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A paleomagnetic study of the Pohue Bay flow and its associated coastal cones, Mauna Loa volcano, Hawaii: constraints on their origin and temporal relationships

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Abstract

Detailed paleomagnetic and rock-magnetic studies of the Pohue Bay flow and associated cones on its coastal flat were made to determine if the origin of the cones was due to primary (volcanic) or secondary (littoral) processes. We used paleomagnetism to determine the temporal relationships between the flow and cones. If the flows and cones are from the same eruption, the littoral origin of the cones is strongly favored. A total of 530 specimens from 232 core samples were collected and studied from the Pohue Bay flow and from lava ponded within the cones. Remanent magnetizations are very stable to stepwise alternating field demagnetization and show small angular dispersion and well-defined characteristic magnetizations. Magnetic carriers correspond to members of the titanomagnetite series with single or pseudo-single domain states. The overall mean directions for the Pohue Bay flow (Dec = 10.8°, Inc = 23.6°, $k = 287.4$ and $\alpha_{95} = 2.3°$) and the lavas ponded within the cones (Dec = 12.8°, Inc = 25.2°, $k = 353$ and $\alpha_{95} = 4.9°$) are statistically indistinguishable and have been drawn from a common Fisherian distribution, supporting a close age relationship. Additionally, the angular dispersion for the combination of the main flow and lavas ponded in cones is small, with a paleosecular variation (PSV) estimate of $S_f = 4.2°$. This small PSV value supports the temporal association between the Pohue Bay flow and associated cones. They can thus be assigned to the same eruption timeframe. Because the source vent of the Pohue Bay flow is far upslope, the cones must therefore be littoral in origin, formed when the Pohue Bay flow entered the ocean. From the secular variation curve and comparison with age-dated flows with similar paleomagnetic directions, we estimate that the Pohue Bay flow was erupted approximately 1300 years ago. We were also able to distinguish both a possibly younger lava flow that later utilized the main tube of the Pohue Bay flow and an earlier sub-set of cones that were possibly formed before the Pohue Bay eruption.

1. Introduction and geological setting

The Pohue Bay flow is located on the southwest flank of Mauna Loa volcano. In this region the volcano slope varies from 5° to a near-horizontal (approximately 1°) coastal terrace up to 3 km wide. The Pohue Bay flow can be followed from the coastline up to an elevation of 920 m, and its vent area (higher still) is on the southwest rift zone (Fig. 1). The Pohue Bay flow was considered to be 740–

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910 years old by Lipman and Swenson (1984). A group of cones within the Pohue Bay flow (Jurado-Chichay et al., 1996) is distributed along about 3 km of coastline (Fig. 2) and consists of at least six cones in various states of erosion and burial. These cones have the same general structure: (1) an outer rim of lapilli- to bomb-sized scoria and spatter that either still is, or once was, a complete cone; (2) one or more inner rims of dense spatter and associated

