DIKE WIDTH CHARACTERISTICS OBSERVED IN INTRA-PLATE VOLCANOES

S.R. Spengler   G.P.L Walker

The mean width of dikes measured in three intra-plate volcanoes (Koolau, Waianae, Pohnpei) is found to increase linearly as a function of distance from the volcanic center. Inter-island differences in mean dike width is attributed to compositional differences of the lavas erupted on the three volcanoes studied. The increase in average dike width down-rift is postulated to control the duration of eruptive events observed along active rift systems, such as Kilauea's east rift zone. In addition, the absolute number of dikes is observed to decrease logarithmically down-rift, in agreement with decreases in intrusive frequency observed down-rift on the active volcanoes of Kilauea and Mauna Loa in historical times (Walker, 1988).

No systematic difference in dike width is observed in a near continuous 3.5 kilometer exposure across the rift system of one of these volcanoes (Koolau). This suggests that the remote-stress distribution within the volcanic edifice is either not greatly affected by the previous intrusion of dikes or that induced increases in compressive stress in the rift zone are relaxed by faulting or other tectonic movement between individual intrusive events.

INTRODUCTION

Subaerial erosion of intra-plate volcanic edifices offers an opportunity to study the dike systems responsible for their growth and development. Several studies (Spence and Turcotte, 1985; Rubin and Pollard, 1987; Rubin, 1990) have analyzed the mechanical nature of dike propagation through a volcanic edifice and have emphasized the need for additional field studies to further quantify their theoretical models. Field studies conducted in the Pacific (Zbinden, 1984; Walker, 1987; Spengler, 1990) have yielded a large amount of quantitative data regarding the spatial variation in dike thickness and intensity within intra-plate volcanoes. These studies are significant because these volcanoes are located in tectonic settings where external remote stresses are either minimal (as in the case of isolated volcanic edifices such as Waianae volcano on Oahu) or can be identified qualitatively (e.g. possible gravitational buttressing effects due to the presence of an adjacent volcanic structure as in the case of Koolau and Pohnpei volcanoes). In this tectonic environment, the influences of complicating external stresses other than those found within the volcanic edifice itself are minimized.

In this paper, we present dike width data measured in three intra-plate volcanoes. This data is then used to gain an insight into the dynamics and structure of the presently active rift system on Kilauea.

PREVIOUS WORK
While various workers have studied the mechanical aspects of the movement of magma through dikes (Hardee and Larson, 1977; Delaney and Pollard, 1982; Spence and Turcotte, 1985; Rubin and Pollard, 1987; Bruce and Huppert, 1989), relatively little attention has been given to documenting the variability of dike widths in various tectonic settings. Delaney and Pollard (1981) measured the variation in physical properties of a group of minette dikes found intruding a flat-lying sequence of siltstone and shale over a distance of three kilometers near Ship Rock, New Mexico. No systematic variation in dike width was observed over the relatively short length over which these dikes were exposed. In the British Tertiary Province, Speight et al. (1982) report that thicker dikes become more preponderant at greater distances from the volcanic centers. Unfortunately no further quantitative information is given in the paper. Helgasson and Zentilli (1985) studied the vertical and horizontal variation in dike thickness observed in 168 dikes of the Breiddalur-Thingmuli dike system in Iceland. They found that the maximum thickness of measured dikes decreases with increasing elevation in the edifice and that the average dike width at a given crustal level was less within the Breiddalur dike system than at the Alfa fjordur dike system. The observed differences in dike thickness at the two sites were attributed to either differences in the regional principal stress in the crust at the time of dike emplacement (i.e. different local spreading rates) or to differences in the pressure of the intruding magma.

In a detailed study of Koolau Volcano, Walker (1987) showed that the average width of exposed dikes tripled between the volcanic center near Kailua and the Waikane area to the northwest and that the increase in width is accompanied by a 70% decrease in the absolute number of dikes present in transects across the complex. He suggested that the lateral distance a dike travels from its source is related to its width; broader dikes being more far ranging and thus more prevalent at greater distances from the eruptive center.

FIELD DATA

In this paper, data from previous published and unpublished studies of Waianae and Koolau volcanoes on Oahu, Hawaii are combined with field studies by the first author on the northeastern end of Koolau Volcano and on the island of Pohnpei, located in the southwestern Pacific. The overall orientation and location of dikes and the Bouguer gravity high on each volcano are illustrated in Figure 1. Dike width and intensity data for the three volcanoes are compiled in Table 1.

