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THREE HAWAIIAN CALDERAS: AN ORIGIN THROUGH LOADING BY SHALLOW INTRUSIONS?

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Abstract. The calderas of Kilauea and Mauna Loa are highly dynamic structures, and in the <200-year historic period have varied in volume by a factor of 2, and gained or lost 1 km^3 per century. The deeply eroded caldera of the extinct Koolau Volcano in Oahu is wider than active Hawaiian calderas, and its lavas have a strong centripetal dip and funnel structure not evident at Kilauea or Mauna Loa. The differences can be attributed to the different erosion depths, and the time integrated subsidence profile of Kilauea is also a stepped funnel (having its apex at Halemaumau). Koolau caldera is the focus of an extraordinarily intense dike complex, and an intriguing feature is the great diminution in dike concentration into the caldera. It is thought that dike injection in any part of the complex generally continued until it reached 50% to 65%. In outer parts of the caldera, the complex was maintained at or rebuilt to this value despite subsidence. In the center of the caldera (where the positive Bouguer anomaly is centered), subsidence evidently greatly outpaced the capacity of dike injections to rebuild the complex. Assuming the same dike injection rate as Kilauea and Mauna Loa yields a volumetric subsidence rate in Koolau caldera exceeding 1 km^3 per century. Hawaiian calderas are much more dynamic than calderas of silicic volcanoes, shaped by frequent small events instead of a few great ones. The temporal and volumetric correspondence of historical subsidence events with eruptions is poor, and this and the high subsidence rates argue for a caldera-forming mechanism that consumes the subsided rocks. It is suggested that subsidence is caused by the great localized excess load of intrusive rocks, carrying the center of the volcano into the thermally weakened lithosphere above the Hawaiian hot spot. It is envisaged that under steady state conditions the magma chamber rises, as the injection of intrusions causes the level of neutral buoyancy (at which the chamber is located) to ascend, and keeps pace with subsidence.

1. Introduction

Several of the younger volcanoes in Hawaii possess calderas, and those of Kilauea and Mauna Loa (Mokuaweoweo) are particularly fine and well-known features. In addition, geological mapping reveals the presence of eroded calderas on several of the older Hawaiian volcanoes [Macdonald, 1965; Stearns, 1966], but their position is not necessarily well reflected by the present topography. This paper stems from recent mapping of the Koolau Volcano on the island of Oahu. Koolau is about 2 m.y. old, and its caldera is deeply eroded.

The calderas of Kilauea and Mauna Loa are clearly defined subsidence structures bounded by young arcuate fault scarps, and appear superficially to be textbook examples of subsided-piston calderas. A different view is given by the internal structure of the Koolau caldera which is exposed at an erosion depth of about 1 km. Koolau caldera is a larger subsidence feature (Figure 1), in which centripetal dip of the lavas appears to dominate the structure and points to downwarping as a major subsidence mechanism.

At first sight the differences that appear to exist between Koolau and the young Kilauea and Mauna Loa calderas seem sufficiently great that these structures could be interpreted to be totally different in kind. This paper explores the alternative viewpoint, namely, that the structures observed appear to be different because they are viewed on different erosion levels; it also reconsiders the whole question of the origin of Hawaiian calderas, based on the new perspective that Koolau provides.

Differing views have been expressed regarding whether caldera formation is a late event at the end of shield growth on Hawaiian volcanoes or is a recurring process, as summarized by Peterson and Moore [1987]. Macdonald [1965] reviewed the evidence relating to the origin of Hawaiian calderas and favored the loss of support from beneath the summit area by withdrawal of magma during flank eruptions as the main causative mechanism. Stearns [1966] favored the view that the subsided basalts were then remelted. A different mechanism is considered in this paper.

2. Young Calderas of Kilauea and Mauna Loa

The calderas of Kilauea and Mauna Loa are highly dynamic structures, in a condition of constant and rapid change. They are the scene of frequent eruptions, on average one in every 2.5 years, that are steadily infilling them. The oldest lava exposed on Kilauea's 10.5 km^2 floor is that of 1885, and most of the floor formed in or since 1921. Recorded history covers only the past 200 years, but this period has witnessed several substantial subsidence events. The 10.3 km^2 floor of Mauna Loa's caldera consists entirely of lavas erupted in and since 1942. The 150-year historic period has been one of a net infilling but with several significant subsidence vents.

The existence of the two calderas in situations where lava eruptions occur frequently, combined with their youthful form, indicates that they are very young features; such calderas must be regenerated at intervals

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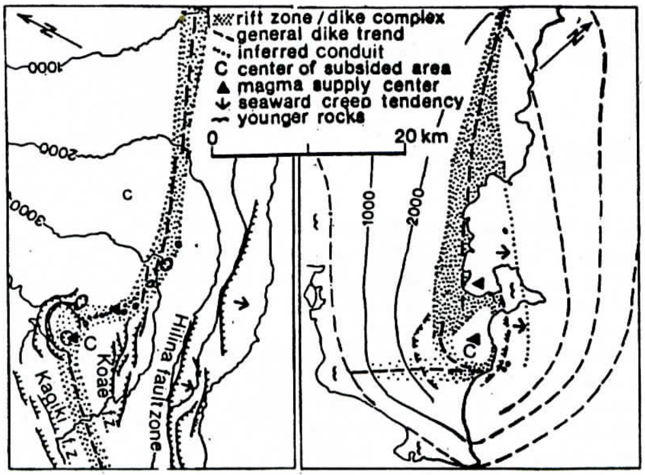

Fig. 1. Maps, drawn on the same scale, of the calderas and their environs of (left) Kilauea and (right) Koolau. Generalized contours shown for Koolau. Heights in feet above sea level. Magma supply centers for Kilauea based on seismic modeling by Ryan et al. [1980], and for Koolau based on dike lineation plunge [Walker, 1987a].

of a few centuries. They contrast with the calderas of more silicic volcanoes where major subsidence events are infrequent and may be separated by intervals of tens to hundreds of millenia.

Kilauea Caldera

Kilauea caldera measures 5 x 3.1 km, but a number of concentric faults with lesser displacements occur outside the caldera proper and increase the subsided area. Two contiguous pit craters, Kilauea Iki and Keanakakoi, further extend the subsidence area. The caldera wall is highest (about 140 m) on the northwest side at Uwekahuna Bluff, where the Hawaiian Volcano Observatory is built, and is lowest on the south side, where at one point the caldera floor lavas have flowed out of the caldera. The total subsidence volume out to the outer ring fractures and including the pit craters is 1.39 km^3; Figure 2 shows the basis on which this volume was determined. In 1825 the volume was nearly 1 km^3 greater.

The caldera wall at Uwekahuna Bluff consists of lavas resting on the Uwekahuna Ash. This ash was dated at approximately 2100 years B.P. [Lockwood and Rubin, 1986], and accumulation of the overlying lavas, and then the formation of this wall of the caldera, thus occupied a total of less than 2100 years. Powers [1948] inferred the existence of an earlier caldera outside the present one at Uwekahuna Bluff. This older caldera was presumably formed and infilled, and then the present caldera formed, during this same 2100-year period [Holcomb, 1987].