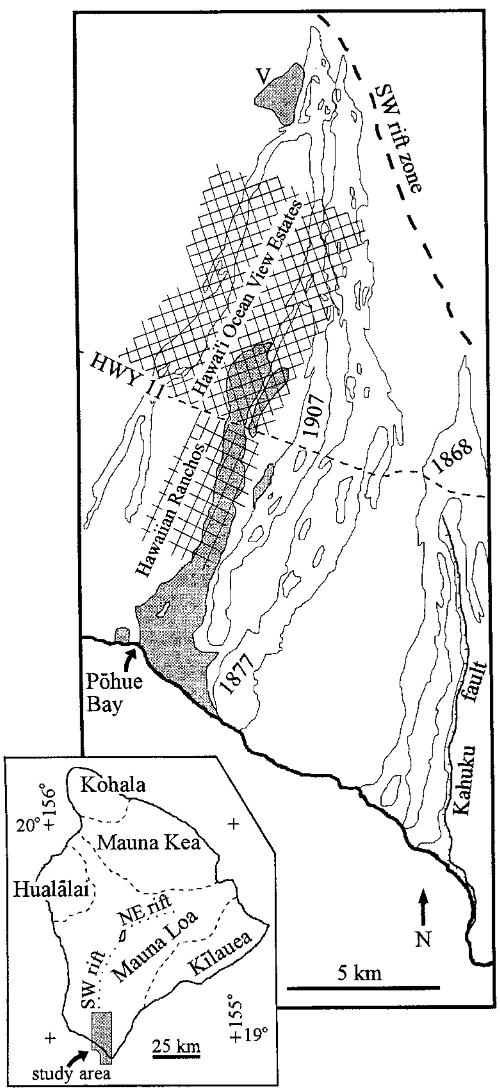

Fig. 1. Location map of the Pohue Bay flow (stippled). Historical flows are also indicated (taken from Lipman and Swenson (1984). Published with permission from the US Geological Survey.).

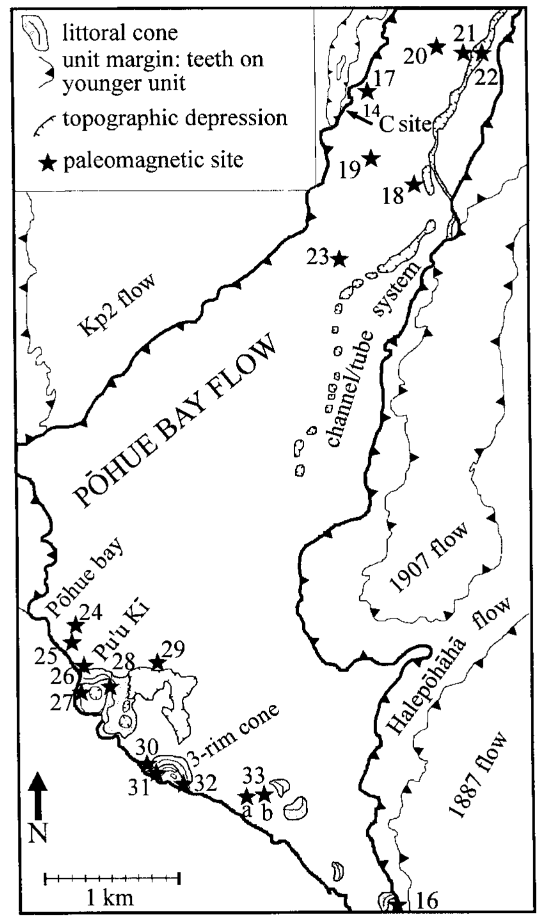

Fig. 2. Location map of paleomagnetic sites on the Pohue Bay flow and within the cones.

ponded lava. These cones have some of the characteristics of primary vent structures, but if they are primary then they are in a distinctly unusual position for Mauna Loa vents. If they are littoral, they differ from the usual configuration of Hawaiian littoral cones (two half-cones). The purpose of this study was to determine if these cones have a primary or secondary (littoral) origin.

Littoral cones develop around secondary or rootless vents as a result of steam explosions that take place when lava flows into the ocean (e.g. Moore and Ault, 1965; Macdonald, 1972; Fisher and Schmincke, 1984). They are similar to secondary vents formed where lava flows into lakes, streams, or marshes (e.g. the 'pseudocraters' of Iceland; Thorarinsson, 1953; Morrissey and Thordarson, 1991; Thordarson and Self, 1993). On the island of Hawaii there are about 50 littoral cones along the coastlines of Mauna Loa and Kilauea volcanoes (Moore and Ault, 1965). Three of the largest formed during the 1840 eruption of Kilauea and the 1868 and 1919 eruptions of Mauna Loa, all of which were associated with channelized high-discharge-rate flows. Additionally, small littoral deposits were formed during the tube-fed pahoehoe eruptions of Mauna Ulu and the continuing Puu Oo–Kupaianaha (Kilauea) eruptions in 1969–1974 and 1986–1991, respectively (e.g. Moore et al., 1973; Peterson, 1976; Heliker and Wright, 1991; Sansone and Resing, 1991a,b; Thordarson and Self, 1991; Mattox, 1993). The littoral cones formed during these recent eruption events were rarely more than 2 m high and developed on the lava bench just inland of the ocean entries.