Waianae volcano was studied by Zbinden (1985) who made approximately 400 measurements of dike width, strike and petrologic type. Thin sections were made for many of the measured dikes and a subset of 85 dikes was chosen for chemical analysis (Zbinden and Sinton, 1988). In this way, dikes related to the shield-building stage of the volcano were differentiated from dikes associated with the alkalic-capping stage of activity. Additional dike width data collected as part of a paleomagnetic study of the Kolekole pass region of Waianae (99 dike measurements, M.D. Knight and G.P.L. Walker, unpublished data) have been combined with Zbinden's data set in this study.
The dike complex of the dissected Koolau shield volcano was studied in detail by Walker (1986, 1987) who made measurements on roughly 3500 dikes exposed within the eroded shield. These measurements were concentrated in 57 localities exposed between the Keolu Hills near Kailua and the Waikane area to the northwest (Figure 1). Widths, trends, and dike intensity as measured both by percentage of outcrop as well as by the number of dikes per 100 meter traverse were recorded for each outcrop locality. Walker's data from near the center of the shield were augmented by further field studies by the first author in and around the northwestern end of the Koolau range to obtain intensity and width information on dikes exposed near the distal portion of the volcano. Additional dike data collected from the Waiahole water transmission tunnels which traverse the Koolau's rift system were obtained from K.J. Takasaki of the USGS (Personal Communication).

Dikes exposed on the island of Pohnpei were studied during reconnaissance mapping of the island in 1988. A total of 410 measurements of dikes were made at numerous localities around the island. Exposures were typically limited to areas where erosion of the overlying, voluminous late-stage volcanics revealed the underlying shield-building lavas. Unlike Waianae and Koolau volcanoes, Pohnpei does not have clearly defined rift systems but, rather, the dikes tend to strike in a radial fashion about the volcanic center (Figure 1).

DISCUSSION

Plots were constructed of the mean and median dike thickness versus distance from the eruptive center on each volcano (Figure 2). The location of the eruptive center was taken to correspond to the location of the Bouguer gravity high. For Koolau and Waianae volcanoes, the site of the Bouguer high was selected from gravity contour maps reported in Strange et al. (1965). The gravity high was located on Pohnpei by a gravity survey conducted by the first author in 1988 (Spengler, 1990). In Figure 2, only outcrops containing a minimum of four measured dikes were plotted. The regression equation for the mean dike widths as well as the total number of dike measurements integrated into the plot are listed in the upper left corner of each plot.

Down-rift Variation in Mean Dike Width

Despite some scatter in the data, a definite increase in mean dike width at greater distances from the volcanic center can be discerned. Some of the scatter in the data may be attributed to the assumption that all dikes emanated from a single locality. Walker (1987) used measurements of the predominant plunge of flow lineations on dikes and Knight and Walker (1988) measured the anisotropy of magnetic susceptibility in Koolau dikes to infer the presence of at least three high-level magma reservoirs that fed the dikes and related lava flows of the Koolau shield. In addition, dike data collected from the water transmission tunnels near the Waikane area show two predominant strike directions (N35W and N55W), consistent with the presence of at least two volcanic center within Koolau Volcano (Takasaki, unpublished field notes). The Waianae data set has the further complexity that both tholeiitic and alkalic dikes are found within the volcanic edifice. The
mean width of 349 tholeiitic dikes was 61 cm while the mean width for 26 alkalic dikes was 103 cm (Table 1). Zbinden (1984) noted that the exposure at Nanakuli ridge (distance = 6.4 km; mean width = 165 cm) contained predominantly alkalic dikes which explains why this locality plots so far off the trend defined by the other localities which are composed predominately of tholeiitic dikes (Figure 2).

**Dike Width Variation Across a Rift Zone**

The scatter in dike width at a given distance from the volcanic center can be illustrated by analyzing dike measurements made in a nearly continuous 3.5 kilometer cross section of the Koolau rift system exposed in the Waihole tunnel system. K.J. Takasaki, J.F. Mink and D.C. Cox of the United States Geological Survey made detailed strike, dip and width measurements on the dikes exposed within the five tunnels which comprise the Waihole system in the late 1950s. The tunnels were drilled roughly perpendicular to the general trend of the rift system in order to intercept dike compartmentalized groundwater for irrigation on the dry leeward side of the island (Takasaki and Mink, 1986). Their original field data was broken up into 100 meter sections striking perpendicular to the average N45W trend of the rift system (Figure 3). The mean dike widths measured in these 100 meter sections show similar amounts of variability as is observed in isolated outcrops exposed in the Koolau at a given distance from the volcanic center. No systematic variation in dike width is observed in going from the high intensity, central portion of the rift zone, to the low intensity marginal zones.

