest-trending dikes. ***C***, Numerical values of dike dips in Koolau dike complex, disregarding both strike direction and dip direction. ***D***, Dips of dikes in Tertiary dike swarm of eastern Iceland (Gudmundsson, 1983); 73 percent are within 10° of vertical (this remains true even after compensation for 5° of later westward tilt). These dips were measured to nearest degree, whereas Koolau dikes are so irregular that their dips were measured to nearest 5°. ***E***, Numerical values of dike dips in Tertiary dike swarm of eastern Iceland, disregarding dip direction.

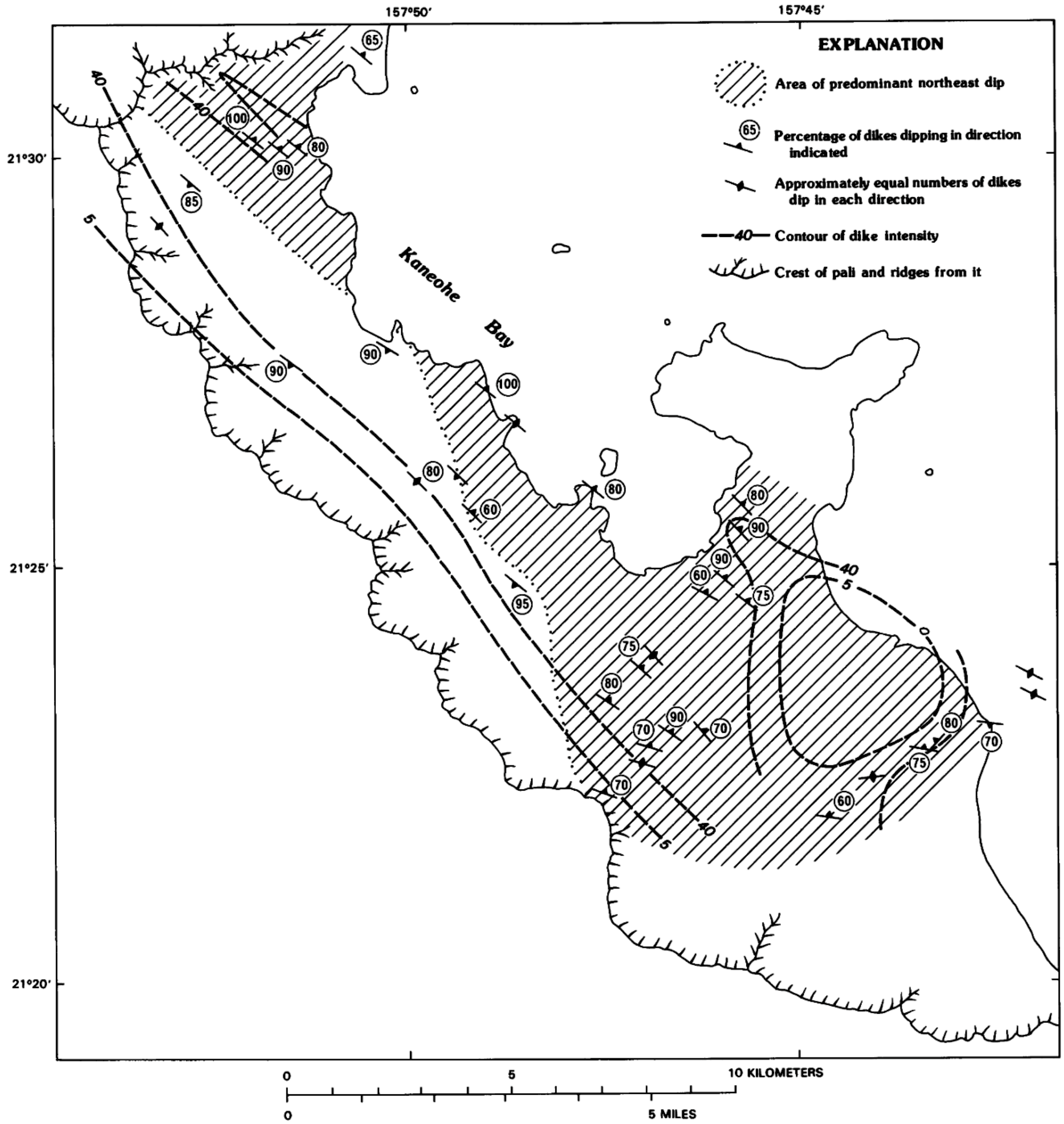


FIGURE 41.17.—Predominant dip directions of dikes in Koolau dike complex. Generally dip is outward on either side of axis of Koolau Volcano. In a large anomalous area, however, predominant northeast dip extends across entire width of complex. Intensity contours from figure 41.3.

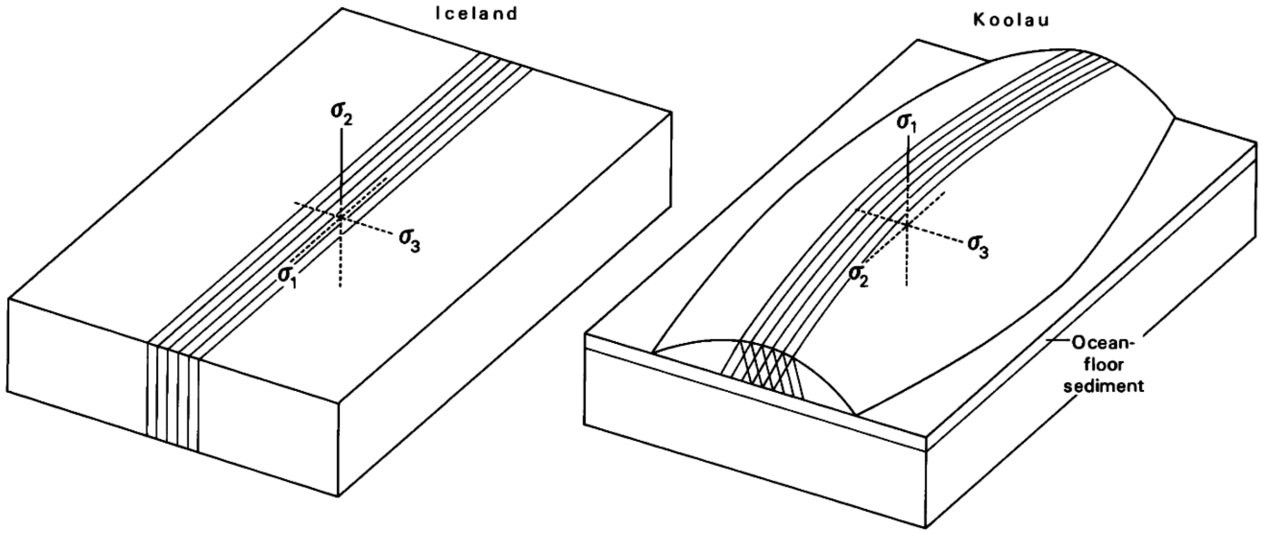


FIGURE 41.18.—Comparison of rift zones in two tectonic settings showing postulated positions of maximum (σ_1), intermediate (σ_2), and minimum (σ_3) stress axes. An oceanic spreading ridge is exemplified by Iceland (see Keith, 1981), which rises 3 km above deep ocean floor in 300–400 km. An intraplate volcanic edifice is exemplified by Koolau Volcano on Oahu, which rises 5 km above deep ocean floor in 60 km. Icelandic rift zone can be regarded as being confined at both ends, and formation of vertical dike fissures is favored. Hawaiian edifice is not confined at sides or ends and is free to move on its underlying layer of ocean-floor sediment (Nakamura, 1980); hence σ_1 is much greater than σ_2 and σ_3 and formation of inclined dike fissures forming two complementary sets is favored.

and intermediate stress axes. Vertical dikes like those in Iceland and complementary sets of faults both form in an extensional setting. How may the vertical orientation of most dikes be reconciled with the nonvertical orientation of normal faults and Koolau dikes?

I propose that the explanation for this is that Hawaiian volcanoes, being high-standing and comparatively steep structures (the Koolau Volcano rises 5 km above the deep ocean floor in 60 km), have a strong tendency to spread laterally (Fiske and Jackson, 1972) and have axes of minimum and intermediate stress both lying in the horizontal plane. The maximum stress axis is vertical and greatly exceeds the other two. In contrast, fissure eruptions in Iceland occur in a setting in which the tendency for gravitationally induced lateral spreading is small (Iceland rises only 3 km above the deep ocean floor in 300–400 km), and under these conditions the maximum stress axis may be horizontally oriented in this direction and if vertical will not be much greater in magnitude than the other two (compare with Keith, 1981). It is postulated that dikes in this situation tend to be vertical.

A possible alternative explanation for the nonverticality of the Koolau dikes is the mechanical anisotropy of a Hawaiian volcanic pile. Ryan and others (1983) pointed out that, though the pile behaves as a mechanical continuum, an elastic solid, the rock is so disjointed in the vertical direction that it lacks mechanical continuity in the horizontal plane. When, for example, horizontal displacement magnitudes are made up of reversible and irreversible components, the restoring forces for the former tend to be either weak or nonexistent. Lateral extension then tends to generate nonvertical fractures. Thus, where a vertical fissure passes up into poorly consolidated ash or sediment, a graben between nonvertical normal faults develops in that deposit; good examples are seen where fissures of Kilauea's southwest rift zone, just outside the caldera rim, transect thick pyroclastic deposits of the 1790 explosive eruption.

Though mechanical anistropy is capable of accounting for the extreme irregularity and nonverticality of the older dikes, it does not readily explain the nonverticality of younger dikes such as are seen cutting well-lithified breccias in locality 3. I conclude therefore that the nonverticality is mainly attributable to the edifice effect—the tendency for lateral spreading in a very high volcanic edifice.

CONE SHEETS AND SILLS

A small proportion (about 1 percent) of the dikes have a dip of less than 50°, and the possibility that they might be cone sheets (as was suggested by Macdonald and Abbott, 1970) must be considered. The essential attribute of cone sheets is that they dip toward a common focus. When the low-angle sheet intrusions found in the present study are plotted on a map (fig. 41.19), no tendency toward a centripetal dip can be discerned, which lends no support to the idea that they are cone sheets. These dikes are therefore regarded as constituting simply the low-angle tail of a Gaussian distribution.

