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Geomagnetic field inclinations for the past 400 kyr from the 1-km core of the Hawaii Scientific Drilling Project

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Abstract. A volcanic record of geomagnetic field inclination for the past ~400 kyr at Hilo, Hawaii, has been obtained from the 941.5 m of core recovered by the Hawaii Scientific Drilling Project. The analysis of 195 lava flows reveals six instances of near-zero inclination and two instances of fully negative inclination (reverse polarity) within an otherwise normal-polarity core. In particular, flow unit 23 (~178 m depth) records a horizontal inclination and may be associated with the Laschamp event; flow units 40 and 42 (~260 m depth) record negative inclinations and are close in age to the Blake event; and flow unit 55 (~320 m depth) records a negative inclination with a relative declination change of ~75° with respect to the overlying flow and is probably the Jamaica/Biwa I/Pringle Falls event. The five instances of shallow inclination found below 400 m depth appear to have resulted from long-term secular variation as they are part of inclination swings between ~0° and ~60° with a periodicity of ~10–50 kyr. In contrast, the inclination shifts at ~178 m and ~320 m depths significantly deviate from long-term trends, suggesting the existence of at least two independent processes producing time variations of the geomagnetic field. The secular variation has a mean of 30.9° (α_{95} = 2.27°), which is significantly shallower than the expected dipole mean of 36°. The dispersion (σ = 12.5°) agrees with global paleosecular variation data for 0–5 Ma and secular variation models.

Introduction

The Hawaii Scientific Drilling Project (HSDP) [*Stolper et al.*, this issue] was conceived in order to study the nature and evolution of a mantle plume hot spot by drilling through the flank of an active ocean island volcano. The initial phase of this program was a "pilot hole," drilled at Hilo, Hawaii (Figure 1). In addition to the petrologic, geochemical, and volcanological information afforded by the recovered core [*Stolper et al.*, this issue], this project provided the unprecedented opportunity to obtain a record of geomagnetic field inclination for the last ~400 kyr from a continuous sequence of lava flows at one location in the central Pacific.

Paleomagnetic studies on the island of Hawaii (known as the "Big Island," Figure 1) have established that Hawaiian basalts record the ambient field direction extremely well [*Doell and Cox*, 1963, 1965; *Hagstrum and Champion*, 1994] and that all flows exposed on the surface were deposited during the Brunhes normal polarity chron [*Doell and Cox*, 1965]. In addition, detailed studies of hundreds of lava flows [*Doell and Cox*, 1971; *Doell*, 1972; *McWilliams et al.*, 1982; *Holcomb et al.*, 1986; *Mankinen and Champion*, 1993; *Hagstrum and Champion*, 1994] and lake sediments [*Peng and King*, 1992] have produced paleosecular variation records as far back as 13,000 years. These records show that the subdued nature of the present geomagnetic field's nondipole component may have persisted for the past several thousands of years and possibly longer, although *Mankinen and Champion* [1993] pointed out that despite attempts at correction [e.g., *McWilliams et al.*, 1982], this may still be the result of sampling very short time intervals. While these and other studies have provided valuable information on recent lava flows and geomagnetic field behavior, continuous records extending into the Pleistocene are difficult to obtain since most of the island is covered by flows less than a few thousand years old.

Although the HSDP core is azimuthally unoriented, the paleomagnetic inclination record may address several important issues regarding geomagnetic field behavior. Sudden polarity changes or excursions, paleointensity, and secular variations of the zonal components of the geomagnetic field can in principle be measured or detected with inclination data alone. This core is particularly interesting because the HSDP record spans the upper half of the Brunhes magnetochron [*Harland et al.*, 1989], a period in which several departures from the stable normal polarity of the field have been previously observed (reviewed by *Champion et al.* [1988] and *Jacobs* [1994]). Volcanic records are not as continuous as sedimentary records and may miss excursions of the geomagnetic field, which are often less than a few thousand years in duration [e.g., *Courtillot and Lemouel*, 1988]; however, volcanic records do not suffer from the time-averaging effect of sedimentary acquisition of remanence which may also cause short-lived events to be missed [e.g., *Thouveny and Creer*, 1992]. When sudden changes of geomagnetic field direction are found in volcanic records,