Kilauea caldera as now seen has a relatively flat floor interrupted only by Halemaumau pit crater, but the topography of the floor varied much over the past 200 years due to repeated subsidence and partial infilling events.

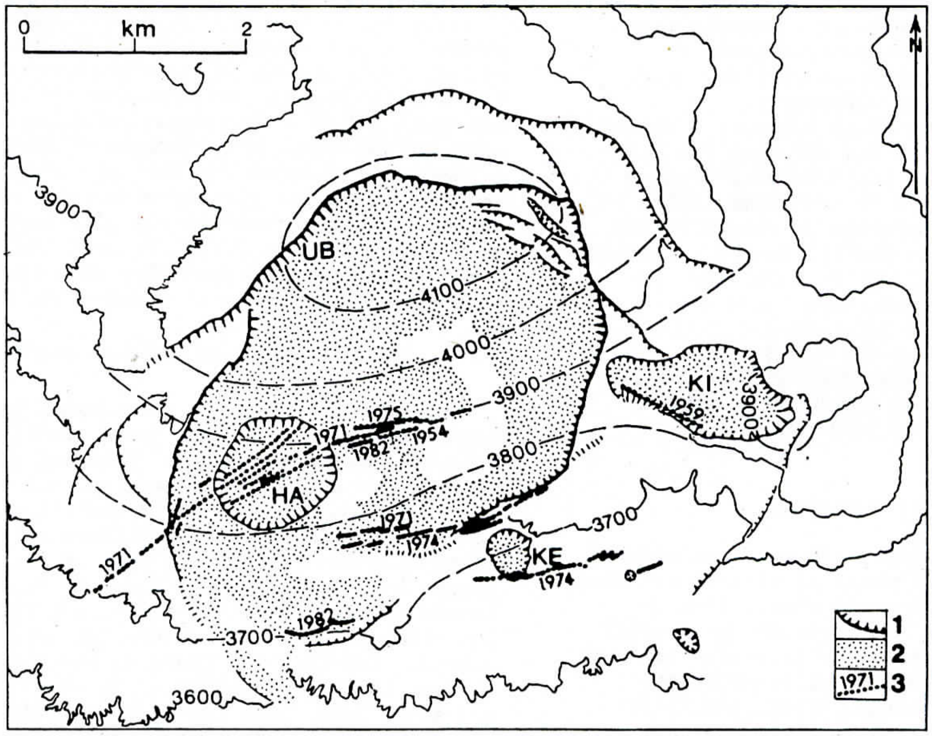

Fig. 2. Map of Kilauea caldera showing contours (dashed lines) reconstructed across caldera from which caldera volume estimated. Heights in feet above sea level. Here, 1, fault scarps; 2, caldera floor lavas, 1919 and younger; and 3, eruptive fissures, 1954 and younger. Pit craters are HA, Halemaumau; KI, Kilauea Iki; KE, Keanakakoi; PU, Puhimau; and UB, Uwekahuna Bluff. Based on maps by Peterson [1967] and Saint Ours [1982].

TABLE 1. Volumes of Caldera Subsidence at Kilauea Volcano During Historical Times

Date	Collapse Volume* 10^6 m^3		Volume of Flank Lava Flows, 10^6 m^3
	of Sharply Defined Depression	Gentle Sinking of Whole Summit Area	
1823	540	---	14
1832	581	---	?
1840	220	---	215
1868	188	---	<5
1886	40	---	?
1891	34	---	?
1894	9	---	?
1916	8	---	0
1919	10	---	74
1922	21	---	9
1924	---	202	0[a]
1955	---	200	141
1975	---	150[b]	0
Total	1651	552	>458

Modified after Macdonald [1965, p. 323]

* Total collapse volume is 2203 x 10^6 m^3, cf. Present caldera volume, 1390 x 10^6 m^3.

[a] Possible submarine eruption east of Kilauea.

[b] After Lipman et al. [1985].

Macdonald [1965, p. 321] summarized the record of subsidence events in Kilauea thus: "In 1825 the center of Kilauea caldera was a pit some 260 m deep, surrounded by a narrow 'black ledge' 30 m or so below the present floor level. This central depression is presumed to have formed by collapse at the time of the flank eruption in 1823. By 1832 the central pit had been filled to overflowing, but in that year it was reestablished in much its former condition by another collapse. Again it was refilled, only to be reformed by collapse accompanying the eruption of 1840. Still again it was refilled, only to sag down in a less extensive depression at the time of the 1868 eruption, and so on." Macdonald's summary of volumetric changes is reproduced in modified form in Table 1.

In the southwestern part of Kilauea caldera is the pit crater of Halemaumau. Today it is only 70 m deep, but in 1924 it was 390 m deep, and since it first came into existence about 1840 it has varied greatly in size; periods of infilling by lava have alternated with periods of subsidence, including both pistonlike depression of the floor and drain-back of fluid lava. Halemaumau is close to the center of ground deformation and fumarolic activity above Kilauea's magma chamber. For most of the period 1840 to 1924 it had continuous lava lake activity on its floor. It is the place where cumulative subsidence reached its maximum value, estimated since 1800 to have exceeded 1 km (based on the historical records compiled by Macdonald [1965] and Macdonald and Abbott [1970]). What proportion of that was drain-back of fluid lava rather than subsidence of rock is not known.

Figure 3 plots profiles across Kilauea caldera, based on this historic record, and a tentative subsidence profile made by integrating the recorded subsidence increments. In addition to these major subsidences, small subsidences involving a wide area extending well outside the caldera were also known to occur in 1924, 1955, and 1975 (Table 1). Such broader subsidence events, though individually small, have a considerable cumulative effect. If they recur at intervals of 20 to 30 years, they could total 1 km^3 per century.

A distinction is made on Kilauea between these occasional broad subsidences and the frequent rapid deflations, recorded by summit tilt measurements, that typically accompany magma excursions from the summit magma chamber. These frequent deflations are interpreted to result from the draining out of a quantity of magma that varies from less than 10 to a maximum of about 70 million m^3 [Dzurisin et al., 1984]. The broader subsidences involve a greater subsided volume, and that of 1975 resulted from an earthquake [Lipman et al., 1985] and was apparently not caused by any high-level magma movement event.

The general form of the subsidence profile at Kilauea is that of a stepped funnel; the funnel is deepest at Halemaumau and may be considered to extend outward at least as far as the faults of the Kaoiki and Koae fault zones (Figure 1) which downthrow toward the caldera.