Only one sill was noted; it is highly irregular, is about 1 m thick, and can be traced for a few tens of meters in a roadcut where the highway climbs the pali at Makapuu Head.

VERTICAL DISPLACEMENTS CAUSED BY DIKE INJECTION

The injection of vertical dikes does not cause any uplift or subsidence of the country rock apart from that which may result by

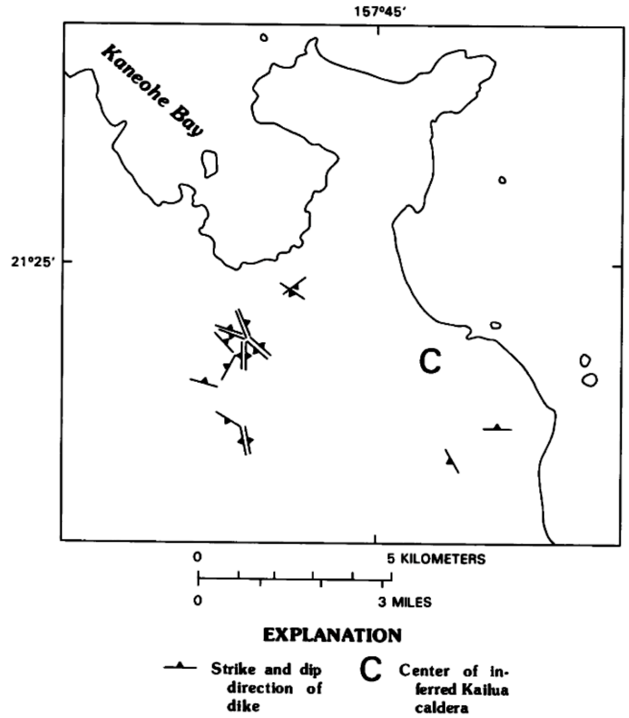


FIGURE 41.19.—Strike and dip direction of 1 percent of dikes in Koolau complex that dip less than 50°. Attitudes show no tendency toward centripetal pattern and thus lend no support to idea that these intrusions are cone sheets.

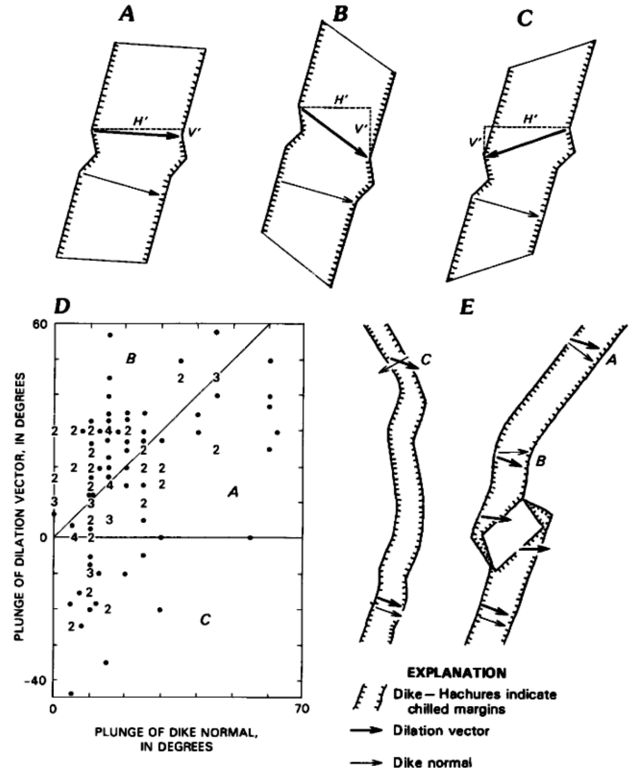


FIGURE 41.20.—Dilation relationships in vertical cross sections of dikes in Koolau dike complex. ***A***, Example of dike in which dilation vector plunges less steeply than dike normal. ***B***, Example of dike in which dilation vector plunges more steeply than dike normal. ***C***, Example of dike in which dilation vector plunges in the opposite direction to dike normal. ***D***, Plunge of dilation vector plotted against plunge of dike normal in sample of 126 dikes from localities 1, 3, 6, 7, and 23. For some dikes dilation vector (given a negative value on the plot) plunges in opposite direction from dike normal, giving a negative value of V'. Letters indicate regions exemplified by dikes in *A*, *B*, and *C*. Duplicate values from different measurememts shown by numbers. ***E***, Schematic profiles across two irregular dikes showing how departures of dilation vector from dike normal can be explained by variations in dip of dike. Note variation in plunge of dilation vector at dike sidestep where rotation of block has occurred.

eventual isostatic adjustment: it simply causes a lateral displacement of the country rock. Pollard and others (1983) have shown that injection of a vertical dike that fails to reach the surface does cause uplift, but the amount is very small.

Because the Koolau dikes are, in general, not vertical, their intrusion by simple dilational opening resulted not only in a horizontal dilation but also in a vertical displacement that uplifted the hanging wall relative to the footwall. The component of dilation in the horizontal plane (H) exceeds that in the vertical direction (V) in dikes dipping at more than 45°, but V approaches H as the dip approaches 45°.

It is generally tacitly assumed that dilational opening of a dike is along the direction normal to the dike. On many of the Koolau dikes it is possible to determine the direction of opening (called here the dilation vector, figure 41.20) by matching features on the two walls of the dike, and it is found that in general this direction does not coincide with the normal to the dike. The components of dilation in the horizontal and vertical directions, referred to as H' and V', respectively, are therefore different from H and V. Few studies have hitherto been made on this aspect of dikes; measurements were therefore made to investigate its significance. Outcrops in the Koolau complex are generally not favorable for determining the attitude of the dilation vector in three-dimensional space; measurements were therefore mostly made where dikes are exposed in vertical section. The data are summarized in figure 41.20*D*.

For about half of the measured dikes the dilation vector plunges more steeply than the dike normal, thereby increasing V' (fig. 41.20*B*). For a small proportion of dikes it plunges in the opposite direction from the dike normal (fig. 41.20*C*); V' is then negative, because intrusion of the dike resulted in a subsidence of the hanging wall relative to the footwall.

For each of the measured dikes, H' and V' were calculated, and their average values together with the two values of dike width (measured along the dike normal and along the dilation vector) are summarized in table 41.2.

TABLE 41.2.—*Widths and dilation components of dikes in the Koolau dike complex*

[All measurements in meters; H, H', horizontal components; V, V', vertical components. H, H', V, V' in per meter of dike width, N]

	Locality							
	1	3	6	7	24	30	Total	Average
Number of dikes	21	28	18	37	16	6	126	--
Measurements along dike normal								
Total dike width, N	8.08	19.76	11.27	23.20	11.58	4.90	78.79	0.625
Average dike width	.385	.706	.626	.627	.724	.817		
H	.891	.944	.899	.911	.941	.990	--	.925
V	.277	.277	.314	.335	.275	.134	--	.290
Measurements along dilation vector								
Total dike width	8.06	21.13	12.02	24.61	12.14	5.08	83.04	.659
Average dike width	.384	.755	.668	.665	.759	.847		
H'	.914	.970	.997	.921	.958	1.009	--	.954
V'	.208	.278	.226	.424	.274	.159	--	.298

It is seen that the average values of H' and V' differ only very slightly from the average values of H and V, and the small difference is probably not significant. This, together with the apparently random scatter of points seen in figure 41.20*D*, suggests that the dilation vector varies randomly about the dike normal. An explanation which appears adequately to explain this randomness is illustrated in figure 41.20*E* and is based on the observed irregularity of most dikes in the complex. It is postulated that on average the dilation vector of each dike coincides with the dike normal, but where a dike trend departs from its average trend the dike normal will depart from its dilation-vector direction.

The average values for H' and V' per meter of dike-normal width are 95.4 cm and 29.8 cm respectively. If the measured dikes are representative, injection of the dike complex having a total H of 3.3–4.8 km would involve a total relative uplift or subsidence (V) of 1–1.5 km, which is comparable to the height above sea level of the Koolau Volcano and is thus not insignificant. Note that axial uplift has accompanied some recent activity in the east rift zone of Kilauea Volcano (Swanson and others, 1976).

The question then arises whether intrusion of the dike complex has caused any significant net uplift or subsidence. The obvious test is by mapping a distinctive stratigraphic horizon right across the complex, but this does not seem feasible because of generally unfavorable topography in the Koolau Range combined with the relatively uniform lithology of the shield lava; the existence of a large collapse caldera in the area where exposures would otherwise be the most favorable is a further hindrance.

In many older, eroded volcanoes, the floor has been strongly updomed; a good example is the Carlingford Tertiary volcanic center in Ireland. Le Bas (1971) attributed the updoming at Carlingford to the intrusion of a swarm of cone-sheets that, like the Koolau dikes, have a significant V' vector. The evidence is, however, ambiguous, because it is also possible that the updoming was caused by an underlying granophyre pluton.

THE CALDERA OF THE KOOLAU VOLCANO

Hawaiian active volcanoes have a central caldera from which rift zones radiate like spokes, and the fact that the northwest and southwest dike complexes of the Koolau Volcano radiate from the Kailua area implies that the center of the volcano was located there. There is good evidence for the existence of a caldera in this general area.

Stearns and Vaksvik (1935) distinguished a Kailua Volcanic Series, occupying a circular area 5 km (3 mi) across centered on Kailua, which they interpreted to consist of lava infilling the caldera of the Koolau Volcano. Woollard (1951) and Strange and others (1965) found a major positive gravity anomaly centered on this caldera, and they attributed it to a concealed high-density intrusive pipe underlying the caldera. The postulated intrusion is not exposed. Adams and Furumoto (1965) and Furumoto and others (1965) explored the gravity high by seismic profiling and found high velocity (v_P=7.7 km/s) rocks at a depth of less than 2 km beneath the caldera.

Certain coarse breccias on the ridge between Kaneohe and Kailua Bays were interpreted by Stearns and Vaksvik (1935, p. 97) as a caldera infilling "a throat breccia such as exists in the bottom of Halemaumau built up chiefly as talus within a crater or caldera, and [which] appears to mark the main vent of the Koolau volcano." They found that the breccia crops out over nearly 2.5 km^2 (1 mi^2), reaches 160 m (520 ft) thick, and consists of angular to subangular fragments mostly under 50 cm in size of amygdaloidal basalt of diverse lithologies set in a fine green matrix. Macdonald and Abbott (1970), however, interpreted the breccia to consist probably of mudflows.