When a flow enters the ocean, liquid lava rapidly converts water into steam, which may expand non-explosively (passively) or explosively depending on the rate at which heat is transferred from lava to water. Explosive vaporization of water fragments the lava, leading to accumulation of volcaniclastic debris. Water can also come into contact with flowing lava within the lava-tube system of pahoehoe flows and produce explosions landward of the actual ocean entry (Mattox, 1993). In many cases littoral explosions are small and no significant pyroclastic cones develop. Occasionally, however, substantial cones are constructed. The most often cited form of a Hawaiian littoral cone consists of two half-cones approximately equal in size on either side of the lava flow that led to their formation (e.g. Fisher, 1968; Fisher and Schmincke, 1984; Fig. 3). Additionally, they are usually considered to be associated with aa lava flows (Macdonald, 1972; Macdonald et al., 1983). On a flow with a moving surface (i.e. not tube-fed), even though clastic material is thrown out in all directions from the point of the explosions, any fragments that land on the flow itself are carried into the ocean, hence the two half-cone morphology is created.

This paper deals with a group of cones situated along the coastal part of the Pohue Bay flow. Previously identified as littoral by Moore and Ault (1965), they consist of more or less complete pyroclastic cones instead of pairs of half-cones and thus more

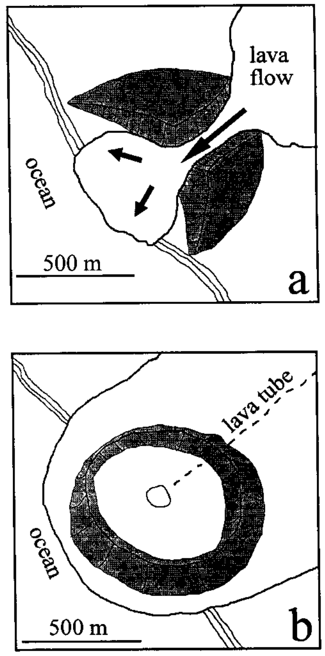

Fig. 3. (a) Typical littoral cone (Fisher and Schmincke, 1984. Published with permission from Springer-Verlag.). (Notice that two piles of pyroclasts are formed at either side of the flow. This is because any pyroclast that lands on the flow itself gets carried away.) (b) The general (present or former) form of the cones within the coastal part of the Pohue Bay flow. (Note that they form complete circular rims.)

resemble primary vents. If these cones are littoral, their association with tube-fed pahoehoe rather than aa also remains to be explained.

The pyroclastics that form as a result of littoral explosions can be difficult to distinguish from those formed as primary vents, and several lines of study have been proposed to differentiate them (e.g. Walker, 1992; Jurado-Chichay et al., 1996). This paper presents a detailed paleomagnetic study of the Pohue Bay flow and lavas ponded within the shoreline cones as one part of an attempt to make this differentiation. We started with the premise that if the cones are littoral and formed as a result of the Pohue Bay flow entering the ocean, then they have the same age as the Pohue Bay flow and should therefore share similar remanent magnetization characteristics. On the other hand, if the cones formed as primary vents and were later surrounded by Pohue Bay lavas, then they may have different remanent magnetization characteristics if enough time separated the events. Holcomb et al. (1986) observed a variable paleosecular variation (PSV) rate for Hawaii of around 4.5° per 100 years for the past 3000 years. This gives a practical limit for the time resolution possible and it also means that high precision (low angular dispersion) both within and between site mean results is required for this study.