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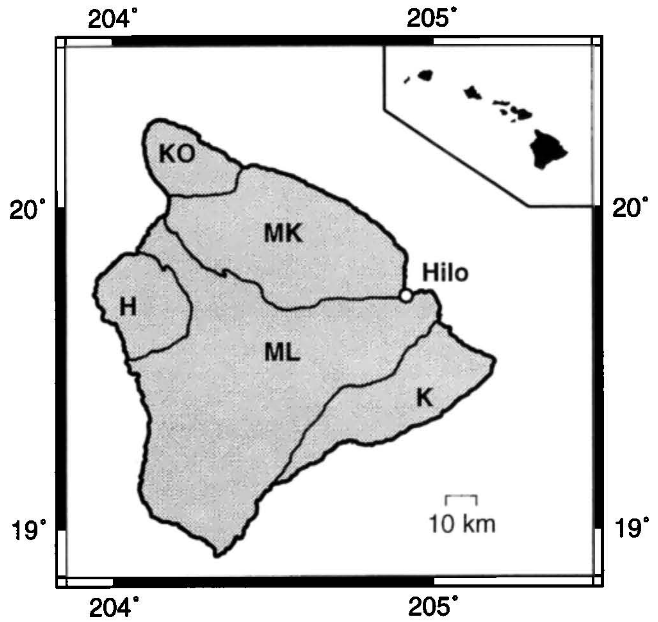

Figure 1. Location map showing the island of Hawaii, largest of the Hawaiian Islands (inset, upper right). The core was drilled near the shore at Hilo (open circle). Boundaries are shown for surficial lava flows from Kohala (KO), Mauna Kea (MK), Hualalai (H), Mauna Loa (ML) and Kilauea (K) volcanoes in order of general age [after *Rubin et al.*, 1987].

there is the opportunity to constrain their ages using geochronologic techniques, as well as to obtain an absolute measurement of the field intensity at that time. The former is required to establish global correlation of geomagnetic field excursions or events, while the latter permits a discussion of the geomagnetic regime responsible for the rapid directional changes.

Unfortunately, there are few volcanic records available which span more than one of these relatively rare events. According to our paleomagnetic studies, the 208 lava flow units comprising the HSDP pilot core record three sudden, large shifts of geomagnetic field inclination and five instances of extremely shallow inclination. The $^{40}Ar/^{39}Ar$ and K/Ar dating of basaltic samples from the core [*Sharp et al.*, this issue] as well as radiocarbon dating of volcanic ashes [*Beeson et al.*, this issue] provide age constraints for several of these geomagnetic phenomena.

Core Description

The 1056-m-deep HSDP hole was drilled through ~280 m of Mauna Loa flows into the flank of Mauna Kea volcano. Core recovery rate was 90%, with the unrecoverable portion being composed of unconsolidated sediments and rubble [*Stolper et al.*, this issue]. Most flow units sampled by the core resulted in at least one or two sections of continuous core approximately 0.3 m in length, and occasional reconstructions of 1–2 m in length were possible. As previously mentioned, the core was not azimuthally oriented. Vertical orientation of the core was preserved immediately after each core run (retrieval of ~3 m of core) by two blue/red line pairs (each pair consisting of blue on left, red on right) drawn along opposite sides of the retrieved core section. The section was then cut into ~0.6-m lengths for boxing and split lengthwise into one archive sample and one sample for subsequent study [*Hawaii Scientific Drilling Project*, 1994].

Core logging identified 227 distinct lithologic units, 208 of which are individual or compound lava flows; the remainder being ash beds, sediments, and soils [*Stolper et al.*, this issue]. The term "unit" refers to either a single lava flow or a compound flow erupted in a short time. "Flow" could therefore be synonomous with "unit" or could be a subdivision of a compound flow unit. The 27 Mauna Loa flows, extending from the surface to 280 m depth, were deposited on shallow slopes (~1°) of lava deltas. Mauna Kea flows, constituting the bulk of the core, were deposited on the relatively steeper slope (~3°–6°) of the volcano (G. P. L. Walker, unpublished manuscript, 1995). As a result, Mauna Loa flows in the core are generally thicker than those of Mauna Kea and contain more intercalated sediment and soil horizons. The boundary between Mauna Loa and Mauna Kea flows is distinguished by major and trace element compositions [*Rhodes*, this issue]. Detailed petrography and petrology of HSDP samples is reported by *Baker et al.* [this issue]. Lava flows from both volcanoes are exceptionally unaltered due to their location away from active hydrothermal areas [*Stolper et al.*, this issue].