New evidence is now available, and in presenting it the distinction is made between evidence for the existence of a caldera, and evidence on the origin of the breccia.

EVIDENCE FOR A CALDERA

New evidence for the existence of a caldera comes from three roadcuts in Highway H3, in two of which (localities 1 and 3) older, amygdaloidal and altered dikes can be distinguished from younger, massive and fresh dikes. In the third (locality 2), which lies at about the same elevation, no older dikes can be identified, and the dike complex is similar in character and intensity to the younger complex at localities 1 and 3. The country rock at locality 2, moreover, consists of more massive lava.

The most plausible explanation for the differences is that the basalt of locality 2 is younger than the older dike swarm of localities 1 and 3; this is consistent with its being the infilling of a caldera postdating the older complex. A schematic view of these relationships is given in figure 41.21. The massive flows of locality 2 are suggestive of ponding in a depression. The lower dike intensity in locality 2 most likely indicates that the lava flows are younger than those exposed in contiguous areas, and less time was thus available for dikes to cut them. An alternative mechanism, namely downfaulting of these thick lava flows, can explain the lower dike intensity but not the absence of strongly amygdaloidal dikes.

Caldera infill can, thus, be identified here by three criteria:

1. It consists mainly of thick massive lava flows unlike the thin pahoehoe flow units that characterize most of the Koolau lava shield.
2. It has a significantly lower dike intensity than contiguous areas.
3. It may lack strongly amygdaloidal dikes like those of the earlier complex found in sites 1 and 3. This lack presumably indicates rapid infilling of the caldera.

Within a large area centered on Kailua the lava flows have dip directions and amounts that are anomalous and quite different from those of the shield lava; the dip, though variable, is on the whole centripetal and varies in amount from 15° to 30° or rarely as much as 60°, whereas the shield lavas dip at 5° to 15° outward from the shield axis. This large area of centripetal dip is interpreted to be a caldera of the downsagged type (Walker, 1984). No comparable feature has been recognized on the active Hawaiian volcanoes, but it could be concealed beneath young lava.

Important evidence bearing on the downsag caldera comes from the Kapaa Quarry, where the country rock consists of thin pahoehoe lava flows that resemble shield building lava. These flows dip in the contrary direction to the shield lava and at an angle (30° to 60°) that is excessive for shield lava. Some flows moreover contain pipe amygdules, which, it has recently been demonstrated, are good paleoslope indicators. Their presence show that the lava was deposited on a slope of less than 4°. The Kapaa quarry lava must therefore have been tilted at least 30°–60° after being deposited. The amount of subsidence by down-sagging can be estimated to have been about 1 km.

The dike complex that cuts the lava of Kapaa Quarry consists of the usual two complementary sets having opposed dips of 65°–85° (fig. 41.23), and this implies that these dikes were injected after the lava had been more or less fully tilted. The dike complex here built up to its full intensity of more than 50 percent after a major episode of subsidence had occurred. Note that where the country rock has the steepest dip, at the northeast end of the northeast quarry, several intrusions follow the stratification of the lavas. Technically these intrusions are sills, but in relation to the volcanic edifice they are dikes.

The approximate extent of the downsag caldera as determined from dip measurements is shown on figure 41.22; it is greater than that given by the other criteria and is similar to that mapped by Stearns and Vaksvik (1935) as constituting the caldera fill of their Kailua Volcanic Series.

The Kailua caldera as delineated by these several criteria varies greatly in intensity of dike injection, from 1 percent to 50 percent or more. Some variation would of course be anticipated in different parts of the same caldera transected by one or more rift zones, but a more plausible explanation is that two or more calderas of different ages occur, the older being cut by more numerous dikes than the younger. This multiple origin is evidenced by the dike relationships in the Highway H3 roadcuts and is consistent with the fact that the Kailua caldera measures at least 13 by 10 km, which is far greater than the diameter of calderas on Kilauea and Mauna Loa (2.5–4.5 km).

The very low intensity of the dike complex in the inner part of Kailua caldera implies that subsidence there was a very fast or late event relative to formation of the dike complex and considerably exceeded 1 km. Most likely this area of low dike intensity is a conventional caldera nested within a much broader area dominated by downsagging.

NATURE AND ORIGIN OF THE BRECCIAS

The coarse breccias that make up much of the ridge between Kaneohoe and Kailua Bays and that are well exposed at localities 1, 3, 4, 5, and 10 have long been enigmatic. Important evidence relating to their origin is that much of the breccia consists of dike fragments (fig. 41.24). This leads to a new interpretation, namely that the breccias consist of the older part of the dike complex (together with country-rock basalt screens), which has suffered an extensive and pervasive brecciation.

The evidence for brecciation of a dike complex seems unequivocal because all stages in disruption of dikes are seen:

1. The dike rock is pervasively brecciated but little relative movement of the fragments has occurred: sufficient to generate angular spaces (infilled with secondary minerals) between fragments but not sufficient to break the continuity of the dike, which is contained by chilled margins.
2. The dike as a whole is still continuous, but it is thoroughly brecciated, and relative movement of fragments has caused it to have a jagged shape.
3. The dike is thoroughly brecciated, and relative movement and intermixture of dike fragments with country rock basalt has occurred, but dike fragments remain concentrated in a relatively narrow zone within the breccia, showing that in-place brecciation of a dike has occurred.
4. The dike is totally disrupted, and all continuity is lost; abundant breccia fragments that possess a chilled edge on one side are all that attest to the derivation of much of the breccia from dikes.

All indications are that the breccia formed by a pervasive fragmentation in place of country-rock lava cut by dikes. The degree of brecciation varied apparently in a rather haphazard way, leaving areas, several meters to tens of meters across, of intact lava and dikes enveloped in breccia. These areas pass upwards and laterally into breccia and generally lack any discrete boundaries.

The measured length of chilled dike margin exposed at locality

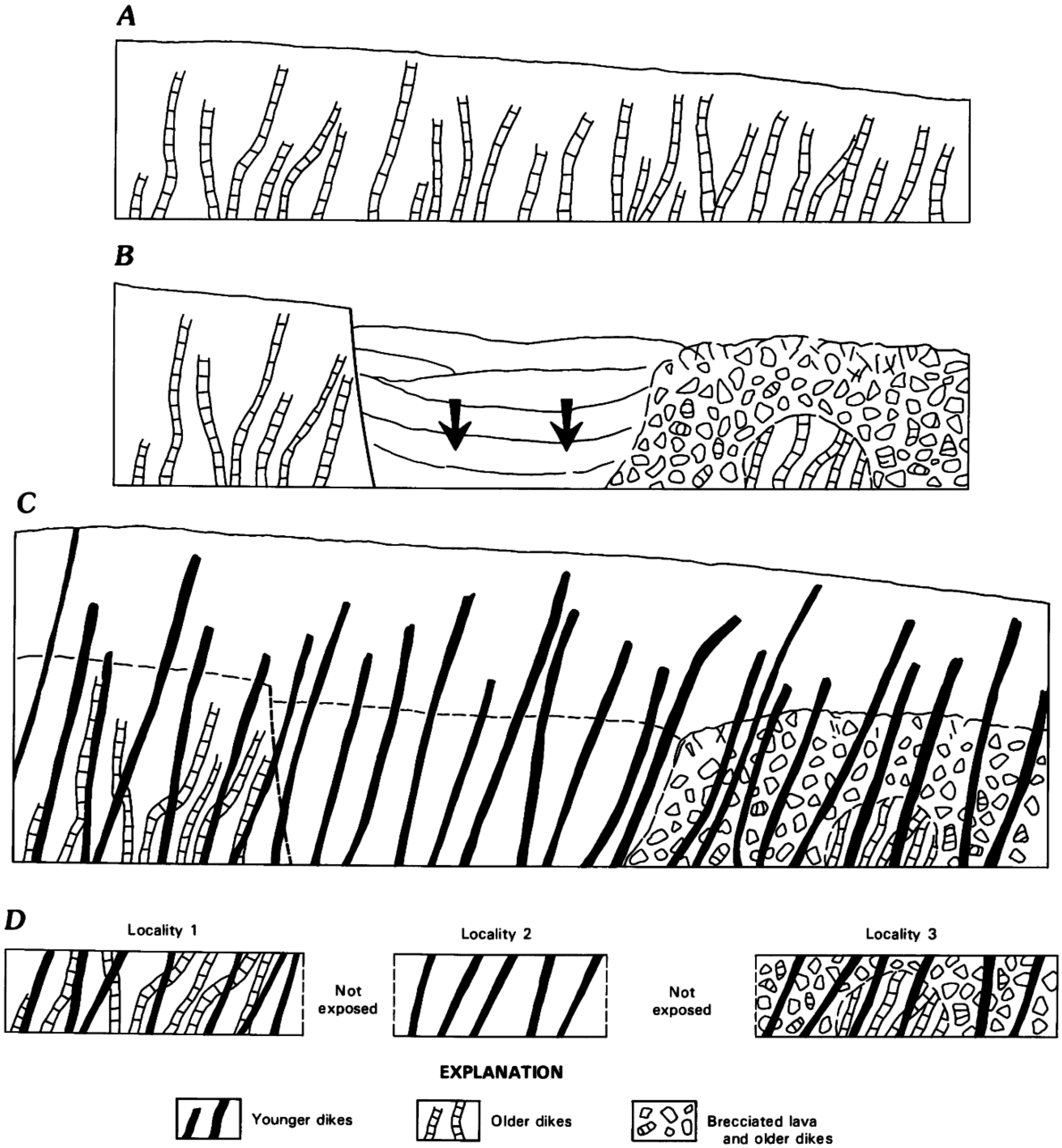


FIGURE 41.21.—Inferred origin of dike relations at localities 1–3. ***A***, Inital intrusion of older dikes. ***B***, Subsequent caldera subsidence (arrows), pervasive brecciation of part of lava and older dikes, and infilling of caldera by thick massive flows. ***C***, Later intrusion of younger dikes. ***D***, Dike relations as presently seen at localities 1–3.