2. Sampling

An average of 12 samples were drilled at each of 20 sites in the Pohue Bay flow, in both upslope areas and on the coastal plain (Fig. 2). The coastal cones themselves consist of loose pyroclasts and are thus unsuitable for paleomagnetic sampling. However, as mentioned above, there are lava flows ponded within these cones that we have used as surrogates. Care was needed to minimize the angular dispersion of magnetization directions that arises during the sampling and measurement procedures. Therefore, sampling sites were selected so as to avoid problems owing to local flow deformation (e.g. inflation under a cooled crust), and subsites (several meters apart) were sampled to detect any local effect in the magnetization directions (e.g. Holcomb et al., 1986). Cylindrical cores of 2.5 cm diameter and 10–20 cm length were collected with a gasoline-powered portable drill and oriented in situ with magnetic and solar compasses. A total of 530 specimens of 2.5 cm length were later sliced from these oriented cores. Duplicate samples at Site 15 were taken to be measured at different laboratories for comparison purposes. One set was measured at the Paleomagnetics Laboratory of the US Geological Survey (USGS) in Menlo Park, California, and the other set (as well as samples for all the remaining sites of this study) at the Paleomagnetics Laboratory of the National University of Mexico. The results from the two laboratories showed excellent agreement.

3. Methods and results

The direction and intensity of natural remanent magnetization (NRM) of all specimens were measured with a spinner fluxgate magnetometer. NRM intensities ranged from 311×10^{-3} to $2666 \times 10^{-3}\,\mathrm{A\,m^{-1}}$. Low-field magnetic susceptibility was

Table 1
Paleomagnetic results; mean directions of all sites

Site	Description	Dec. (deg)	Inc. (deg)	k	α_{95} (deg)	R	n
15	Spongy pahoehoe, channel overflow	11.1	23.9	464.4	2.1	10.9785	11
16	Pahoehoe, ponded within SE-most cone	355.1	17.1	123.2	5.0	7.9432	8
17	Aa from channeloverflow	11.4	16.6	249.5	2.8	11.9559	12
18	Pahoehoe channel overflow	15.4	20.4	116.4	4.2	10.9141	11
19	Aa flow margin	12.0	25.3	169.4	3.2	12.9292	13
20	Aa	10.9	29.8	206.4	3.0	11.9400	12
21	Pahoehoe channel overflow	8.4	27.0	295.5	2.7	10.9662	11
22	Toothpaste–aa infilling channel	5.6	14.2	211.7	3.0	11.9480	12
23	Late pahoehoe squeeze-out	11.4	18.7	115.0	4.1	11.9043	12
24	Pahoehoe surrounding cones	9.2	22.3	908.2	1.4	11.9879	12
25	Pahoehoe squeeze-out from 24	10.5	31.3	363.9	2.4	10.9725	11
26	Pahoehoe at sea cliff (same as 24 and 25)	8.5	26.1	237.0	2.9	9.9670	10
27	Pahoehoe ponded in cone	15.7	25.5	679.7	1.8	10.9853	11
28	Pahoehoe ponded in cone	10.4	20.7	278.6	2.7	10.9641	11
29	Pahoehoe surrounding cone	12.0	19.3	361.2	2.3	11.9695	12
30	Pahoehoe surrounding cone	10.8	26.2	183.6	3.2	11.9401	12
31	Pahoehoe ponded in cone	12.4	30.0	56.4	6.1	10.8227	11
32	Pahoehoe ponded in cone	12.8	24.4	271.2	3.1	8.9705	9
33A	Toothpaste lava outside cone	10.3	18.3	279.7	2.4	13.9535	14
33B	Pahoehoe outside cone	8.7	25.6	2813.1	1.7	3.9989	4
All sites		10.1	23.2	170.1	2.5	19.8883	20

measured with a Bartington MS-2 (Oxford, UK) system equipped with the laboratory dual frequency sensor. Measurements were made at low frequencies and showed large between-site variation, with mean values from 171×10^{-4} to 3915×10^{-4} SI units. Site-mean NRM declinations ranged from 358.7° to 15.6° and inclinations from 34.2° to 17.1°. Site mean angular dispersions as indicated by α_{95} and k parameters (Fisher, 1953) varied from 1.4 to 10.1 and from 61 to 890, respectively. Site 16 presents the highest dispersion and Site 24 the lowest (Table 1).