Sampling and Measurements

Four to six 2.5-cm-diameter samples were drilled from 195 flows within the HSDP core using a diamond-tipped, water-cooled coring bit. A vertical orientation line was drawn parallel to the sides of the HSDP core segment on the flat face of the HSDP core split. Samples were then drilled, centered on this line, perpendicular to the HSDP core axis at various azimuths (due to the azimuthally unoriented nature of the core). When continuous sections of core were encountered, samples were drilled with the same azimuth. After drilling, a longitudinal orientation mark was drawn along the top of each paleomagnetic samples before being trimmed to a length of 2.2 cm. End chips were tagged and saved for possible future use.

Measurements were made using a computer-controlled, magnetically shielded cryogenic magnetometer with a background noise level of 5×10^{-12} A m^2, located within a magnetically shielded room at the California Institute of Technology (Caltech) Paleomagnetics Laboratory. The 618 samples were subjected to progressive, static, three-axis, alternating field (AF) demagnetization to 80 mT in steps ranging from 2.5 to 15 mT. Inclination data for 104 samples were also obtained by *Garnier et al.* [this issue] as part of their paleointensity analyses, which employed thermal demagnetization techniques. The inclination data resulting from their study is used in the flow averages along with our data obtained from AF demagnetization. Progressive thermal demagnetization using 50°C steps was performed on seven samples of our study in order to determine relative declination changes between multiple components of magnetization in partially remagnetized flow units, as discussed below.

Rock magnetic investigations of HSDP core samples were also undertaken by *Garnier et al.* [this issue]. Their high field thermomagnetic analyses and magnetic hysteresis measurements indicate that the primary carrier of magnetic remanence in these samples is pseudo-single-domain magnetite and/or titanomagnetite.

Sources of Uncertainty

With any volcanic rock core there is the possibility that apparent large shifts of paleomagnetic directions are the result of sample misorientation, inverted segments of core, block rotation, slumping, local magnetic anomalies, or self-reversing magnetic components. Sample and core segment orientations were the first factors checked when apparent polarity reversals were found in the data. This eliminated six apparent "events" which were highly suspect because they occurred within flows with otherwise normal inclinations. Since sample end pieces could be matched to the sample using the longitudinal orientation mark and end pieces could be matched with the outer core surface using vesicles, fractures, and/or one or both of the blue/red orientation lines, sample orientation could be verified. If there was any doubt, then new samples were drilled in the same segment. In four of the six cases of core inversion, comparison of the blue/red vertical orientation lines with the orientation marks made during our sampling revealed that short segments of the core (typically <0.3 m) were inverted during packaging or subsequent handling. In order to confirm this, we carefully examined the broken ends of adjacent segments and compared lithologic and structural variations (grain size, olivine content, vesicles, fractures, flow boundaries, etc.) in adjacent sections. Continuity of these variations could be used independently of the orientation lines to reconstruct the vertical orientation of questionable segments. In two cases, segments of broken core were clearly inverted before the lines were drawn.

In all cases of inclination change described in this paper, the relevant core sections can be unambiguously fitted to adjacent core segments with normal inclinations and all lithologic/structural variations are oriented consistently within the context of that particular region of the core. When present, the partial thermal overprints from normal-polarity overlying flows rule out multiple-flow slumps and self-reversing magnetic components. Thermomagnetic experiments and determinations of paleointensity did not reveal evidence for self-reversing mineralogy [*Garnier et al.*, this issue].

During the drilling operation, the position of the hole at depth was obtained by magnetic single-shot surveys to determine the direction and angle of the drill hole. This was used to test the validity of our assumption that the sides of the core were positioned vertically. These measurements show that the hole was an average of 1.7° from vertical, with a surface projection of the bottom of the hole located 31.32 m from the top of the hole at an azimuth of 248° (Table 1). Individual depth intervals between measurements smoothly ranged from 0.5° to 2.5° from vertical. Based on these data we can assign a specific uncertainty to samples from each depth interval (Table 1).