Mauna Loa Caldera (Mokuaweoweo)

The caldera of Mauna Loa is a more or less elliptical depression measuring 4.5 x 2.7 km; it is 6.4 km long when the contiguous pit craters of North Pit and South Pit are included. The highest point on the west rim stands 176 m above the level of the flat floor. The volume of the caldera plus pit craters as it was immediately prior to the 1984 eruption is 0.97 km^3; Figure 4

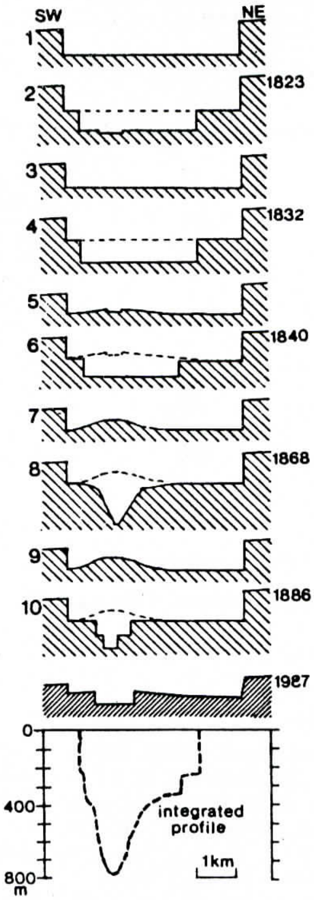

Fig. 3. Profiles across Kilauea caldera at specific times in the nineteenth century, based on the record compiled by Macdonald [1965] and Macdonald and Abbott [1970]. The present profile is also shown for comparison. The subsidences are integrated in the lowest profile. Vertical exaggeration x5.

shows the basis for this estimate. When the caldera was first surveyed in 1841 it had an inner pit 240 m below the summit, and when it was next surveyed in 1874 this inner pit had deepened to 300 m.

The inner pit became infilled by 1914, North Pit was infilled to the level of its northern rim in 1940, and South Pit was infilled to the level of its rim in 1949. The period since 1841 has thus seen a net infilling of the caldera. Lockwood and Lipman [1987] estimate that 1 km^3 of lava accumulated in the caldera since 1843, thus being about one-quarter of the total lava output of Mauna Loa within the 144-year time period. The subsidence events that produced the pit crater of Lua Poholo between 1874 and 1886, and East Bay since 1885, were by comparison negligible in volume.

Mokuaweoweo is a very young feature. Flows beheaded by it have been ^{14}C dated as young as 590 ± 70 years [Decker et al., 1983], which is therefore the maximum age for the last major collapse event. The mid-nineteenth century caldera volume of about 2 km^3 is 3 times greater than the lava volume erupted in the largest historic eruption of Mauna Loa (0.62 km^3 in 1872; Lockwood and Lipman [1987] and 16 times greater than the average volume (0.124 km^3) erupted.

Dike Injection Rate on Kilauea

Hawaiian calderas are the loci of numerous dike injection events. The frequency of dike injections is an important parameter on Hawaiian volcanoes and is used below to estimate the subsidence rate in Koolau caldera.

Information about the frequency of dike injections on Kilauea and Mauna Loa is available from the historic records as summarized in Figure 5. In this figure, each fissure eruption is assumed to mark the injection of a dike extending laterally from the presumed volcano center out to the lowest eruptive vent. For Kilauea (Figure 5a) a presumed dike injection event in 1924, when there was possibly a submarine eruption on the submerged portion of the east rift zone, is included.

On Kilauea the number of dikes is greatest at or near Halemaumau, totaling at least 28 in 200 years. Six subparallel eruptive fissures dating from 1954 to 1982 can be seen today on the caldera floor (Figure 2). This figure of 28 dikes in 200 years is a minimum, since it excludes the many noneruptive dike injection

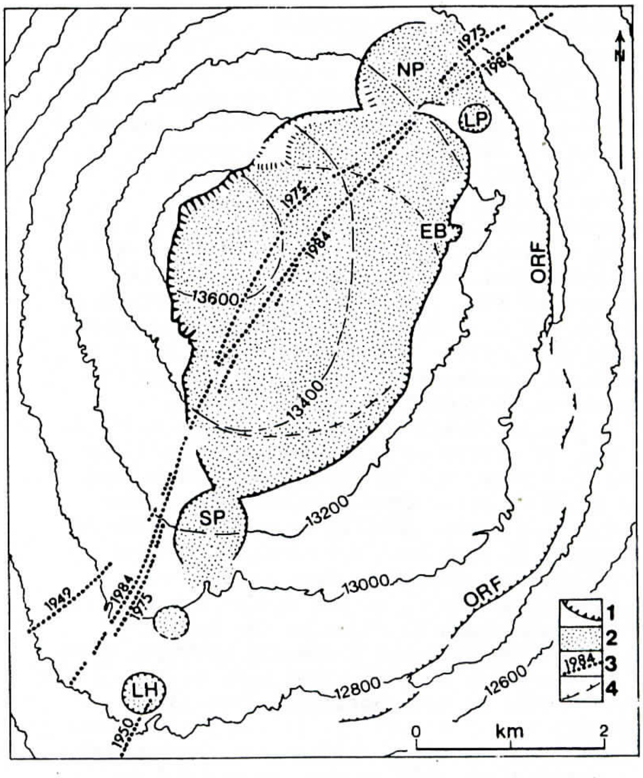

Fig. 4. Map of Mauna Loa caldera (Mokuaweoweo) showing contours (dashed lines) reconstructed across caldera from which caldera volume estimated. Heights in feet above sea level. Here, 1, fault scarps; 2, caldera floor lavas, 1942 and younger; 3, eruptive fissures, 1949 and younger; and 4, pre-1914 inner caldera. Pit craters are NP, North Pit; LP, Lua Poholo; EB, East Bay; SP, South Pit; and LH, Lua Hou. ORF is outer rift fracture. Based on maps by Macdonald [1971] and Lockwood et al. [1987].