The stability and vectorial composition of NRM were investigated in detail for at least one specimen from each sample by stepwise alternating field (a.f.) demagnetization, using a Schonstedt a.f. demagnetizer (Reston, VA). The characteristic remanence (ChRM) direction was estimated for each sample from linear segments going through the origin in the corresponding vector plots (Zijderveld, 1967), or if necessary (only for Site 16) from principal component analysis (Kirschvink, 1980). Examples of vector plots are shown in Fig. 4. In general, a well-defined component was isolated after removing a small secondary low-coercivity component. Some 10–20% of the initial magnetization intensity still remained after demagnetization in 80–100 mT. As a detailed definition of magnetization directions was required, all remaining specimens were a.f. demagnetized using the optimum field range (at least three steps, to construct a vector plot for each specimen) defined from pilot samples. For some sites all specimens from the core samples were subjected to detailed a.f.

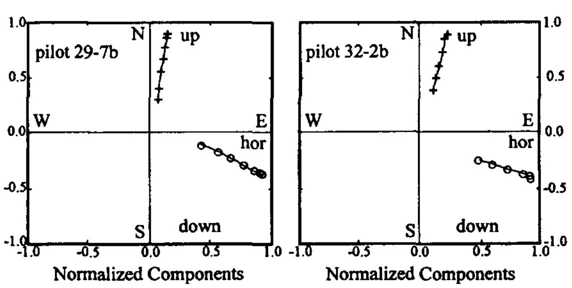

Fig. 4. Vector diagrams of demagnetization by alternating fields (a.f.). (Note that the flow example (Sample 29) and cone example (Sample 32) show one stable component of magnetization after the first or second a.f. step; this indicates a small secondary viscous component.) +, Data in the horizontal plane; ○, data in the vertical plane.

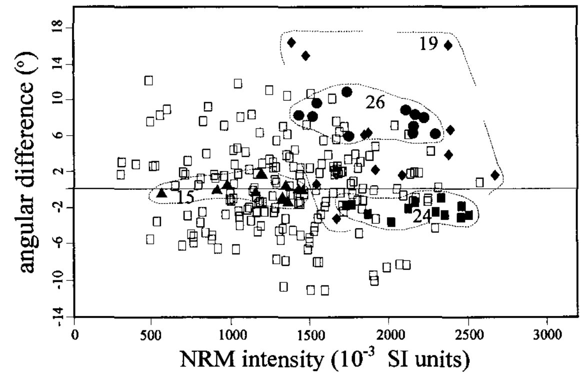

Fig. 5. Angular differences between solar and magnetic azimuths. (Notice that differences are up to 17°, and that there is no direct relationship between the angular difference and the intensity.) Four sites are differentiated to illustrate how the angular differences vary by sites (▲, Site 16; ◆, Site 19; ■, Site 24; ●, Site 26).

demagnetization. Mean directions and corresponding Fisher statistics (Fisher, 1953; Irving, 1964) for the characteristic magnetizations were calculated by a sequential vector averaging procedure. First, sample mean directions were calculated by giving unit-weight to specimen directions, and then site-mean directions were calculated from the corresponding sample directions (Irving, 1964).

For comparison purposes, mean directions were calculated with both the magnetic and solar orientations. The angular difference between solar and magnetic azimuths was as high as 17°. There is no apparent correlation between the angular difference and NRM intensity (or low-field susceptibility), as can be seen in Fig. 5. However, the distribution of angular differences does not appear to be random. Samples within a given site cluster with respect to the angular difference, if not the intensity (Fig. 5). We have highlighted four sites: Site 19 presents a considerable angular difference variation with only a slight NRM intensity variation, whereas the other three (Sites 16, 24 and 26) have restricted angular difference distributions. In particular, two of them (Sites 16 and 24) are from pahoehoe sheets and display large differences in intensity but little difference between the magnetic- and solar-derived directions (+2°). Site 26 is also in pahoehoe lava, but near a sea cliff, and the cliff may be providing a magnetic anomaly that increases the spread in the magnetic and solar directions (8°). Site 19 is in an aa flow, and perhaps the rough clinkery surface of the flow may be causing the spread in both intensity and solar–magnetic difference, in contrast to the systematic and low values observed for pahoehoe outcrops (Fig. 5). We could not determine a simple general correlation between the solar–magnetic compass orientation angular difference, NRM intensity and site characteristics (lava type, nearby structures, etc.). Flanigan and Long (1987) presented an aeromagnetic map of the Mauna Loa SW rift, and there is a magnetic gradient of about 600 nT across our field area. This magnetic anomaly seems insufficient to explain the differences observed between solar and magnetic azimuths, and may be contributing only a couple of degrees to the angular differences. On the other hand, the magnetic anomalies associated with the outcrops can be larger. Because magnetic compasses are affected by local field anomalies and outcrop magnetizations, we used only the solar-compass-derived mean directions in our analyses.