Detailed studies of the sources of error in outcrop-based paleomagnetic studies of Hawaiian lava flows have been performed by *Doell and Cox* [1963] and *Holcomb et al.* [1986]. Given the results of their studies and the circumstances of this study, the two largest presumed sources of error in our data are the possible rotation of blocks or intraflow deformation after individual flows have cooled below their blocking temperatures and the influence of magnetic anomalies existing over the paleosurface where the flow was deposited. Block rotations are difficult to detect, but in general, the upper portions of some flows show the most evidence for possible small-scale block rotations during cooling. These areas, identified by their rubbly, blocky appearance, were avoided by sampling the interiors of flows. The shifts in inclination reported here are typically recorded in only one or two flow units. It would be unlikely for large-scale block rotation or slumping to affect these units without affecting immediately underlying or overlying units. Flow contacts in units suspected of rotation were examined for this, as large rotations of individual units should drastically alter the continuity of flow contacts. The error due to intraflow deformation measured by *Holcomb et al.* [1986] was ~2.0°.

Table 1. Measurements of the Deviation of the Drill Hole From Vertical

Depth, m	Deviation, m N-S	Deviation, m E-W	Deviation, m Total	TAD, deg	PAD, deg
0.00	0.00	0.00	0.00	0.00	
68.28	0.01	−0.59	0.59	0.50	0.50
184.10	−0.18	−2.59	2.60	0.81	0.99
288.65	−1.02	−5.91	6.00	1.19	1.86
367.28	−1.80	−9.25	9.42	1.47	2.49
457.20	−2.44	−12.52	12.76	1.60	2.12
548.64	−3.26	−15.60	15.93	1.66	1.99
640.08	−3.95	−18.49	18.91	1.69	1.86
731.52	−4.51	−21.42	21.89	1.71	1.87
827.23	−5.51	−24.38	24.99	1.73	1.85
944.88	−6.94	−27.39	28.26	1.71	1.59
1054.61	−8.22	−30.23	31.32	1.70	1.60

Adapted from [*HSDP*, 1994]. N-S is deviation in north (positive)/south (negative) plane; E-W is deviation in east (positive)/west (negative) plane; total is the resultant of N-S and E-W deviations; TAD is total (average) angular deviation at the measured depth; PAD is partial angular deviation, or the deviation from vertical between successive measurements. The PAD is used in computing the uncertainty of the inclination measurements for paleomagnetic samples.

The uncertainties arising from local magnetic anomalies are perhaps the largest unknown factor and, according to some workers [*Baag et al.*, 1995], could render paleomagnetic data from highly magnetic rocks such as basalts completely uninterpretable. On the other hand, *Doell and Cox* [1963] performed comparisons of paleomagnetic measurements and geomagnetic observatory data for historic flows, and discrepancies were estimated to be 1°–1.5°. An analysis of hundreds of paleomagnetic sampling sites by *Holcomb et al.* [1986] led to an estimate of 2.2° for the error due to local magnetic anomalies, and *Hagstrum and Champion* [1994] found that paleomagnetic directions recorded by historic flows were not significantly affected by local magnetic anomalies.

We computed the 1σ error for individual lava flows by assuming ±2° of error from intraflow deformation and ±2.2° of error from magnetic anomaly effects [*Holcomb et al.*, 1986] along with the appropriate value of vertical uncertainty from Table 1. These uncertainties were added in a root-mean-square fashion to the within-flow dispersion inherent in the paleomagnetic data. The resulting 1σ error for all 195 lava flows has a mean value of 4.96°, which is consistent with the estimate of ~5° for intraflow variations by *Hagstrum and Champion* [1994]. Some flows with high dispersion may actually be compound flows composed of distinct subunits. This is the case for flow unit 15, which we subsequently divided into two flows for this study. While uncertainties of this magnitude may be significant for highly detailed secular variation studies for short time periods [e.g., *Holcomb et al.*, 1986; *Hagstrum and Champion*, 1994], they are relatively insignificant for the purposes of this study, where the relevant inclination shifts are of