Rubin and Pollard (1987) discussed the effect that previous intrusion of dikes would have on the compressive stress regime of the material through which later dikes propagate. The lack of any significant difference in dike width within the low dike intensity and the high dike intensity portions of the rift system suggests that the increased compressive stress induced within the rift system by prior dike intrusion probably becomes relieved over a time scale similar to the intrusion rate at a given site within the rift system. Minor faulting or larger tectonic movement resulting from large earthquakes may facilitate relieving the rift system of excess compressive stress.

**Variation in Number of Dikes Down-Rift**

An estimate of the absolute number of dikes present within the Koolau rift system can be made at three different localities along the rift zone. Walker (1987) estimated that 7,400 dikes are present in a transect just south of Kaneohe bay (near the caldera). This estimate was made from field measurements collected at outcrops which generally range in elevation from 75-150 meters. Roughly 20 kilometers from the eruptive
center, the dikes exposed in the Waihole water transmission tunnels can be totaled. If one assumes that the rift zone is roughly symmetrical, it is estimated that about 950 dikes transect the entire rift zone at the average 240 meter elevation of the tunnels. In the Laie-Haaula area, roughly 30 kilometers from the eruptive center, dikes are exposed in the deeply dissected Maakua, Kaipapua, Wailele and Malaekahana valleys on the eastern side and in Kamananui valley on the western side of the Koolau crest. The dike outcrops range in elevation from 185-310 meters elevation and have an average width of 170 centimeters. The maximum dike intensity measured is about 5 percent at two localities 2.5 kilometers apart on opposite sides of the crest. Assuming that the shape of the cross-axis variation in dike intensity is similar to that observed within the Waihole water transmission tunnels, a maximum dike intensity of 25% is estimated for the center of the rift zone yielding a total of 165 dikes for the traverse at this locality.

The number of dikes at the three localities was adjusted to a common elevation by assuming that the dike intensity decreases linearly to zero at the top of the volcanic pile, as has been observed in the Tertiary dike swarm in the Berfjodur-Breddalur area of Iceland (Walker, 1960). The presence of few dikes in the walls of Kilauea Caldera (Casadevall and Dzurisin, 1987) suggests that this upward decrease in the number of dikes is also true for intra-plate volcanoes. Extrapolation of the dike data at the three localities to sea level yields values of 8300 dikes in the caldera region, 1460 dikes at Waikane and 500 dikes near Laie. This decrease in the number of dikes observed down-rift within Koolau Volcano can be compared to the distribution of historical intrusive events along Kilauea’s East Rift Zone (Walker, 1987). Figure 4 shows that the intrusive rate decreases logarithmically down-rift within both volcanoes.

Magma Composition Control of Mean Dike Width

The majority of dikes on Pohnpei range in composition from basanite to alkali olivine basalt. In contrast, the dikes on Koolau volcano are almost exclusively tholeiitic, whereas both tholeiitic and alkalic dikes are found on Waianae volcano. These compositional differences are reflected in the mean dike width measured within the various volcanoes studied. Table 2 lists the mean and median width of dikes on the three volcanoes in this study. Dike width data as well as measured widths of mugearite-trachyte composition dikes found on Kohala Volcano, West Maui and Pohnpei (total of 8 dikes) were also considered. The average composition of these dikes were determined based on chemical analyses of dike material and shield-building lavas from each volcano. The mean composition and width of both tholeiites and alkalic lavas were calculated based on the analytical information presented in both Zbinden (1985) and Zbinden and Sinton (1988). The mean composition of the Pohnpei and Koolau shield lavas were obtained from the following sources (Spengler, 1990 and Roden et al., 1984). The viscosity of the dike magma was then calculated using the method of
Bottinga and Weill (1972).

Figure 5 plots the mean dike width measured in the volcanoes discussed above versus the calculated viscosity of the intruded magma. The strong correlation between the mean dike width and the calculated viscosity verifies theoretical studies (i.e. Hardee and Larson, 1977) which indicates that for a given driving pressure gradient, the width of a propagating dike should vary as a function of magmatic viscosity.