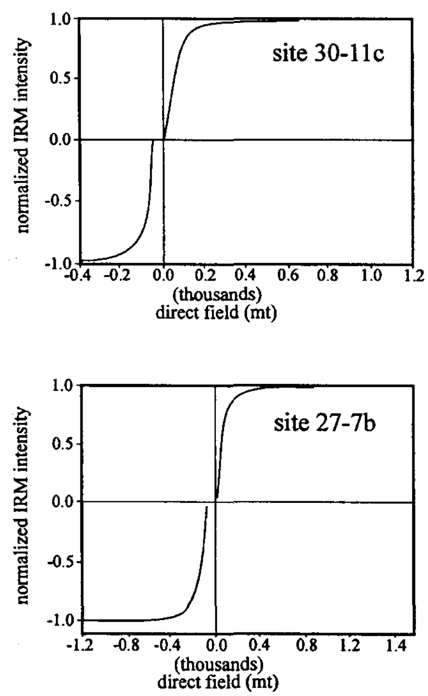

Fig. 6. Acquisition curves of the isothermal remanent magnetization (IRM). (Note that the curves saturate below 1 T, indicating that titanomagnetite is the source of the magnetization.)

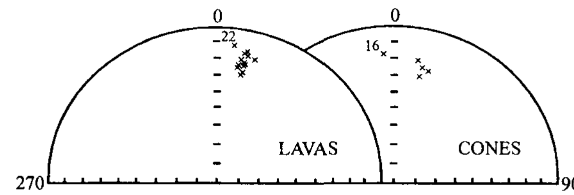

Fig. 7. Equal area stereograms of flow sites (a) and cone sites (b). (Note that in both diagrams all the sites cluster, very well with the exception of the outliers (Site 22 of the lavas and Site 16 of the cones), and that the clusters are in the same location.)

Site mean directions and statistical parameters (using the solar compass orientations) are summarized in Table 1. Most site-mean directions are characterized by a small angular dispersion, with α_{95} between 1.4° (Site 24; pahoehoe flow surrounding the cones) and 6.1° (Site 31; pahoehoe lava ponded inside a cone) (Table 1).

Magnetic carriers in the samples were investigated using the coercivity spectrum characteristics from a.f. demagnetization and by isothermal remanent magnetization (IRM) analysis. One specimen per site was given an IRM in steps with a pulse magnetizer up to maximum fields of 2.5 T. After reaching saturation, fields were applied in an opposite direction (Fig. 6). Samples saturated in low fields, between 0.2 and 0.5 T, indicating the predominance of titanomagnetite minerals. From available results (a.f. coercivity, low-field susceptibility, Q coefficients, IRM acquisition curves, angular dispersion of NRM and ChRM, and vectorial composition and stability) the characteristic remanence corresponds to a primary thermoremanent magnetization (TRM) residing in titanomagnetite minerals of single domain (SD) or pseudo-single domain (PSD) states.