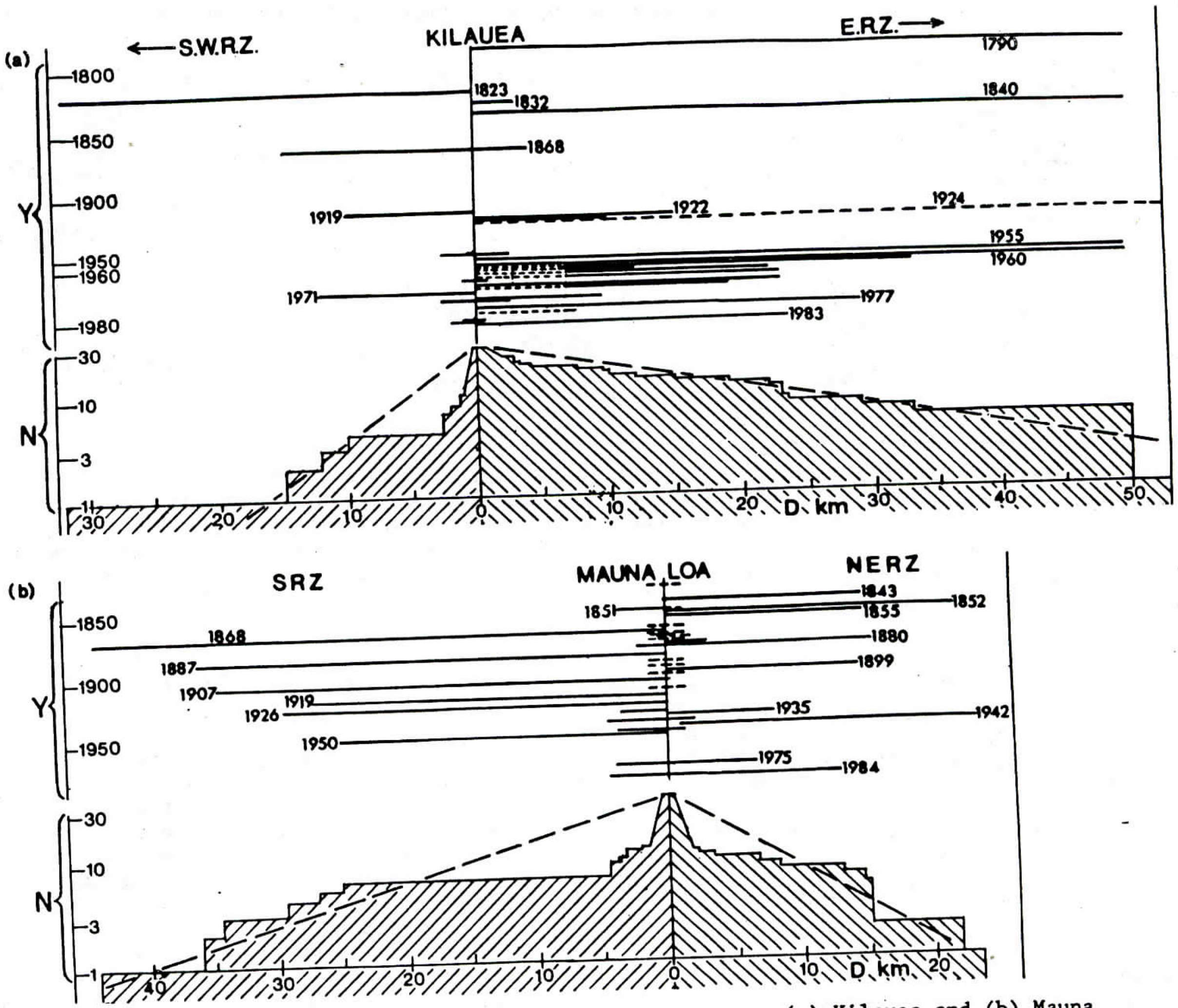

Fig. 5. Historical records of dike injection events on (a) Kilauea and (b) Mauna Loa. Each horizontal line in Y represents a fissure eruption for which the feeder dike is assumed to extend from the volcano center out to the lowest flank vent; distances D are measured from the volcano center. Note that for Kilauea the time scale is changed: 1960-1988. For each volcano the underlying plot N sums the dikes injected in the historic period.

events. It also excludes the many eruptive events that were confined to Halemaumau.

The period 1955 to the present has seen repeated dike injection events into Kilauea's east rift zone (ERZ). The active part of the middle ERZ from Pauahi Crater to Puu Kahaualea varies from 1 to 2 km wide (Figure 6). Many of the fissures in it are broken into en echelon segments where their trend is oblique to the curving axis of the zone. In the section between Napau Crater and Puu Kamoamoa, as many as six near-parallel fissures occur, separated by distance intervals of <0.1 to 1.0 km and time intervals of <6 months to 20 years, and are interpreted to mark the traces of six separate dikes.

There are however also places where two eruptions took place successively on what appears to be the same fissure line, where it is not known if the two successive magma excursions formed a single confluent intrusion, or whether a second dike followed the edge or still-hot middle of the first dike. The August 1968 and February 1969 eruptions are a good example. Some of the fissure system of the prolonged 1969-1971 Mauna Ulu eruption moreover was apparently utilized also in the 1972-1974 eruption. There is therefore uncertainty regarding the total number of dikes injected since 1955.

The upper ERZ is cut obliquely by the fissure direction, and the few eruptive fissures in this section tend to be short and strongly broken into en echelon segments. Eruptions in this section were few and small in volume. Some kind of subsurface conduit system must exist through this section, joining Kilauea caldera with the middle ERZ. It seems very unlikely that each magma excursion produced a separate dike; Swanson et al. [1976a] summarize the seismic evidence supporting the concept of a fluid core along the upper ERZ that transmits magma aseismically southeastward to the point where diking is initiated. Despite the high dike injection rate, there are remarkably few dikes exposed in the walls of Kilauea caldera [Casadevall and Dzurisin, 1987].

Measured dilations accompanying the 1955

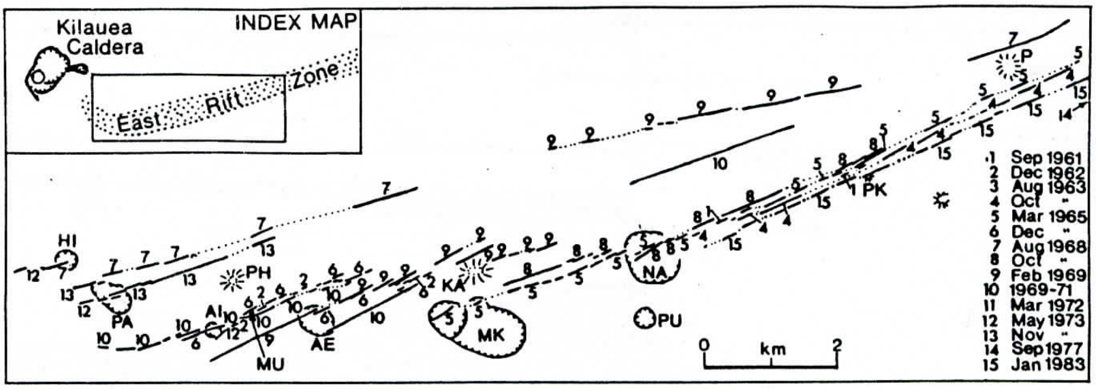

Fig. 6. Map of a portion of Kilauea middle east rift zone showing fissure vents for the period 1961 to 1983. Pit craters are (left to right) HI, Hiiaka; PA, Pauahi; AI Aloi; MU, Mauna Ulu summit crater; AE, Alae; MK, Makaopuhi, PU, Puaialua; and NA, Napau. Cones are PH, Puu Huluhulu; KA, Kane Nui o Hamo; PK, Puu Kamoamoa; and P, Puu Kahaualea. Based on maps by Swanson et al. [1979] and Wolfe et al. [1987].

lower ERZ, February and May 1969 middle ERZ, and September 1971 southwest rift zone eruptions of Kilauea were 140, 35, 110, and 50 cm, respectively [Swanson et al., 1976b]. These are the presumed widths of the dikes injected and are comparable with dike widths measured in the Koolau dike complex of Oahu [Walker, 1987a].