**What does it all mean?**

Different mechanisms can be postulated to explain the observed increase in mean dike width away from the eruptive center. Individual dikes may become wider downrift as a result of a systematic decrease in the remote stress field produced by the geometry and structure of the volcanic edifice. This variation in the state of stress would be induced by the vertical variation in bulk density within the volcanic edifice, the presence of horizontal tensile strengths due to the gravitational loading of the volcanic edifice, or could be generated by the previous intrusion of dikes (Rubin and Pollard, 1987). Since the mean width of dikes is not systematically different in the low and high intensity parts of the rift zone at a given distance from the volcanic center (Figure 3), the stress regime produced by the previous intrusion of dikes does not appear to be sufficient to affect the average width of dikes.

Due to the discontinuous nature of outcrops on these oceanic islands, direct field observations can not verify whether progressive widening of individual dikes does indeed occur. It is important to note, however, that wide dikes do occur at localities close to the volcanic center and that the observed increase in mean and median dike width is due to an increase in the relative percentage of wide dikes downrift rather than a progressive change from all narrow to all wide dikes. In other tectonic environments where more continuous dike exposures are available, the average width appears to stay more or less constant along strike (Delaney and Pollard, 1981).

A simpler explanation for the observed increase in dike width is that narrow dikes are simply not robust enough to propagate far from their magmatic source. In this "Propagation of the Thickest" model, dikes that are injected into the rift zone with lower magmatic pressures will quickly cease to propagate as they are overcome by the strength and elastic stiffness of the host rock. Narrow dike propagation is also retarded by thermal factors. Delaney and Pollard (1982) showed that small differences in dike thickness can have a profound influence on the solidification rate of magma within the dike. A general estimate of the actual time required to solidify a dike can be calculated with the method outlined by Spence and Turcotte (1985). Using a
temperature contrast of 800°C between the intruding magma and country rock and the physical properties
given in their paper, cooling times on the order of a day are calculated for proximal dikes (median width~50
cm) and 1-2 weeks for distal dikes (median width~200 cm).

The variation in width of dikes that emanate from the volcanic center is also controlled by differences in the
driving magmatic pressure. Epp et al. (1983) suggested that distal eruptions along Kilauea's east rift zone tap
the summit reservoir at lower levels and drain it more deeply than summit eruptions. In this scenario, distal
dikes propagate deeper through the rift zone and are driven by a higher hydraulic pressure than more proximal
events that emanate from shallower chambers with accompanying smaller magma-reservoir pressures. The
higher initial magma pressure would thus lead to propagation of a wider crack during dike intrusion (Hardee
and Larson, 1977; Spence and Turcotte, 1985) for these distal eruptions. Petrologic evidence for this
mechanism comes from submarine lavas dredged from the distal end of Kilauea's east rift system which have
higher olivine contents than lavas near the summit which is indicative of draining from lower levels of the
sub-summit magma reservoir (Moore, 1965).

One potentially useful application of this dike width data is that variations in dike widths may prove useful for
locating volcanic centers in older eroded volcanoes where all geomorphic evidence of the original volcanic
caldera has been removed.

DIKE WIDTH CONTROL ON ERUPTIVE STYLE

The physical size and stress regime around the 1.8-2.7 Ma Koolau and the presently active Kilauea volcanoes
are quite similar (Walker, 1988). In particular, both volcanoes are buttressed against an older volcanic
structure and are down-faulted along their unbuttressed side. The sub-aerial length and profile of the
dominant rift systems (Kilauea's east rift zone and the northwest rift zone on Koolau volcano) are also quite
similar. Owing to the physical similarities of the two rift zones, data gathered on the exposed dike system of
Koolau volcano is useful in explaining down-rift variations in eruptive style observed in historical eruptions
along the active rift system of Kilauea.

Eaton and Murata (1960) first noted that the volume of flank eruptions on Kilauea are typically much larger
than summit eruptions. In his study of surficial flows on Kilauea, Holcomb (1987) noted that the percentage
of surficial aa progressively increases from the summit to the lower east rift zone. This increase in aa downrift
may be a reflection of: 1) higher discharge rates issuing from the progressively wider dikes found downrift; 2)
the change of some flows from pahoehoe to aa downslope. Higher discharge rates promote the rapid loss of
volatiles and lead to the preferential formation of aa rather than pahoehoe flows. In addition, a Deep-Tow survey and sea floor photography have discovered that the proportion of sheet flows increases with depth along the distal submarine segment of Kilauea's east rift zone (ERZ) (Clague et al., 1988; Lonsdale, 1989). These sheet flows are characteristic of voluminous submarine eruptions with high discharge rates and are thought to be related to the periodic collapse of the summit caldera at Kilauea (Holcomb, 1987). Lonsdale (1989) observed large, 2-8 meter wide cracks near vertical walls along the crest of the submarine portion of the east rift zone. These cracks were created by dilation during dike intrusion and are thought to reflect the actual width of the subsurface dike due to the high depth:width ratio of the cracks and the jig-saw puzzle fit of the fractured rocks on either side of some cracks (Lonsdale, 1989). It was noted that these cracks are wider than typical dikes exposed within Hawaiian rift zones. This range in dike width is similar, however, to the typical dike widths observed in the distal portion of Koolau volcano.