Site mean ChRM directions for the lava flow sites form a tightly clustered distribution (Fig. 7). The exception is Site 22 (in toothpaste– aa lava infilling channel), which falls some degrees away from the group (Fig. 7(a)). Corresponding ChRM directions for the lavas ponded in the cones also show a well-defined group, except for Site 16 (Fig. 7(b)). Overall mean directions for the lava flow and for the lavas ponded in the cones were calculated using procedures similar to those for PSV analysis (e.g. McWilliams et al., 1982; Bohnel et al., 1990) incorporating two-tier analysis (Watson and Irving, 1957; McFadden, 1982) and 'outlier' analysis (McFadden, 1980). The overall mean direction for the lava flow sites is Dec = 10.8°, Inc = 23.6°, with $k = 287.4$ and $\alpha_{95} = 2.3°$ (Table 2). Inclusion of the Site 22 outlier direction does not greatly change the parameters (Table 2). The corresponding overall mean direction for lava ponded in the cones is Dec = 12.8° and Inc = 25.2°, with $k = 353$ and $\alpha_{95} = 4.9°$ (Table 2), which is statistically indistinguishable from that for the lava flows (test after McFadden and Lowes (1981)). A similar conclusion is obtained by application of the statistical test developed by Bogue and Coe (1981), which estimates the likelihood that two particular units were magnetized during a geomagnetic interval shorter than the time scale of geomagnetic variation. The small statistical uncertainties obtained for the Pohue Bay flow allow us a very good precision for the statistical comparisons. From the tests, contemporaneous magnetization (i.e. the interval is short compared with the time scale of secular variation) seems the likely explanation for the similarity of paleomagnetic directions rather than fortuitous coincidence of ancient field directions. Because of the small number of sites in the cones, statistical parameters vary depending on inclusion of data for Site 16 (Table 2). Additionally, the overall mean direction for lavas and cones combined shows a small angular dispersion ($k = 301$ and $\alpha_{95} = 2°$) with Dec = 11.2° and Inc = 24.0°. The corresponding PSV estimate is $S_f = 4.2°$; this is considerably lower than the PSV estimate of around 11° reported in earlier studies (e.g. Doell and Cox, 1971, 1972; McWilliams et al., 1982).

4. Discussion and conclusions

In summary, the results show that lavas in the main part of the Pohue Bay flow and those ponded in the cones all present similar paleomagnetic (directional) characteristics and thus a relatively close age relationship. We conclude that the flow and cones formed during the same eruption, and because the vents for the flow are far upslope on the rift zone, the cones must therefore be littoral in origin. These cones represent an undescribed type of littoral cone in the sense that they are circular, large, and formed inland from the coastline associated with a pahoehoe flow (Jurado-Chichay et al., 1996).

The directions from the sites in the lava flows have been drawn from a common Fisherian distribution (McFadden, 1980), with the exception of Site 22. This site is in the toothpaste lava–aa flow that fills the upslope channel. This site may represent a younger flow or post-cooling deformation within the channel. The number of sites in the cones is too small for statistical discrimination of distribution type; Site 16, the most southeasterly cone, is an outlier. This might be due to a vent anomaly or an older age (supported by field evidence (Jurado-Chichay, 1993)).

The Pohue Bay flow had been assigned an age of around 740–910 years BP based on degree of weathering (Lipman and Swenson, 1984). Holcomb et al. (1986) constructed a curve for the variation in direction from Hawaiian lavas that covers the past 3000 years and used this curve for dating purposes. This curve for directional changes represents an averaged and simplified view of the paleomagnetic

Table 2
Fisher statistics and paleosecular variation calculations

	Dec (deg)	Inc (deg)	k	α_{95}	R	n	S_t	S_w	S_b	S_f	N_{mean}
All cones	9.1	23.7	81.1	8.5	4.95065	5	9.0	6.8	8.8	8.7	10.0
Cones w/o 16	12.8	25.2	352.6	4.9	3.99149	4	4.3	6.7	3.8	3.6	10.5
All flows	10.4	23.0	228.5	2.5	14.93874	15	5.4	5.3	5.1	5.0	11.2
Flows w/o 22	10.8	23.6	287.4	2.3	13.95477	14	4.8	5.3	4.6	4.4	11.2
All w/o 16 and 22	11.2	24.0	301.1	2.0	17.94355	18	4.7	5.6	4.4	4.2	11.0

N, Number of sites; k and α_{95}, Fisher precision parameters; Dec, declination; inc, inclination; S_t, S_w, S_b, and S_f, angular dispersion parameters.