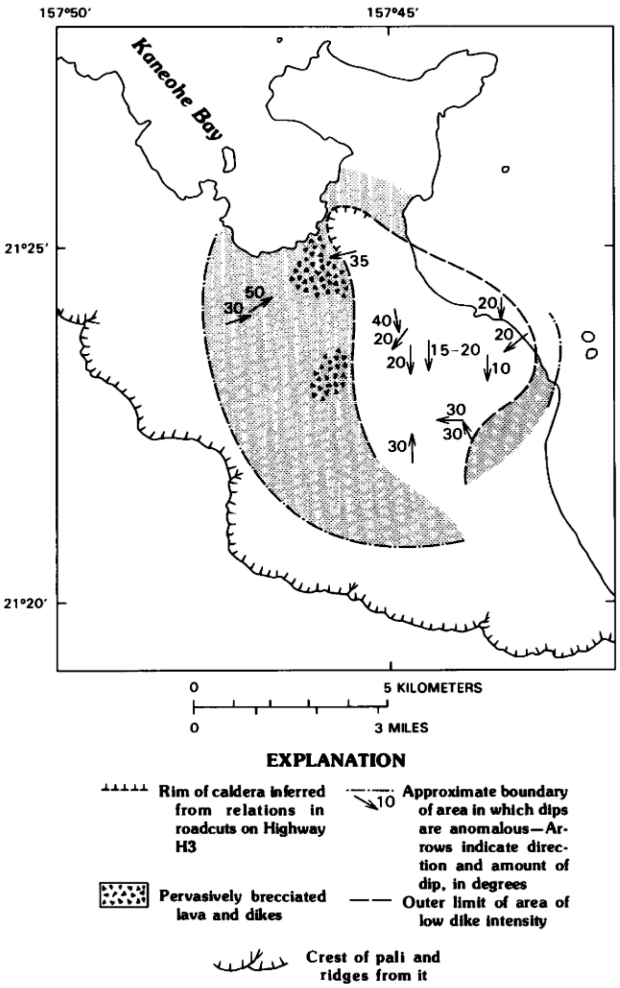


FIGURE 41.22.—Evidence indicating position and extent of caldera complex (shaded) in Kailua area. Area of low dike intensity shown in more detail in figure 41.3; relations in roadcuts on Highway H3 shown in figure 41.21.

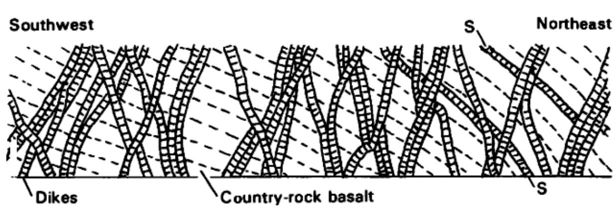


FIGURE 41.23.—Schematic relations at Kapaa Quarry. Strongly tilted lava flows are cut by dike complex in which dikes form two sets; opposing dips of sets are equal in amount, indicating that complex was intruded after lava had been fully tilted. Some dikes (S) cutting steeply inclined lava are conformable and technically sills, but they are better identified as inclined dikes.

3 varies from 0–2.6 m per square meter of rock surface, and the average of 20 measurements is 1.2 m. Where the older dike complex is intact at the same locality and has a local intensity of 100 percent in dike clusters, the measured total length of chilled margin per square meter averages 2.9 m. This is consistent with derivation of the breccia from a moderately intense (about 40 percent) older dike complex cutting lava.

The abundance of dike fragments would be opposed to the idea that the breccia is a kind of talus that accumulated in a crater or caldera: exposures at a level sufficiently high to generate talus on a Hawaiian volcano contain very few dikes. Casadevall and Dzurisin (chapter 14) counted only 18 dikes on the 6.5-km-long western and northern wall of Kilauea caldera, for example. The absence of stratification in the breccia and the way in which dikes show various degrees of in-place brecciation are opposed to an epigene formation for the breccia.

An alternative breccia-forming mechanism is hyaloclastic brecciation of dikes injected into rocks saturated by ground water. There are many places at localities 3–7 and 28 where green rims, presumed to be propylitized glass, are unusually conspicuous and thick, and some hyaloclastic fragmentation has almost certainly occurred. It seems, however, to have been on a small scale. Another alternative mechanism is auto-brecciation of dike injected into dike. What seem to be unequivocal examples of this are found among earlier dikes on the Mokulua Islands and in outcrops west of Waikane, but the brecciation is very localized.

The best explanation is that the bulk of the breccia is of tectonic origin and developed in place at or near the margin of a caldera, where the strain, instead of being confined to discrete fault planes, was distributed over a broad zone. As here envisaged, the stress acted on a pile of lava with a great many planes of weakness of various kinds, cut by a swarm of highly irregular dikes that had been injected into water-saturated rocks and hence were strongly jointed. The stress therefore caused a pervasive brecciation.

Formation of the breccia at localities 3–5 was followed by a metamorphic event that produced a widespread propylitic alteration accompanied by the deposition of laumontite, epidote, calcite and other secondary minerals (Fujishima and Fan, 1977). This event effectively lithified the breccia so that to the younger dikes it behaved as a rigid rock.

ORIGIN OF CALDERAS OF BASALTIC VOLCANOES

Many large basaltic shield volcanoes possess a caldera. Fine examples occur on oceanic islands such as Grand Comore, the Galapagos, Hawaii, Mauritius, and Reunion; other examples occur in continental-margin settings and include Masaya (Nicaragua) and Osima (Japan). The calderas of basaltic volcanoes differ in six important respects from calderas of volcanoes that have significant amounts of felsic or silicic products:

1. They tend to develop by incremental subsidence events and not consequent on a single major eruption (whether explosive or effusive).
2. Subsidence events are sometimes but not always correlated with eruptive activity.

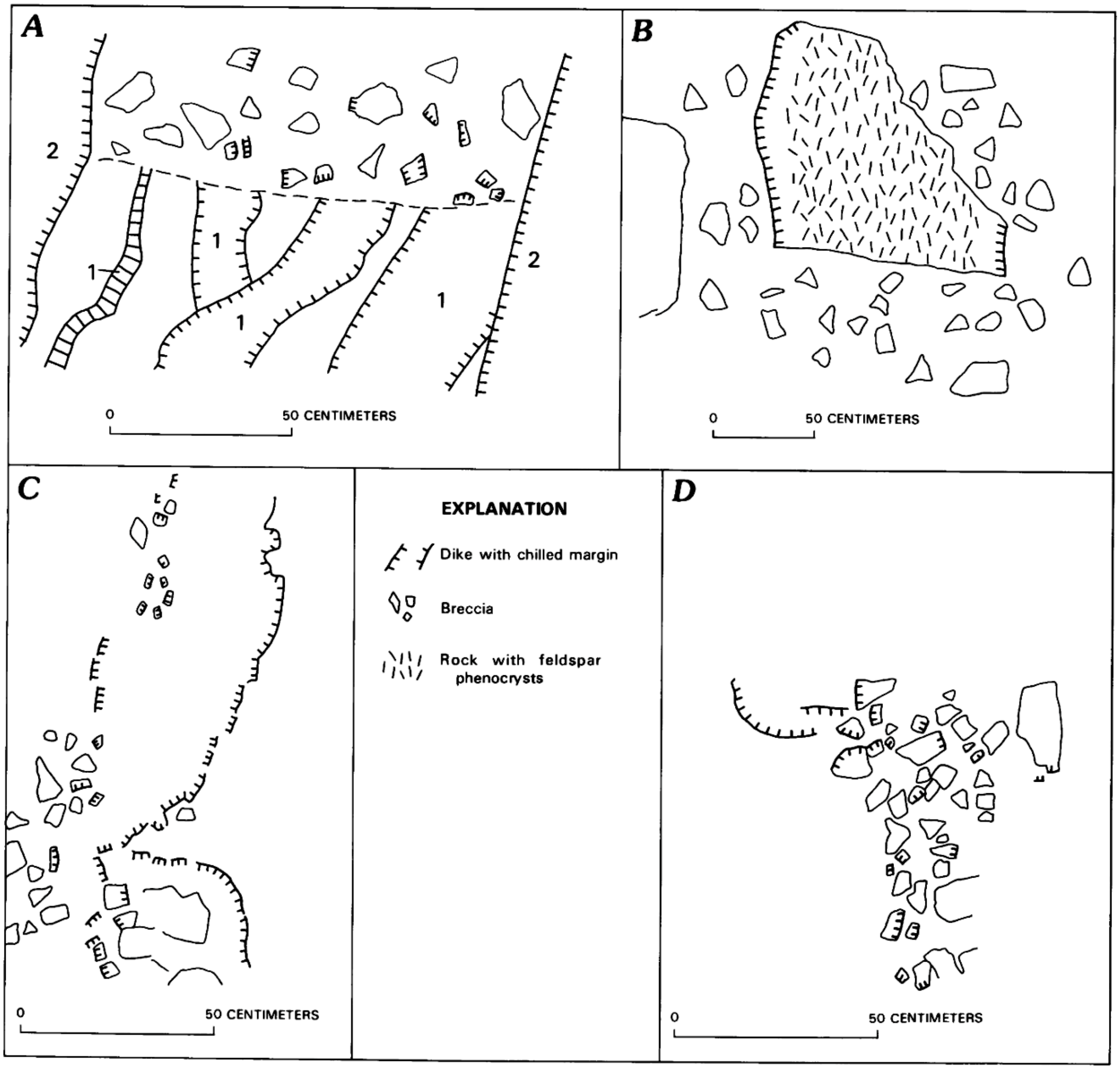


FIGURE 41.24.—Relations shown by breccia at locality 3. ***A***, Group of older dikes (1) terminates abruptly against breccia. Some fragments in breccia originate from dikes and have chilled margin on one side. Younger dikes (2) intruded after breccia had been lithified. ***B***, Intact but isolated fragment of richly feldspar-porphyritic dike. ***C***, Dike with one margin fairly complete but other brecciated and the fragments somewhat dispersed. ***D***, Breccia containing dispersed dike fragments characterized by chilled margins on one side.