Dike Injection Rate on Mauna Loa

Figure 5b plots the known or inferred historic dike injection events on Mauna Loa. Each fissure eruption is assumed to mark the injection of a dike extending laterally from the presumed volcano center out to the lowest eruptive vent. The center, directly above the presumed position of the magma chamber, lies outside the caldera [Decker et al., 1983]; here distances were measured from a point in the southwestern part of the caldera. For some of the summit eruptions the lateral limits of the dike are uncertain and are plotted arbitrarily along the whole length of the caldera. The total number of identified dike injection events is 34 in the 155 years since 1832.

The dilation of Mokuaweoweo that accompanied the 1975 and 1984 eruptions, measured by trilateration surveys across the caldera, amounted to about 80 cm and 50 cm, respectively. These are the presumed widths of the dikes injected and are comparable with values measured in the Koolau complex.

Outward Decrease in Dike Injection Rate

The rate of outward decrease in number of dikes from the center conforms roughly to a logarithmic distribution for both Kilauea and Mauna Loa. It is steepest for the northeast rift zone of Mauna Loa, perhaps because this zone is effectively buttressed by Mauna Kea and Kilauea and has least freedom to dilate. It is least steep for the ERZ of Kilauea, reflecting the high mobility of the south flank of this part of Kilauea.

3. Subsidence Versus Lateral Collapse Structures

A problem that is common to many volcanoes and is acute on Kilauea is how to distinguish between structures resulting from downward subsidence (caldera subsidence, as into a partially vacated magma chamber) and those resulting from collapse involving lateral mass movement. Subsidence and lateral collapse have both been proposed, for example, for the Valle de Bove on Etna [Guest et al., 1984; McGuire, 1982]. Structural collapse may be surficial, of the landslide or debris flow type (Figure 7a), or it may involve movement on deep-reaching listric faults (Figure 7b). Subsidence and lateral collapse are driven by gravity: they involve the transfer of a large volume of rock to lower elevations.

Additionally, part of a volcano may move sideways over a deep decollement [Nakamura, 1980] (Figure 7c) without any rock volume being necessarily transferred to lower elevations. The force responsible for the movement is then not directly gravitational, although it may ultimately be gravitational, manifest indirectly as a hydrostatic pressure in magma. The movement cannot therefore strictly be described as "collapse": it is side-slip.

The faults of the Hilina fault system are interpreted to be gravity collapse structures on deep-reaching listric faults [Swanson et al., 1976b], but the dilation in Kilauea's ERZ may be accompanied by side-slip; the two kinds of movement are linked to the extent that movement on one is related temporally with movement on the other [Lipman et al., 1985].

The Koae and Kaoiki fault systems are disposed on either side of Kilauea caldera (Figure 1), and throw down toward the caldera. The Koae fault system is very active and gives rise to conspicuous surface features. Major vertical displacements took place, for example, in the seismic swarm of December 1962 [Fiske and Koyanagi, 1968]. It is in line with the middle ERZ, and dike injections undoubtedly take place into it from time to time; the events in

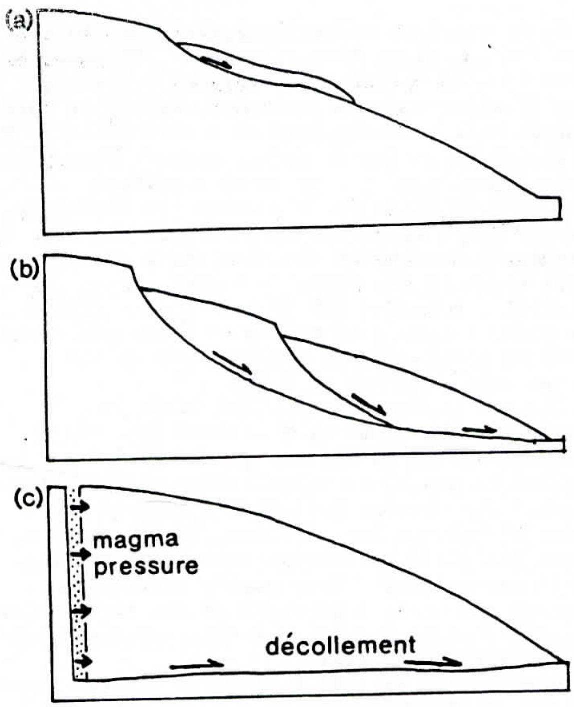

Fig. 7. Kinds of lateral mass movement postulated to occur in Hawaii: (a) landslide, (b) movement on deep-reaching listric fault, and (c) side-slip on deep decollement.

December 1962 could have resulted from the injection of a dike.

These fault systems seem capable of being interpreted in several ways. Duffield [1975] and Lipman et al. [1985] interpret them to be systems of inward facing listric faults resulting from crustal extension, with subsidence of the ground (including Kilauea caldera) between (Figure 8a). Alternatively the faults could be the outermost members of a system of caldera faults. Another interpretation is that the faults are the surface manifestation of non-vertical dikes.

Regarding this last interpretation, it should be explained that measurements of dike dip and displacement-vector plunge in dikes of the Koolau complex [Walker, 1987a] reveal that dike injection on average results in 30 cm of vertical movement for every meter of horizontal dilation. Where dikes have a systematic outward dip on either side of a rift zone, the middle of the zone will show a net subsidence relative to the sides (Figure 8b), and the amount of relative subsidence should increase toward the caldera as the dike number increases. The subsidence is gravitationally driven, and the nonverticality of the dikes can be explained as due to the nonhorizontal distribution of bulk-rock density zones in the margins of the rift zone.

4. The Koolau Caldera

Introduction

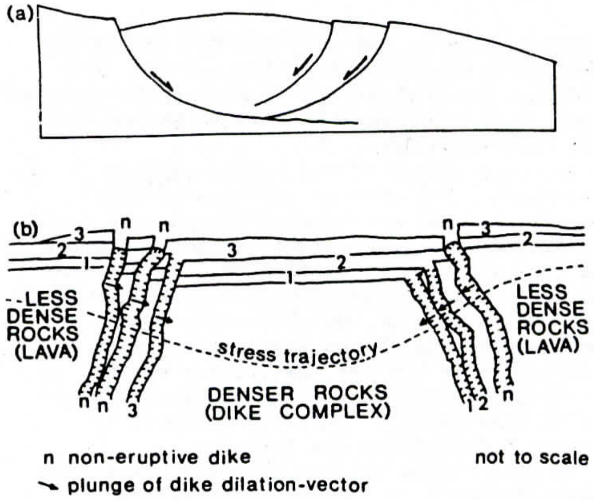

Fig. 8. Two interpretations of inward throwing fault systems symmetrically disposed on either side of Kilauea caldera. (a) Subsidence between facing listric faults. (b) Subsidence of the land between outward dipping dikes. The dike-dilation vectors are parallel with the stress trajectory. The trajectory is nonhorizontal because of the nonhorizontal distribution of bulk-rock density in a rift zone setting.