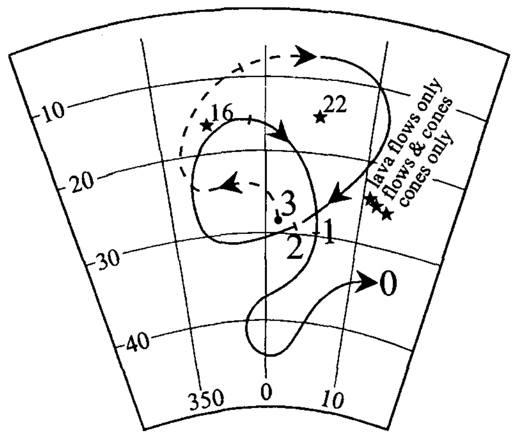

Fig. 8. Directional changes observed for Hawaii during the last 3000 years (from Holcomb et al. (1986). Published with permission from the Geological Society of America Bulletin.). Large numbers indicate ages in thousands of years before present (BP). ★, Mean remanent directions for Sites 16 and 22, lavas only (excluding Site 22), cones only (excluding Site 16), and lavas and cones together (excluding Sites 16 and 22). (Note that the mean remanent directions fall a few degrees off the curve close to the 2000–2500 and 1000–1300 year loops.)

field variation in the region. Keeping these limitations in mind, we have attempted a comparison of the Pohue Bay paleomagnetic data, grouped into lava flows, cones, and lava flows and cones with the curve (Fig. 8). The mean directions for Sites 16 and 22 are also plotted in the figure (see discussion below). The Pohue Bay flow mean directions for the three groups fall a few degrees off the curve, approximately the same angular distance from two segments: the 2000–2500 years BP and the 1000–1300 years BP segments. A radiocarbon-dated Kilauea lava sampled by J.P. Lockwood (locality: 19°27.62′N, 155°14.86′W, elevation 1141.5 m) has a similar paleomagnetic declination (8.0°), and a ^{14}C age of 2770 ± 150 years BP (J.P. Lockwood, personal communication, 1993), supporting an age associated with proximity to the 2000–2500 years BP segment of the directional change curve (Fig. 8). However, the ChRM inclination of this particular Kilauea flow is 27.9°, relatively far from that of the Pohue Bay Flow. One of the referees also called to our attention that an age of 2770 years BP represents a very old surface age for Mauna Loa flows that lie this close to the southwest rift. A number of Mauna Loa flows have both inclinations and declinations close to the values of the Pohue Bay flow (F.A. Trusdell and J.P. Lockwood, personal communication, 1995). They include the LM-92-05 Wood Valley flow with Dec = 9.4°, Inc = 22.2° (this compares well with the overall Pohue Bay mean of Dec = 10.1°, Inc = 23.2°), and a radiocarbon date of 1360 + 150 years BP (F.A. Trusdell, personal communication, 1995). From the comparison of the paleomagnetic directions with the curve of directional changes in Hawaii (Fig. 8), it is not possible to obtain a definite correlation. However, taking into account the field observations and comparison with other lava flows, it appears that around 1300 years represents a probable age for the Pohue Bay flow.

A charcoal sample we found underneath the Pohue Bay flow (see Fig. 2 for location) was dated by the accelerator mass spectrometer (AMS) radiocarbon method at the University of Arizona and gave a ^{14}C age of 305 ± 45 years BP. This date is unfortunately too young, considering that the overlying Halepohana flow (Lipman and Swenson, 1984) has been ^{14}C dated at 1040 ± 95 years BP (J.P. Lockwood, personal communication, 1993). Furthermore, charcoal from ancient Hawaiian archeological sites on top of the Pohue Bay flow yielded ^{14}C ages of 595 ± 80 years BP (Soehren, 1966).

Finally we would like to emphasize the importance of using a solar compass for orienting paleomagnetic cores when working on basaltic lavas. The precision required for a study of this type is unobtainable if the cones are oriented solely with a magnetic compass. Indeed, none of the results presented in this paper would have been statistically significant with the magnetic-compass-oriented data.

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