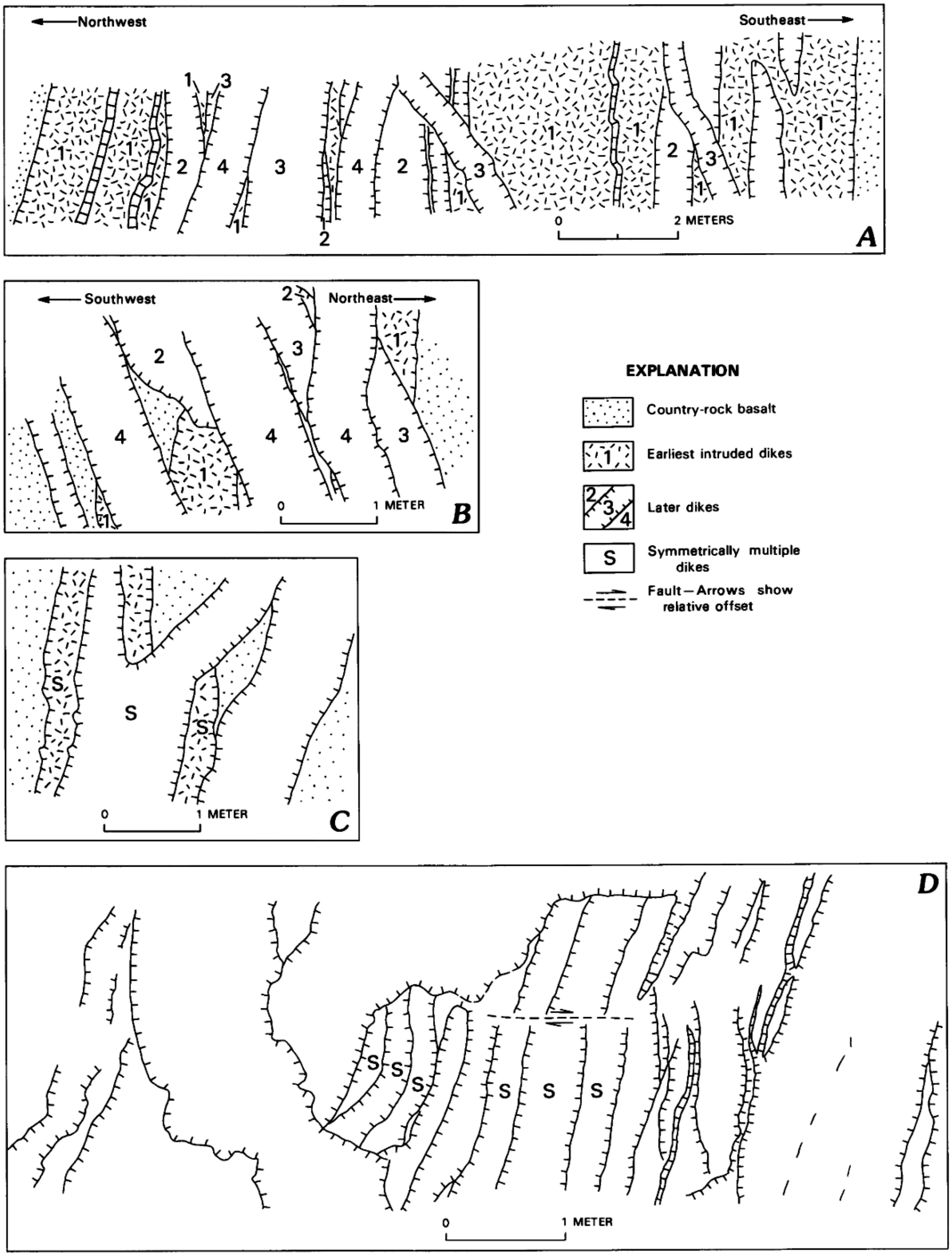


FIGURE 41.25.—Examples of multiple dike clusters. ***A***, Cluster of 14 dikes totaling 13.6 m thick at locality 23. Oldest dike is unusually wide (about 6.4 m) and is split into many screens. Country-rock screen at northwest end of cluster is 16 cm wide; that at southeast end is 330 cm wide. ***B***, Dikes intersecting at acute angle forming braided pattern (locality 5). ***C***, Symmetrically multiple dike (locality 3). ***D***, Part of a cluster of more than 14 dikes (locality 1). Four of the dikes are symmetrically multiple pairs.

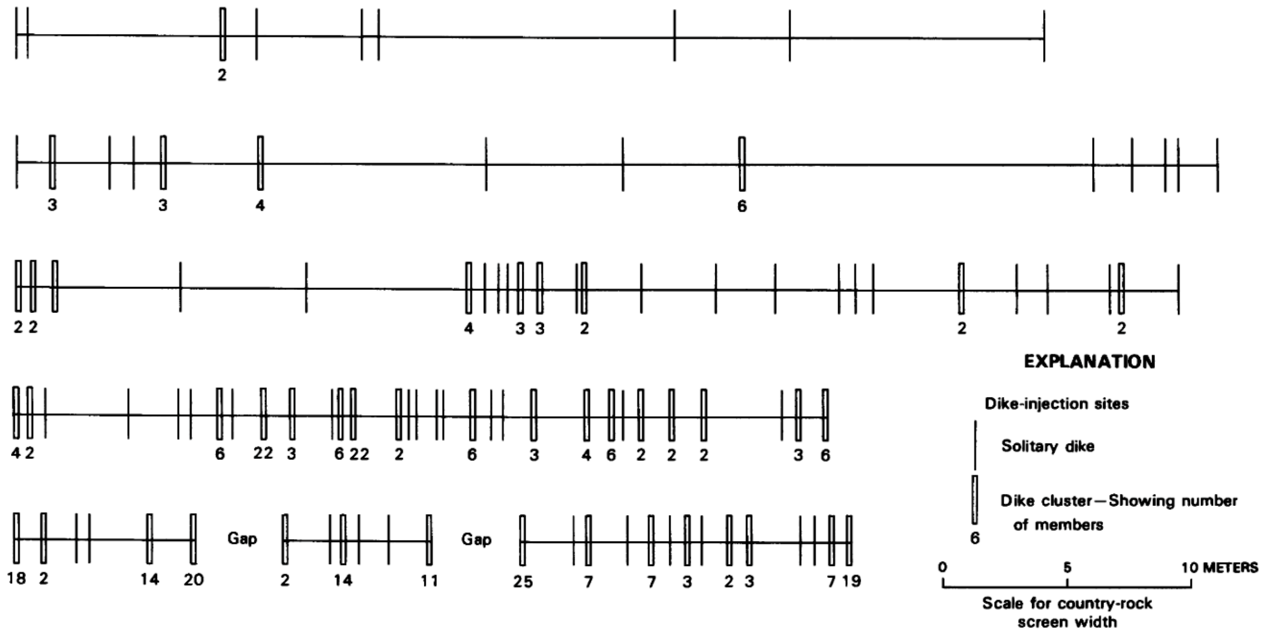


FIGURE 41.26.—Distribution pattern of dikes in representative exposures of Koolau complex (localities 47, 5, 2, 20, and 41, from top down), showing how number of dike-injection sites and multiple dikes vary. As intensity of dike complex increases, so dike spacing decreases and number of dikes in multiple clusters increases. Widths refer only to country-rock screens; dike widths are ignored.

3. They tend to have a complex history of alternating subsidence and partial infilling by lava flows, and significant changes in topography may occur on the more active volcanoes in a period as short as a century. These changes are well documented for Kilauea and Mauna Loa by Macdonald and Abbott (1970).
4. They tend to have a number of more or less concentric fractures on which downdropping has occurred instead of a single bounding fault, and the displacement on these faults tends to increase inwards; Kilauea is a good example. They also are often associated with or contain pit craters.
5. They coincide approximately with positive Bouguer gravity anomalies, in contrast with the negative anomalies shown by calderas associated with felsic and silicic volcanism.
6. They are transected by one or more rift zones along which activity is concentrated; in deeply dissected examples they are seen to be in line with, or are cut by, intense swarms or complexes of dikes and associated intrusions.

I now propose a new concept for the origin of basaltic calderas: that their subsidence is a consequence of the high density of the intrusive complex combined with the reduced strength of the lithosphere above a hot spot, which makes localized downward creep possible. Macdonald (1965) considered but rejected the idea that the calderas were caused by the weight of intrusions because he did not consider the possibility of creep occurring.

The pile of basaltic lava that constitutes much of the edifice of a Hawaiian volcano is estimated to have an overall density of about 2.35 g/cm^3 (Kinoshita and others, 1963), whereas a dike complex having >50 percent intensity is likely to be at least 0.35 g/cm^3 denser. Large gabbroic and ultramafic intrusions are likely to underlie the caldera and may be as much as 1.0 g/cm^3 denser than the lavas. A complex of dikes and associated large intrusions therefore represents a great localized and unevenly distributed load, the cause of the large Bouguer anomalies of the Koolau Volcano (Strange and others, 1965) and the active volcanoes on Hawaii (Kinoshita and others, 1963).

The very low dike intensity in the central part of the Kailua caldera is interpreted to indicate that the subsidence rate there exceeded the buildup rate of the dike complex, whereas in marginal parts of the caldera the reverse applied. This is important evidence in support of the postulated caldera-forming mechanism, in which the subsidence rate should be greatest at the locus of magmatic activity.

GROWTH MECHANISMS OF THE KOOLAU DIKE COMPLEX

PREFERENTIAL DIKE PATHWAYS

A large proportion of dikes in the Koolau complex are multiple and occur in parallel clusters, in which most commonly the members lie alongside and in chilled contact with one another without any intervening country-rock screen (fig. 41.25).