Consider now the eroded caldera of the Koolau Volcano on Oahu. The caldera is here defined as a wide area, centered on Kailua, in which the lava flows have a centripetal dip (Figure 9). The dip tends to increase toward the center of this area, suggesting that the structure is funnellike. Evidence that the centripetal dip was caused by tilting and is not an original depositional dip is given by the fact that the caldera lavas consist mostly of massive flows much thicker than those of the volcano flanks. Depositional slopes range from 4° to 13° on the flanks, and the average lava flow unit there is 0.7 m thick. In contrast, many of the caldera lavas exceed 10 m thick. The implication is that these massive flows were erupted onto nearly horizontal ground such as occurs in or

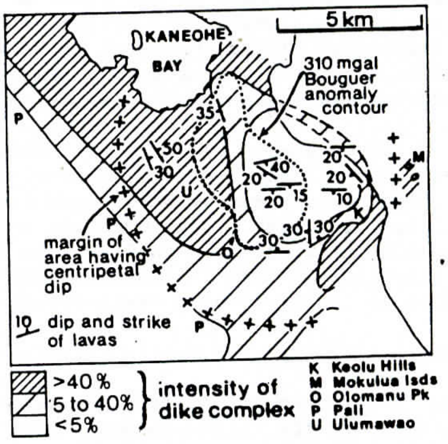

Fig. 9. Map of the caldera of Koolau Volcano, Oahu, showing centripetal dip. Dike intensity contours after Walker [1987a]. Bouguer anomaly peak contour after Strange et al. [1965].

around a caldera, and some may have ponded in topographic depressions. Additionally, pipe amygdales occur at several places in the caldera lavas, indicating depositional slopes of 4° or less [Walker, 1987b].

The full extent of the Koolau caldera is not well known. The area of centripetal dips embraces most of the Ulumawao Ridge, the Keolu Hills, and Olomanu Peak and extends southwest to the foot of the Pali cliff line. On the east the caldera margin apparently occurs inshore of the Mokulua Islands, which contain thin northeast dipping flank lavas. The major uncertainty is how far the caldera extends to the northwest and whether it embraces part or all of Kaneohe Bay. Suitable outcrops to resolve this problem are lacking.

In much of the caldera area the rocks have been affected by a pervasive propylitic alteration. Additionally the large positive Bouguer gravity anomaly of the Koolau Volcano reaches its maximum in the caldera area [Strange et al., 1965], where seismic refraction profiling by Adams and Furumoto [1965] revealed the existence of high-velocity rocks ($V_p = 7.7$ $km\ s^{-1}$), assumed to be mafic/ultramafic intrusives, at a shallow (2 km) depth. The Bouguer anomaly given by the Koolau Volcano is very similar to those given by Kilauea and Mauna Loa [Kinoshita et al., 1963].

The Koolau Volcano contains a remarkable complex of intrusive dikes, and the dikes have an interesting distribution in the caldera. In an outer zone of the caldera the dike intensity is over 50%, and in an inner zone it drops to as low as 1%. The number of dikes per kilometer across-strike drops from 500 to 1200 in the outer zone to as low as 10 in the inner zone. This inward diminution in dike intensity is thought to be highly significant.

It is possible that this diminution is an original feature caused by a reluctance of dikes to be injected into the inner zone of the caldera. This is, however, unlikely because eruptions from fissures, and hence the formation of dikes, on Kilauea and Mauna Loa is most frequent near the centers of calderas. Much more likely, the diminution is a consequence of the subsidence of most of the dikes to below the present erosion level. Supporting evidence for subsidence is the close spatial correlation of low dike intensity values to the central part of the downwarped region delineated by centripetal lava dips.

In several places the dike intensity in Koolau caldera decreases very abruptly, and probably these intensity steps mark the locations of faults. Exposures are too scanty to enable these supposed faults to be mapped, but they suggest that the form of the subsidence profile is likely to be a stepped funnel.

Subsidence Rate in the Koolau Caldera

It is possible to estimate the amount of subsidence in the Koolau caldera from the centripetal lava dip. Assuming that the lavas were originally horizontal, extrapolation of the dip angles yields a subsidence of about 1 km at the center of the caldera. This is likely to be a minimum value, since it does not include any fault-bounded subsidences.

It is possible to estimate the subsidence rate from the dike intensity data. Consider a prism of rock that is subsiding at a uniform rate (S kilometers per century), having an upper surface that is maintained at a uniform level by continual additions of lava. Suppose that dikes are injected into the prism at a uniform frequency (D dikes per kilometer per century), and all dikes reach the surface. If the measured intensity of the dike swarm at any given depth in the prism is N dikes per kilometer, then $S = D/N$ (Figure 10a). Figure 10b plots a family of curves of S against D and N for an erosion depth (appropriate to the Koolau dike complex) of 1 km.

For the Koolau caldera, the value of N is known, and the value of D derived from the historic record of Kilauea and Mauna Loa may be applied to Koolau to calculate plausible values for S. The 28 dike injection events in 200 years at Kilauea and 34 events in 155 years at Mauna Loa yield an average dike injection rate of 18 per century. This number distributed through the whole 9 km width of the Koolau dike complex yields an average D value of two dikes per kilometer per century.

Application of this D value to Koolau caldera yields subsidence rates of 0.02 km per century in an area 4 km across, and 0.2 per century or more in a small area in the middle of the caldera. Figure 11a plots the variation in N in and around Koolau caldera, and Figure 11b gives the corresponding values of S. Integration of the subsidence contours in Figure 11b gives a volumetric subsidence rate of 1.3 km^3 per century.

5. The Origin of Basaltic Calderas

A common view is that basaltic calderas are similar in origin to the calderas of silicic volcanoes in that caldera subsidence takes place into a magma chamber vacated by an equal volume of magma. One of the first rigorous attempts to measure the volume of subsidence and of erupted magmas was that by Williams [1942] at Crater Lake. He found a volume discrepancy, but subsequent work [Bacon, 1983] has shown that this discrepancy does not exist.

A volume correspondence has not been demonstrated for calderas of basaltic volcanoes. In the Askja eruption of 1874-1875 (Iceland), the erupted volume of basaltic plus silicic magmas was one-fifth of the subsidence volume [Sigurdsson and Sparks, 1978], and at the major subsidence in 1968 of Fernandino caldera (Galapagos), the magma volume known to have been erupted was only about 10% of the subsidence volume [Simkin and Howard, 1970]. A possible explanation is that the remaining volume is contained in dikes.

Several subsidence events in Kilauea caldera have been linked with eruptions. Those of 1823, 1840, 1868, and 1924 are good examples (the first is speculative), and Table 1 summarizes the estimated volumes involved. The 1924 subsidence in Halemaumau was linked with a probable major magma excursion into the ERZ and a possible submarine eruption; the subsided volume was relatively small. Major subsidences that took place in Mokuaweoweo in the mid-nineteenth century have not been closely correlated with eruptions.