An increase in average eruptive volume per event at down-rift locations is consistent with the dike width data presented in this paper. The number of dikes (roughly corresponding to intrusive events) is observed to decrease logarithmically down-rift. The volume of the volcano also decreases down-rift, but in a more linear fashion. If the intrusion/extrusion ratio for dikes is similar for proximal and distal portions of the rift zone, there must be a corresponding increase in volume per eruptive event in moving down-rift.

The duration of distal flank eruptions are also typically longer than rift zone eruptions that occur close to the summit caldera. Using historical eruption data from Kilauea's ERZ, one can test whether the difference in solidification rate for distal and proximal dikes controls eruption duration by assuming that the dike width distribution within Kilauea and Koolau volcanoes is similar. The regression line for Koolau volcano (Figure 2) can then be used to estimate the median dike width for the different historical ERZ eruptions of Kilauea based on the distance from the summit. For the sustained eruptive events at Puu O's and Mauna Ulu, only the first phases of activity were plotted since these most clearly reflect the initial dike propagation event. The time required to solidify the calculated dike width associated with each eruption was then calculated using the physical properties given in Spence and Turcotte (1982) and again assuming a 800°C temperature differential between the intruding magma and country rock. The resulting calculated time was then compared to the actual duration of each volcanic event. From the resulting graph (Figure 6), it is apparent that the calculated time for solidification, based on the estimated dike width from the regressed Koolau data, closely matches the actual duration of many of the historical eruptions on Kilauea. Thus the data suggests that to a first approximation, down-rift variations in dike width controls the duration of eruptions along the rift zone on Kilauea.
The extended duration of some eruptions, such as the 1955 eruption and the activity at Puu O'o and Mauna Ulu, may be related to the advection of heat by flowing magma which can control the temperature distribution along the wall rock/dike contact. Bruce and Huppert (1989) have shown that the time required for a dike to solidify is dependent on which kind of thermal regime exists; one in which heat loss to the walls exceeds heat advection which leads to solidification of the dike; and a second in which initial heat loss may exceed advection, but in which advection and latent heat effects eventually exceed the heat losses into the country rock allowing the dike to remain open for extended periods of time and even become widened by thermal erosion. This feedback mechanism could explain how the magmatic conduit system stayed open for such a prolonged time during these extended eruptive phases. In the case of Mauna Ulu and Puu O'o, the duration of these eruptions was probably controlled by the decay in magma driving pressures and supply rate from the region of magma storage.

CONCLUSIONS

It has been shown that: 1) the mean width of dikes increase as a function of distance from the volcanic center on three intra-plate volcanoes; 2) no systematic difference in dike width is observed in exposures across the rift system in one of these volcanoes; and 3) the number of intrusive events within the rift zone is observed to decrease logarithmically downrift. Inter-island differences in average dike width for the intra-plate volcanoes studied are shown to be most likely related to viscosity of the intruding magma. The overall increase in dike width and decrease in intrusive frequency leads to eruptions of longer duration and greater volume along the distal portions of the rift zones. The majority of intrusions on Kilauea's east rift zone appear to have occurred within a thermal regime in which heat loss to the country wall rock exceeds the rate of heat advection within the flowing magma.

REFERENCES


Figure 1: Dike Orientation in Relation to Bouger Gravity High, Pohnpei, Waianae and Koolau Volcanoes
Figure 2: Mean and Median Dike Width as a Function of Distance from Eruptive Center
Figure 3: Variation in Dike Width and Dike Intensity Measured in the Tunnels of the Waiahole Water Transmission System, Koolau Volcano
Figure 4: Calculated Solidification Time Versus Actual Eruption Duration
## TABLE 1

Dike Width and Intensity Data for Pohnpei, Koolau and Waianae Volcanoes

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Volcano, Outcrop ID, Mean Dike Width (cm), Median Dike Width (cm), Distance from Eruptive Center (km), Number of Dikes, Dike Intensity (%), Data Source.
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Dike Width and Intensity Data for Pohnpei, Koolau and Waianae Volcanoes

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