These dike clusters indicate that dike margins were structural planes of weakness that offered very favorable pathways guiding later intrusions. This is underscored by the fact that when an intrusion trends obliquely to an earlier dike it commonly changes course and follows the margin of the earlier dike for a space before resuming its oblique trend. The ease with which a dike breaks apart

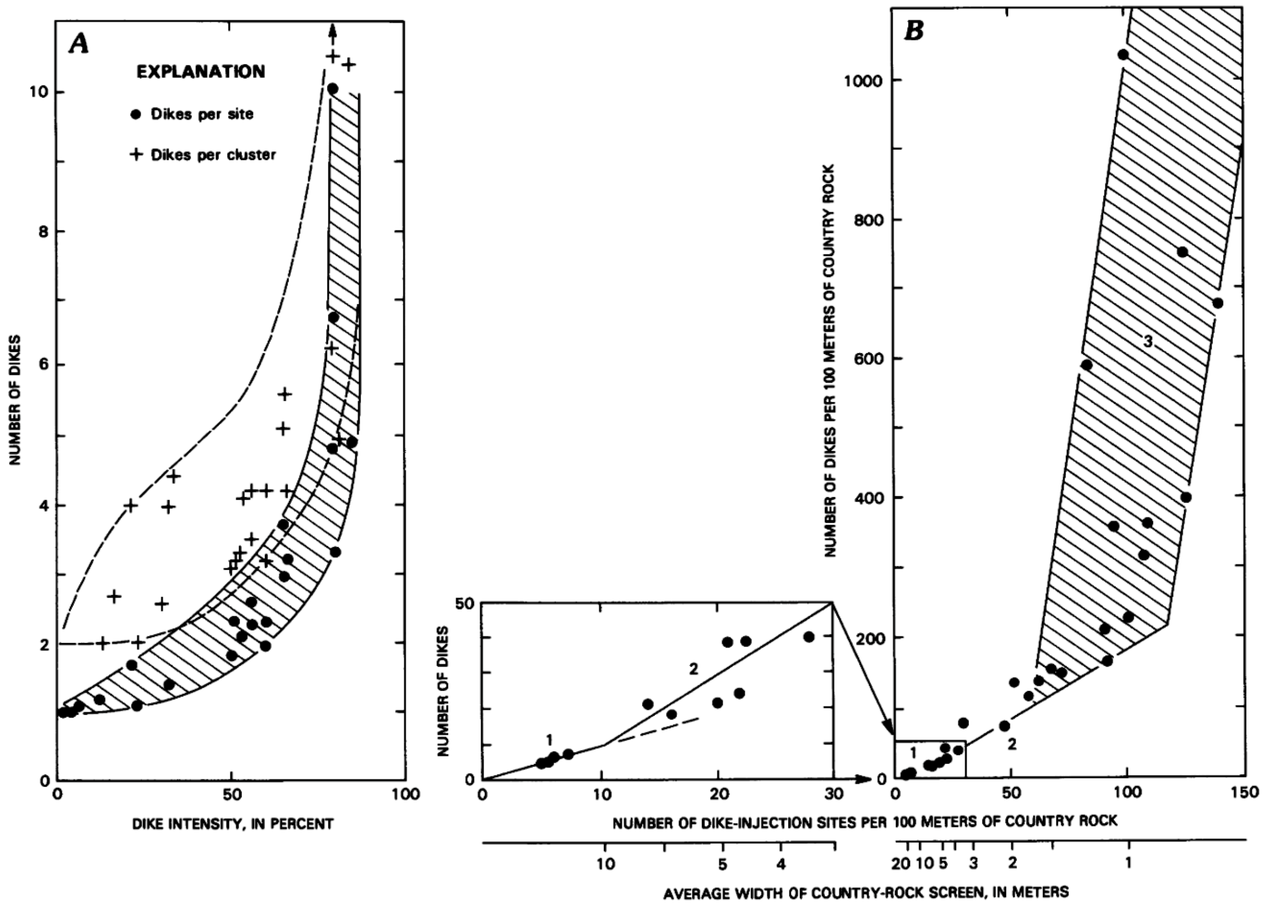


FIGURE 41.27.—Diagrams illustrating build-up of dike complex. ***A***, Plot of number of dikes per site and per cluster against dike intensity of complex. As intensity increases, average numbers of dikes per site and per cluster increase. ***B***, Plot of number of dikes and dike-injection sites per 100 m of country rock. In segment 1, the numbers are comparable. In segment 2, number of dikes increases twice as fast as number of sites, showing that half the dikes are forming multiple clusters. In segment 3, number of dikes increases much faster than number of sites because most of dikes are entering multiple clusters.

from the country rock or from an adjacent dike is clearly evident in any roadcut.

Data on dike spacings from a number of localities covering a wide range of dike intensities (fig. 41.26) form a basis from which to assess the manner in which the dike complex developed. It is assumed that these outcrops record stages in a progressive process, halted at each location by the cessation there of further dike injections. A dike-injection site is defined as a site in which either a solitary dike or a multiple dike cluster occurs.

Two features of the relationships shown in figure 41.26 are portrayed in figure 41.27: the average number of dikes per intrusion site, and per multiple cluster, increases at an increasing rate as the dike intensity increases (fig. 41.27*A*); and the number of dikes rises increasingly rapidly as the number of dike-injection sites per 100 m of country rock increases (or the average country-rock screen width decreases) (fig. 41.27*B*).

The dike-injection pattern has been reconstructed from figure 41.27*B* as follows. The first dikes to be injected all followed independent pathways through the country-rock basalt and subdivided the basalt into screens. In this early stage the number of dikes per unit width of country rock equaled the number of dike-intrusion sites (segment 1 on figure 41.27*B*).

When the average screen width decreased to less than 10 m, a proportion of the dikes began to follow the margins of previously intruded dikes instead of new pathways through the country rock, and the first dike clusters were thus formed.

As the dike-swarm intensity increased, and the average screen width decreased from 10 m to less than 2 m, roughly the same number of dikes followed margins of previously intruded dikes as followed new pathways in the basalt; the total number of dikes then increased at about twice the rate that the number of dike-injection sites increased (segment 2 of figure 41.27*B*). Because of the strong tendency for dikes to intrude into existing clusters, where planes of weakness were concentrated, the average number of dikes per cluster increased faster than the proportion of clusters to solitary dikes.

With further dike injection, the proportion of dikes following margins of preexisting dikes became very much greater than that following new pathways through the lava (segment 3 of figure 41.27*B*). It is thought that at this stage the average country-rock screen width tended to become stabilized at about 1 m. The screens were pushed farther and farther apart as more dikes were injected into the clusters between them until, in the most intense parts of the complex, narrow screens occur at intervals of tens of meters.

SYMMETRICALLY MULTIPLE DIKES

A proportion of the dikes in multiple clusters were intruded inside earlier dikes; an example is shown in figure 41.25*A* in which a broad dike is cut by 13 subparallel dikes situated at various distances from its margins. This particular example is unusual because the first dike fused the country rock, to which it is firmly welded, and later dikes hence showed no tendency to follow these margins.

A few dikes are symmetrically multiple, with the youngest intrusion in the middle and the halves of earlier narrow intrusions that have been split up the middle symmetrically disposed on either side (fig. 41.25*C*, *D*). The best examples are seen on the Mokulua Islands, where as many as four successively injected members occur in the same narrow multiple dike. Each member has chilled against the earlier member.

Solitary dikes of the Koolau complex in general lack any visible median parting or plane of weakness such as could direct a later intruded dike. This raises the possibility that the middle of a dike may be a preferred pathway for thermal reasons. The center of a cooling dike remains fluid longest and after solidification remains hot longest. Even if solid, the still-hot center remains mechanically weak. Thus Ryan and Sammis (1981) demonstrated that the value of Young's modulus at 700 °C is 10 percent less than it is at 25 °C.

HOW MANY DIKES?

An interesting question is the total number of dikes in the Koolau complex. Exposures are too incomplete to permit this to be determined by counting, but they are adequate for a good estimate to be made.

In a transect of the complex just south of Kaneohe Bay the exposed intense part is 6 km wide (fig. 41.3), and the intensity over this width varies from 30 to 63 percent. If the average intensity is 50 percent, dikes would total 3.0 km. In marginal zones on the southwest side and presumably also on the northeast side of the complex, the dike intensity drops from 40 percent to 5 percent in about 1 km. At an average intensity of 15 percent, these two strips would contribute 0.3 km, bringing the total dike width to 3.3 km.

The average width of dikes at different localities in this transect varies from 55 to 75 cm (fig. 41.9). If we take 65 cm as an overall average, this yields a total of about 5,100 dikes in 3.3 km of dike width. This estimate is probably a minimum: if the complex possesses bilateral symmetry about the Koolau lava-shield axis shown on figure 41.1, the full width of the intense part of the complex would have been about 9 km, increasing the total width of dikes to 4.8 km and the number of dikes to 7,400.

Consider now the number of dikes in a transect of the complex at or near Waikane. The intense part of the complex there is 3.5 km wide and has an average intensity of about 45 percent, giving 1.6 km total width of dikes. To this may be added 0.8 km for the low-intensity strips 2 km wide on either side, giving a total dike width of 2.4 km. The average width of dikes at different localities in this transect varies from 115 to 175 cm. If we take 150 cm as an overall average, this yields a total of 1,600 dikes.

The number of dikes in any given transect cannot be equated with the total number of dikes in the complex; estimation of the latter requires a knowledge of the length-width ratio of the dikes, on which no direct information is available. Gudmundsson (1983) assumed a length-width ratio of 10^2–10^3 in eastern Iceland. If we apply this on Oahu, dikes 50 cm wide would have a length of 50–500 m. This is unrealistically short; it is more than an order of magnitude less than the known length of eruptive fissures on Kilauea and Mauna Loa, and seems incompatible with the origin of the dikes by lateral movement outwards from the volcano center.

If it is assumed that the number of dikes decreases linearly from 7,400 in a transect along the south of Kaneohe Bay to 1,600 at Waikane and to zero at the northwest tip of the Koolau Volcano, and that the average dike length is 5 km, then the dikes would number about 30,000.

DIKES IN THE BUILDUP OF KOOLAU VOLCANO

Koolau Volcano is deeply dissected; the highest point on the Koolau Range is 960 m (3,150 ft) above sea level, and the original shield crest, extrapolated from the generalized contours of figure 41.1 would have been about 1,100 m above present sea level (actual elevation must have been higher, because the edifice has subsided since then) without allowing for the Kailua caldera. Characteristics of the older dikes such as at locality 3 indicate intrusion at a shallow depth, possibly 100 m or less, at an early stage of shield growth; the younger dikes seen in the same outcrop could have been intruded at a depth of 1,000 m or more.

No information exists on what proportion of dikes fed lava flows. No example is known on Oahu of a lava connected with its feeder dike. Recent experience on Kilauea indicates that dike-injection events without lava eruption are more frequent than fissure eruptions (Dzurisin and others, 1984), and even among the latter some (for example, the two caldera eruptions in 1982) erupt only a negligibly small amount of lava. Most of the Koolau dikes are very narrow, and it is likely that few erupted much lava.