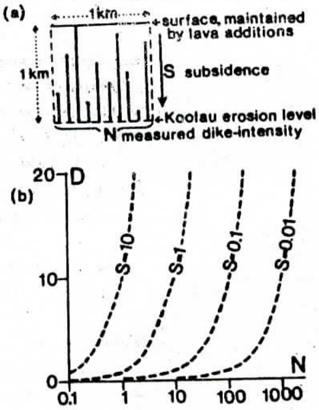

Fig. 10. (a) Diagram illustrating the basis for the relation $S = D/N$, the measured dike intensity (N) at any given depth (1 km at Koolau) being dependent on the dike injection rate (D) and subsidence rate (S). It is assumed that all dikes reach the surface, and the surface level is maintained by additions of lava. (b) Curves of equal S value (subsidence rate: km/century) plotted against N (dike intensity: number/km at depth of 1 km) and D (dike injection rate: number/km/century) for depth of 1 km.

Many eruptions of Kilauea and Mauna Loa were unaccompanied by caldera subsidence, notably those of Kilauea since 1955 (total erupted volume of 1.5 km^3, plus an unknown volume of dikes) and the 24 eruptions of Mauna Loa since 1872 (total erupted volume of 2.8 km^3, plus an unknown volume of dikes).

The historic record of Kilauea and Mauna Loa shows that, while significant subsidences can accompany eruptions, most eruptions are not so accompanied and the volume correspondence is poor. The caldera volumes are larger than magma volumes discharged in any known eruptions of Hawaiian volcanoes.

6. Causes of the Subsidence

It is inferred that the subsidence profiles at Kilauea and Koolau have the form of stepped funnels, and in the central region of the funnels, subsidence may amount to several hundred meters per century. The historical record of Kilauea and Mauna Loa shows that on both volcanoes the caldera volume has changed by a factor of 2 and has increased or decreased by 1 km^3, in about a century. The intensity diminution of the dike complex into the Koolau caldera implies that the volumetric subsidence rate was about 1.3 km^3 per century, assuming a dike injection rate equal to the historic rate on Kilauea and Mauna Loa.

These subsidence and infilling rates are very high and have an important bearing on the mechanisms of subsidence.

Outermost Parts of the Funnel

Subsidence in the outermost parts of the funnel, amounting to several meters per century, may occur in events such as those of 1924, 1955, and 1975. It could be caused by a general crustal extension on listric faults (Figure 8a), the space at Kilauea being made available by southward movement of the mobile flank of the volcano. The very extensive subsidence of the summit area of Kilauea that accompanied the M 7.2 1975 Kapalana earthquake [Lipman et al., 1985] is consistent with this mechanism. Alternatively, it could be caused by the nonverticality of intruded dikes (Figure 8b). At an injection rate of 18 dikes per century, and assuming (based on the Koolau dike complex) that the average dike is 73 cm wide and has a vertical displacement of 30% of the horizontal width, the total vertical displacement would be 4 m per century due to this cause.

Main Parts of the Funnel

The subsidence in the main parts of the funnel is too concentrated to be caused by crustal extension, and too great to be caused by the injection of nonvertical dikes, and in the Koolau caldera it is accompanied by an inward tilting of the lava flows. Some kind of caldera subsidence appears therefore to be indicated. The very high subsidence rate poses the problem, however, of accommodating about 1 km^3 per century of subsiding basalt.

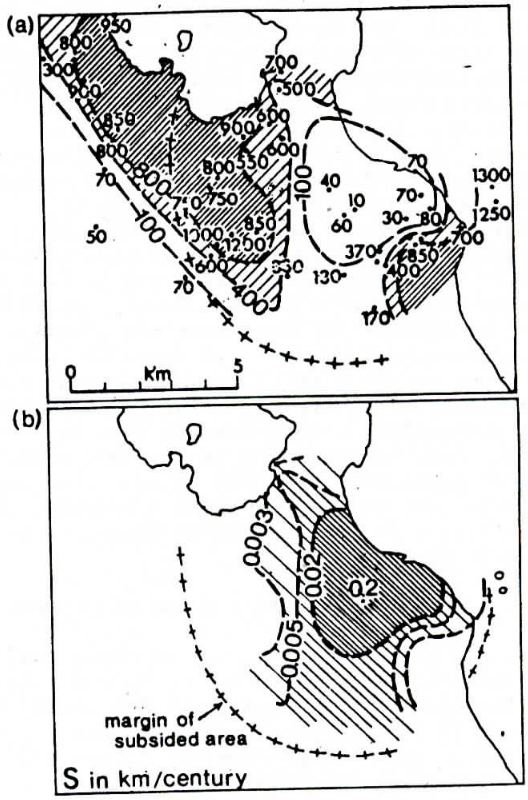

Fig. 11. (a) Map of the caldera of Koolau Volcano, Oahu, showing dike intensity as the number of dikes per kilometer across-strike, based on measured outcrops averaging 135 m long [Walker, 1987a], normalized to the number per kilometer. In marginal parts of the caldera the intensity exceeds 800; in the center it drops to 10. (b) Inferred subsidence rate, based on the dike intensity values and assuming the same dike injection rate as on Kilauea and Mauna Loa.

The sizes of Hawaiian magma chambers are not known. The minimum size is set by the amount of magma that leaves the chamber in rapid deflation events, and for Kilauea it is about 70 million m^3. It would seem impossible to accommodate 1 km^3 of rock per century in a magma chamber of this small size. If the magma chamber is much larger, a good temporal and volumetric coincidence of caldera subsidence with erupted or dike injected magma might be expected. The coincidence appears in fact to be poor.

An appealing alternative is that the subsided basalt is consumed instead of accommodated. Stearns [1966] favored remelting of the basalt. Another possibility is that the basalt is consumed by subsidence into the thermally weakened lithosphere of the Hawaiian hot spot (to a level much deeper than the magma chamber).

It is envisaged that the magma chamber is localized at the level of neutral buoyancy [Ryan, 1987; Walker, 1986] between lava flows that are less dense than basaltic magma, and lava flows loaded with intrusions (or intrusions alone) that are more dense than basaltic magma. This is the level at which magma is gravitationally stable. As the roof rocks become denser (because of dike injections into the basalts) and as cumulates form on the chamber floor, the magma chamber rises. Under steady state conditions, the ascent rate of the magma chamber balances the subsidence rate of the caldera rocks, so that the depth to the magma chamber remains constant. Dikes plus cumulates account for the high positive Bouguer anomaly that reaches a maximum near the centers of Kilauea and Koolau calderas (Figure 12).

Ryan et al. [1980] and Klein et al. [1987] identified a deep-reaching seismic pipe beneath Kilauea. This pipe is 3 km wide and is centered below Halemaumau at depths shallower than 20 km, and it broadens to 10 km or more and plunges steeply southwest in the depth range 20 to 40 km. Klein et al. [1987] regard the earthquakes as occurring in a zone of deformation of brittle rock, surrounding a magma conduit that is probably much narrower than the seismic area. It is proposed here that this seismic zone could well represent the zone in which subsidence of intrusion-loaded lavas is now envisaged to be concentrated.