The volume ratio of dikes to lava in subaerial parts of the Koolau Volcano is readily estimated after making two assumptions, namely, that the original volcano possessed a bilateral symmetry about its axis (fig. 41.1) and that the intensity of the dike complex decreases linearly upwards. This second assumption was documented for eastern Iceland by Walker (1974), but has not been demonstrated in the Koolau Range because of the unfavorable topography. All that is known is that the dike intensity in Kapaa Quarry does not measurably decrease through 95 m of elevation increase.

The reconstructed form of the Koolau Volcano and the distribution of dikes in it are shown in a transverse section in figure 41.28. The maximum total width of dikes in a transect is 4.8 km; the derived total dike cross-sectional area is thus about 2.4 km^2. The subaerial part of the volcano on the same transect has a cross-sectional area of 13 km^2; dikes therefore compose 15–20 percent of the subaerial volume. Intrusions are likely to constitute an increasing proportion at deeper levels.

Mention was made earlier of several localities where dikes of different ages intersect orthogonally; this is not readily explained if dike trends are determined primarily by the overall form of the volcanic edifice. The dike complex has a total dike width of 4.8 km near the caldera, decreasing to zero very rapidly toward the southeast and less rapidly in the opposite direction. These variations in width caused local stresses concentrated near the caldera, where the rate of change was greatest. Such local stresses may have been sufficient to cause the injection of the transverse dikes.

COMPARISON OF KOOLAU VOLCANO WITH KILAUEA

The active Hawaiian volcano that is most closely similar to Koolau appears to be Kilauea. Both are very strongly elongate structures having a single dominant rift zone intersecting the caldera, and they are comparable in size. The subaerial part of Kilauea is 30 percent higher and 43 percent longer. The bathymetric chart of Oahu shows a marked increase in slope at 500 m off the north tip of Koolau; if this marks the earlier shoreline then Koolau would have been 77 km long and 1,600 m high before subsidence to its present level. These dimensions are almost identical to those of subaerial Kilauea.

Both volcanoes are buttressed on one side by an older volcanic structure, though the Waianae buttress of Koolau is much smaller than the Mauna Loa buttress of Kilauea. Kilauea shows strong seaward creep on the unbuttressed side. Much of the unbuttressed side of the Koolau Volcano has already collapsed, and the predominantly northeast dip of dikes in part of the Koolau complex may be an early manifestation of this process.

The similarity between Koolau and Kilauea extends also to some of the less immediately obvious features, notably the asymmetry of each volcano along its length (fig. 41.29); their calderas do not occupy a central position, because one rift zone is longer and has been built up higher and wider than the other.

The caldera is assumed to mark the effective center of the volcano, below which magma rises from its deep source and then moves to intrusive or eruptive sites. The plunge of flow lineation on the dikes, however, appears to point to two main magma sources in the Koolau Volcano, one below Kailua caldera and the other below Kaneohe Bay. Possibly the bay is occupied by another caldera or by an extension of the Kailua caldera. Alternatively, the position of Kaneohe Bay is analogous with the setting of Mauna Ulu (site of the 1969–74 eruption) on Kilauea. Some of the Mauna Ulu magma may have come up a separate pathway, which branched off from the main Kilauea one (Ryan and others, 1981), and the Kaneohe Bay center may be a similar branch.

The curvature of the Koolau dike complex west of Kailua is reminiscent of the curvature of the Chain of Craters segment of Kilauea's east rift zone. Surface ground fissures along the Chain of Craters form an echelon group in which the individual fissures preserve the main trend of the east rift zone, and it can only be surmised whether these ground fissures overlie a swarm of dikes paralleling the Chain of Craters (as was proposed by Duffield, 1975; some kind of conduit by which lateral magma movement occurs must unquestionably be present along the chain).

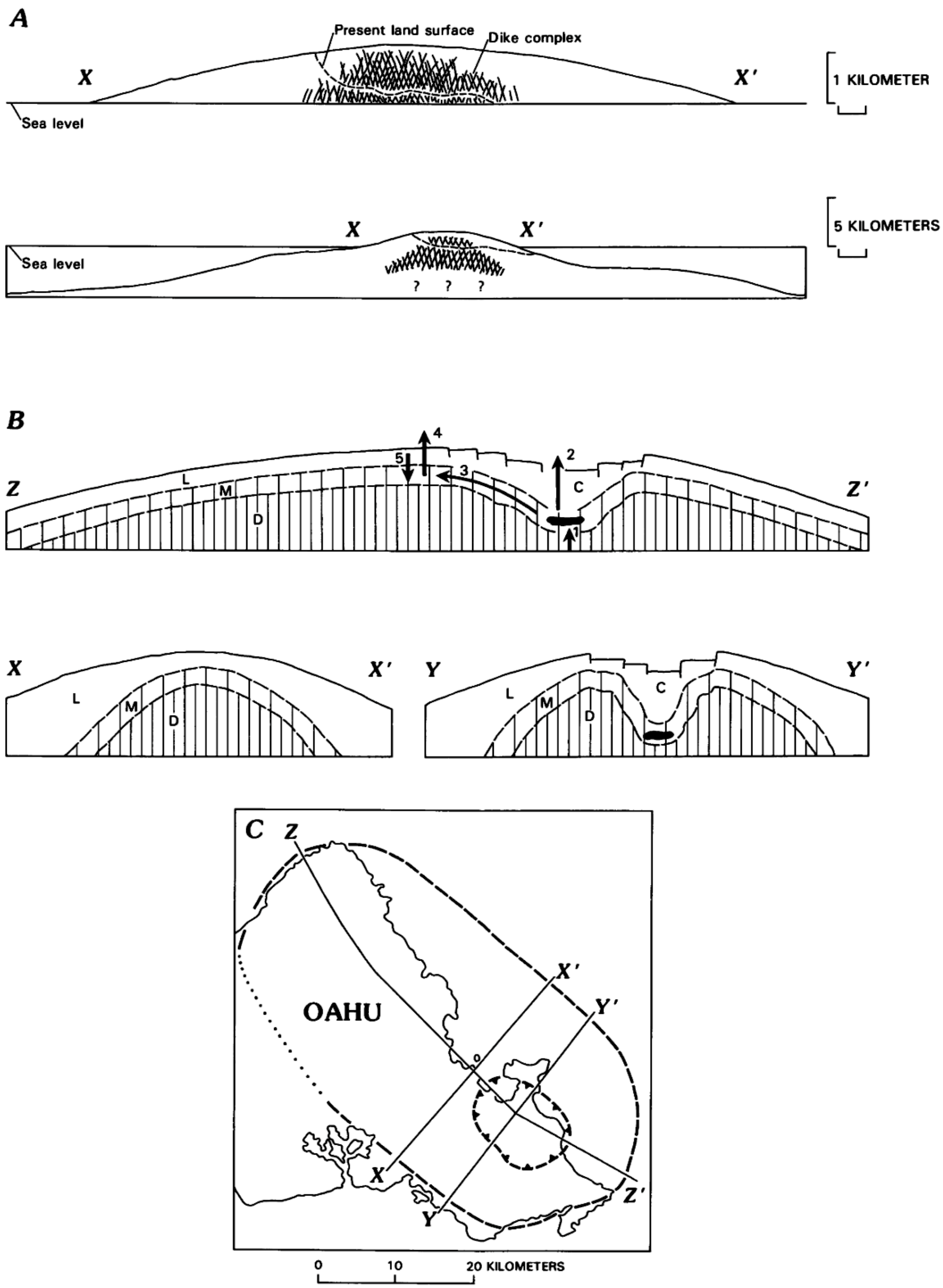
In summary, there are such close similarities between Koolau and Kilauea Volcanoes that the main dike complex in the one may be accepted as a close and valid analog to the subsurface region of the east rift zone in the other.

A MODEL FOR THE FORMATION OF THE KOOLAU DIKE COMPLEX

In a number of respects the Koolau dike complex is unique among described examples of the dike swarms associated with volcanic centers. The nondivergence of the dikes northwestward from the Kailua center shown on figure 41.5 contrasts with the radial or fascicular structure usually found, in which there is at least some degree of divergence away from the volcanic center. The Koolau complex is unusually coherent and the intensity rises inward from less than 5 percent to 50 percent or more in a remarkably short distance and then tends to be fairly uniform at 50–65 percent across its width, unlike the Gaussian intensity distribution found across most described dike swarms. The Koolau complex also reaches a far higher intensity (maximum 85 percent) than most swarms, which peak at 25 percent or less.

A model for the formation of the Koolau complex that explains these unique features and takes account also of the implications of recent magmatic activity on Kilauea Volcano (Walker, 1986) considers that three effects constrain the intrusion of dikes in the complex. One is the edifice effect, which tends to localize dike injection parallel with the long axis of the volcano. A second is the existence of plentiful pathways along margins of existing dikes in the complex. The third is a hydrostatic effect by which magma is able to reach a high crustal level in the relatively high-density environment of the dike complex.

Consider the third effect more closely. The generally high fluidity of Hawaiian tholeiitic magma gives it great freedom to move through the disjointed lava shields, and in these free conditions it comes to move into and become localized in those regions of the volcano in which it is gravitationally most stable. These regions are the marginal zones of the dike complexes, in which the average density of the rocks—a mix of lava flows and 5–50 percent of dikes—is closely comparable with that of weakly vesicular tholeiitic magma (fig. 41.28*B*).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It can be surmised that when part of a dike complex has built up to 50–65 percent intensity it becomes denser on average than tholeiitic magma so that magma tends to avoid it; hence an intensity of significantly more than 65 percent is attained only locally.

Because of increased vesiculation, the magma density may then decrease so as to fall below that of the lava, and when this happens the magma rises to the surface. This concept explains well the activity of Kilauea Volcano in recent years, in which dike injection events into the rift zone without lava effusion have occurred repeatedly and the eruptions have been mostly short events characterized by vigorous fire-fountaining. The geyserlike regularity of eruptive phases 4–46 in the 1983–6 activity of Kilauea is also strongly suggestive of a gas-accumulation control. Moreover it has often been observed that after magma has reached the surface and degassed, much of the degassed lava flows back down into fissures and presumably returns to the gravitationally stable zone.