7. Origin of Kilauea's Chain of Craters

The pit craters on Hawaiian volcanoes are subsidence structures similar in form to, but much smaller than, calderas, and they should be included in any discussion of subsidence structures, even though they may not contribute to understanding the calderas.

Kilauea Volcano is unique for its large number of pit craters, particularly the Chain of Craters along the upper and middle east rift zone. One of the widest of these craters is Makaopuhi, measuring 1.5 by 1.0 km, and narrowest is Devil's Throat less than 100 m across. Deepest is Makaopuhi, the western part of which was 300 m deep until it was partly infilled by Mauna Ulu lava in 1969-1974.

In many of the magma excursions into the ERZ since 1955, magma traveled aseismically through the upper section, suggesting the existence there of a wide and well-established horizontal conduit that conveys magma from the storage chamber beneath Kilauea into the ERZ in which magma may be stored between excursions. This conduit carried magma on many occasions from 1955 until mid-1986, and continuously for a long period in the Mauna Ulu eruption and also for the long and continuing period since July 1986.

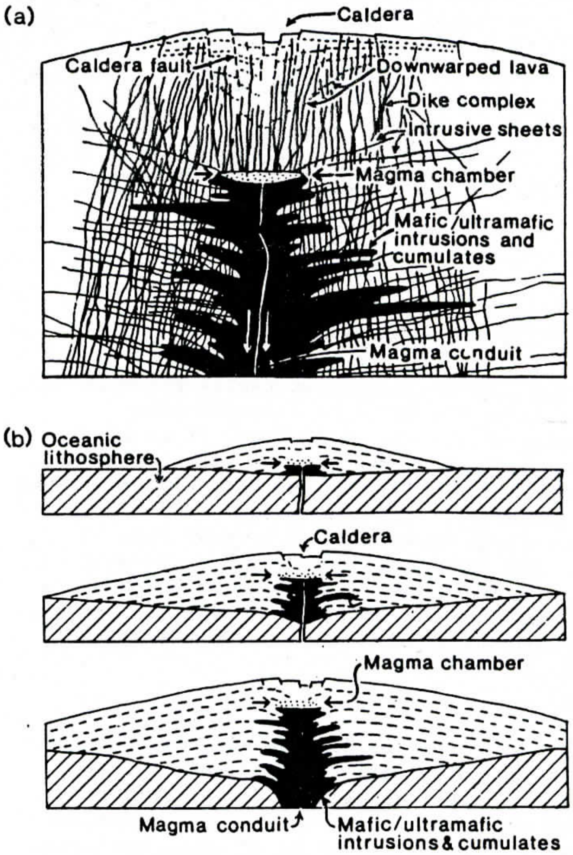

Fig. 12. (a) Schematic view of the internal structure of the caldera area of a major Hawaiian volcano. Caldera subsidence due to the load of intrusions and cumulates. (b) Schematic view showing stages in the evolution of a major Hawaiian volcano. Under steady state conditions the magma chamber (located between the two arrows) remains at a constant depth.

The precise nature of this magma conduit is not known; it could be a wide dike or a widened portion of a dike. No structure that could be positively identified as a long-lived magma conduit has been found in the Koolau dike complex, perhaps because the Koolau Volcano is not sufficiently deeply eroded to reveal one.

A mechanism that appears capable of accounting for the pit craters is illustrated by Figure 13, in which the conduit is shown underlying the Chain of Craters. Collapse of the conduit roof locally occurs; some of the debris is carried away by magma flowing through the conduit, and an underground vault develops. With time the vault enlarges upward by repeated roof collapses and approaches the ground surface. At lower levels this vault is likely to be filled with magma. The vault finally breaks through the surface, and a pit crater is

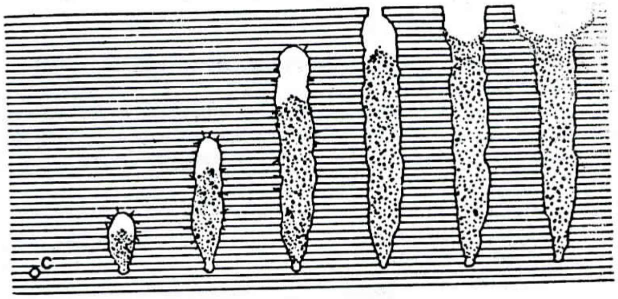

Fig. 13. Schematic section through the upper part of Hawaiian volcanic edifice showing stages in the development of a pit crater. An intriguing possibility is that certain breccias recognized in deeply eroded parts of extinct Hawaiian volcanoes such as Koolau [Walker, 1987a] may represent the subsurface breccia pipes below ancient pit craters. C, subsurface conduit.

formed which subsequently widens by wall collapse.

Hawaiian pit craters are ephemeral structures. They appear on the surface and widen by wall collapse. Devil's Throat pit crater in the Chain of Craters formed in about 1921 and is still <100 m wide. Widening also occurs where contiguous pit craters join to form figure-eight-shaped structures such as Pauahi. Pit craters are destined, however, to be infilled with lava. Two, Aloi and Alae, were completely infilled by Mauna Ulu in the 1969-1974 eruptions and no longer exist.

The total volume 30 years ago of the Chain of Craters, including Kilauea Iki and Hiiaika subsidence bowls, was 0.45 km^3. Most of the craters are less than 500 years old [Holcomb, 1987], indicating a total subsidence rate of at least 0.09 km^3 per century. This is an order of magnitude less than the caldera subsidence rate. In the past 30 years the total volume of pit craters decreased to 0.36 km^3 due to infilling by lava flows.

8. Summary and Conclusions

The active calderas of Kilauea and Mauna Loa are highly dynamic structures that are known to be capable of changing in size by a factor of 2, subsiding locally by hundreds of meters, and gaining or losing up to 1 km^3 in a century. There is no reason to suppose that they were any more or less dynamic in the 150- to 200-year historic period than they were previously; the past century has, however, been one of net infilling.

Certain features of the long-extinct and deeply-eroded Koolau caldera, notably the remarkable and extreme inward diminution in dike intensity, suggest that when it was active, it may have been equally dynamic.

The study of Koolau well complements that of the active calderas, and the striking differences between them can be reconciled in terms of differences in erosion level. Downfaulting and sagging both contribute to the subsidence, but evidence for the former is more clear at the active calderas, and evidence for the latter is more clear at the extinct one.

The stepped-funnel form of the subsidence profile, the extreme rapidity of subsidence, and the very poor correspondence of subsidence volumes with eruptive volumes, do not favor the view that Hawaiian calderas originate simply by subsidence of a rock cylinder into a partially vacated magma chamber. Instead they lead to the idea that the subsided rocks are consumed.

A feature of Koolau Volcano is the extraordinarily high intensity of its dike complex, and a number of circumstances suggest that caldera subsidence is causally related to crustal loading by intrusions.

An appealing mechanism is that, when the caldera-filled lavas are sufficiently loaded with dikes and cumulates, they subside into the thermally weakened lithosphere above the Hawaiian hot spot.

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