SUMMARY AND CONCLUSIONS

When I began to study the Koolau dike complex I did not anticipate that it would prove to be in any way unusual, yet a wide range of unexpected features has emerged. Earlier workers were handicapped by a general paucity of good exposures, and the present study was feasible because of many new outcrops generated in the past 10 years. Some unexpected features were revealed only because of the quantitative nature of the present study, made possible by these new outcrops.

The Koolau dike complex is much more intense, and contains five to ten times more dikes, than was previously realized. Indeed, it is the most intense documented example of a dike swarm of volcanic-edifice type, and its 4.8 km of total dike width compares with the 1–2 km of total dike width for Tertiary dike swarms in eastern Iceland (Walker, 1974; Gibson and others, 1966), Scotland (Speight and others, 1982), and the Columbia River basalts (Taubeneck, 1970). If cone sheets are included, then some of the intrusive complexes in Scotland (for example, Mull; Bailey and others, 1924) will have an intensity closely comparable with Koolau.

One of the most intriguing features of the Koolau complex is the nonverticality of the dikes, which form two sets having opposing dips of 65° to 85°. These are interpreted to be complementary sets, closely analogous with normal faults in an extensional environment, and are thought to have resulted when the maximum principal stress direction acted vertically and was much greater in magnitude than the principal stresses acting in the horizontal plane. The nonverticality is a consequence of dike injection into a high-standing volcanic edifice. The dikes tend to dip out from the axis of the Koolau Volcano, but there is a large anomalous area in which the dikes predominantly dip in a contrary direction, toward the northeast. This seems to reflect a tendency, manifested very early in the history of the complex, toward seaward creep in that area; this creep later culminated in the major collapse of that same part of the volcano.

The Koolau complex displays many of the features of a sheeted dike complex, although it occurs in an intraplate setting unlike the sheeted complexes of the ophiolite suite. The sheeted structure resulted because the Koolau dikes showed a pronounced tendency to intrude along the margins of earlier dikes. As the dike-complex intensity increased, so an ever-increasing proportion of dikes utilized such planes, leading to the development of multiple dike clusters tens of meters wide containing tens of members. Some dikes followed a pathway along the middle of an earlier dike, which, when still hot, was a favored site for thermal reasons.

Many dikes possess a flow lineation on their margins, and the measured attitudes point to two main centers, about 5 km apart and situated at 2–3 km below present sea level, from which the dikes are presumed to have risen obliquely into higher parts of the edifice.

Because of their nonverticality, injection of the Koolau dikes involved a significant vertical component of dilation totaling more than 1,000 m. The contribution of this vertical component to the buildup of the Koolau shield is not known; we cannot distinguish absolute uplift of a dike hanging wall from subsidence of a dike footwall.

The Koolau dike complex is much denser than the lava pile and is so intense and concentrated as to represent a great localized load, reflected in the high positive Bouguer anomaly. The unequal bulk-density distribution in the volcano is considered to have had two consequences: one was to channel magma batches into a zone, in marginal parts of the dike complex, in which the magma was gravitationally most stable; the other was to tend to cause differential subsidence where the dike complex was widest and heaviest.

The preferential channeling of magma into a zone at the margins of the dike complex, where the magma density matches the bulk-rock density, is the key mechanism of a proposed model which explains buildup of the dike complex into a remarkably coherent structure having an intensity plateau at a level of 50–65 percent. This mechanism also explains the strong propensity of Hawaiian tholeiitic magma to remain underground, evidenced clearly by the record of the most recent magmatic activity; even when, because of vesiculation, magma does reach the surface, it may then promptly plunge underground again when it loses its gas bubbles.

The tendency for differential subsidence can account for the calderas of Hawaiian volcanoes: I propose that their subsidence is

FIGURE 41.28.—Relation of dike complex to bulk-density zonation and magma pathways of Hawaiian volcanoes. ***A***, Profiles across Koolau lava-shield volcano on two different scales, showing setting of dike complex. ***B***, Schematic profiles across a Hawaiian volcano such as Koolau, showing bulk-density zonation and typical magma pathways. L, lava shield cut by only a few scattered dikes, less dense than nonvesicular tholeiitic magma; M, marginal zone of dike complex, intensity 5–50 percent, into which nonvesicular or weakly vesicular tholeiitic magma tends to be channeled because of matching densities; D, dike complex, intensity >50 percent, denser than nonvesicular or weakly vesicular tholeiitic magma; C, caldera complex; calderas of varying sizes and ages where density zones are strongly depressed; 1, magma residing in a chamber in zone M where it is lowest (in caldera complex). This is gravitationally most stable situation for nonvesicular magma in entire edifice; 2, rapid vesiculation carries a magma batch to the surface, producing caldera (summit) eruption; 3, slow vesiculation carries a magma batch into a rift zone channeled along zone M; 4, vesiculation carries a magma batch to the surface, producing rift-zone eruption; 5, degassed lava returns to zone M. ***C***, Map of Koolau Volcano showing location of profiles in *A* and *B*.

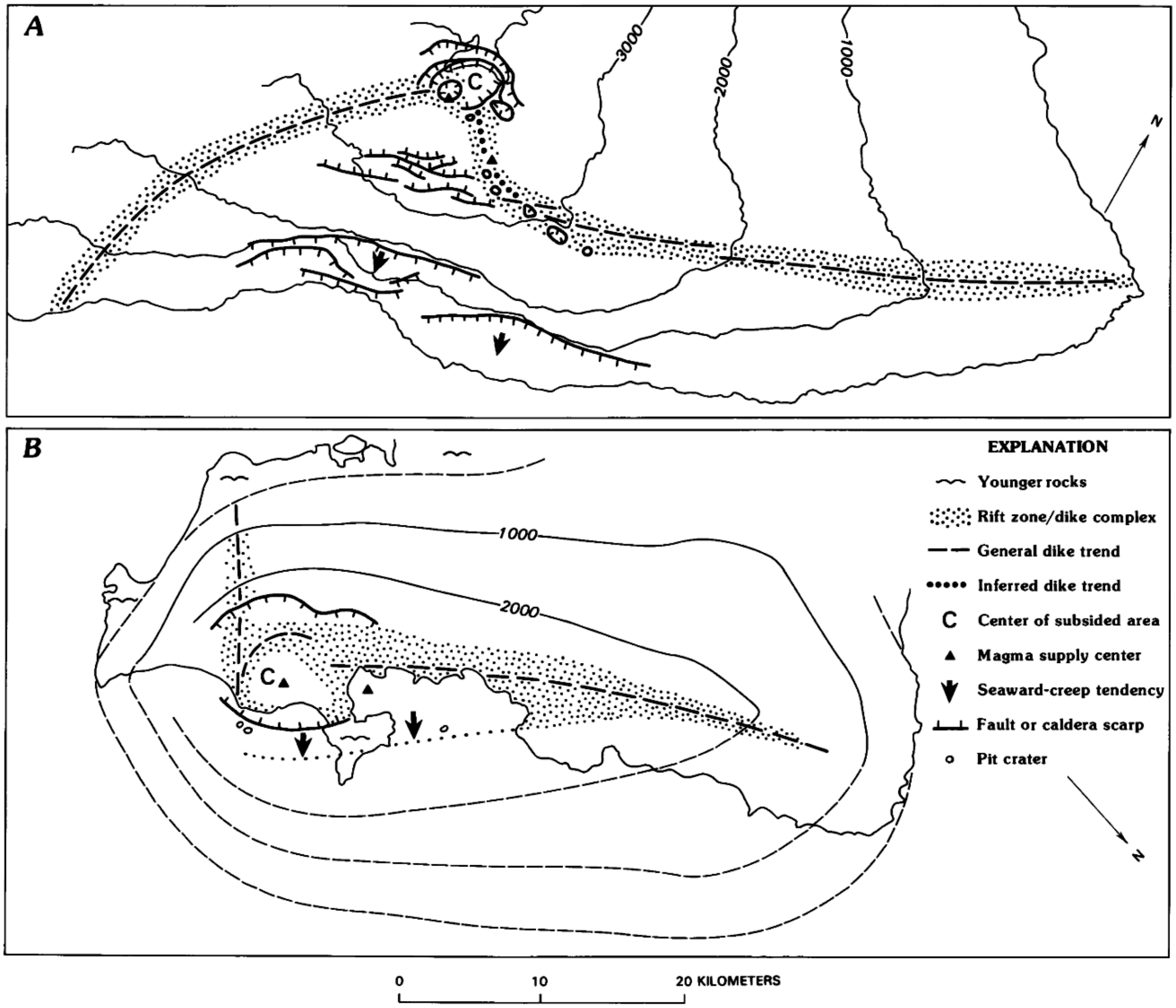

FIGURE 41.29.—Maps of Kilauea and Koolau Volcanoes at same scale. ***A***, Kilauea on the Island of Hawaii. Volcano contour interval 1,000 ft; heights in feet above sea level. ***B***, Koolau Volcano on Island of Oahu. Contours, in feet above present sea level, are generalized from present topography to show original form of volcano; dashed where very uncertain because of deep erosion.

caused by the load of intrusions and is possible because the hot lithosphere above a hot spot is sufficiently weak to permit downward creep of a prism of the dike complex.

The Koolau Volcano has a broad subsidence area that measures at least 10 km by 12 km. In part this is an area of general downsagging, and in part it may consist of discrete down-faulted cauldrons. The Kailua caldera is now exposed at an erosion level 1 km beneath the final top surface of the Koolau Volcano, and variations in the makeup of the caldera rocks can be explained by an imbalance between two processes that operated at different rates. One process was subsidence, which caused high-level rocks having few or no dikes to appear at today's erosion level. The other process was the injection of dikes seeking to rebuild the dike complex to the 50 percent to 65 percent intensity at the same level. In some outer parts of the Kailua caldera where subsidence was caused by downsagging, the rebuilding of the complex was completed. In the middle part of the Kailua caldera, subsidence greatly exceeded the capacity of dike injection to rebuild the complex. It is thought that Kilauea caldera is a good present-day analog, and the magma chamber which is postulated to be situated in the marginal zone of its dike complex is now 3–5 km deep, maintained at that depth by rapid subsidence.

This mechanism is consistent with features of Hawaiian calderas such as their highly dynamic nature—great changes in caldera geometry can occur within a century—and the fact that the calderas are the locus of dike injections.

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