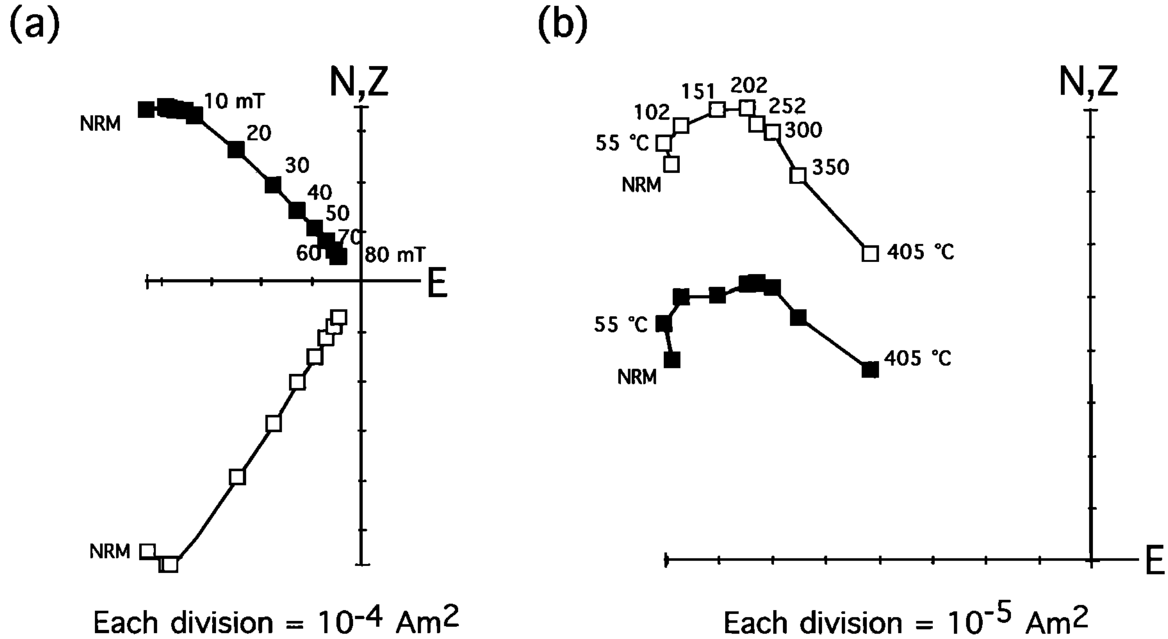

Figure 2. Demagnetization diagrams. Orthogonal projections of declination onto the horizontal plane (solid squares, vertical axis north) and inclination onto the vertical plane (open squares, vertical axis Z or up). (a) Alternating field demagnetization of a typical sample with positive inclination. Demagnetization levels are in milliteslas. (b) Thermal demagnetization of a negative-inclination sample from unit 55, showing a partial positive-inclination overprint from the overlying flow, unit 54. Demagnetization levels are in degrees Celcius.

the order 25°–80° and long-term secular variation changes are of the order 60°.

General Results

Nearly all samples exhibited stable demagnetization behavior, with highly linear demagnetization paths occurring after AF levels of 0–40 mT (Figure 2a). Inclinations for individual samples were determined by principal components, least squares analyses [*Kirschvink*, 1980] and were averaged for each of the 195 sampled flows along with inclination data from thermal demagnetizations of single samples from 104 of the same flow units [*Garnier et al.*, this issue]. Of the flow units which have both types of data, thermal and AF demagnetizations produced nearly identical results. Twenty-four samples near the tops of flow units showed strong evidence for partial remagnetization by the overlying flow, and these were removed for computing flow averages, leaving 705 total samples. The inclination data may be downloaded directly from the HSDP World Wide Web site (http://expet.gps.caltech.edu/Hawaii_project.html) or the Caltech Paleomagnetics Laboratory site (http://www.gps.caltech.edu/MagLab/) and will be updated as more samples are analyzed.

Flow inclination means and their $\pm 1\sigma$ total uncertainties are shown in Figure 3 as a function of depth and interpolated age. The age interpolation was performed as three separate linear fits (0–180 m, 180–416 m, and 416–1050 m), based on K/Ar and ^{40}Ar/^{39}Ar dates on whole rock samples [*Sharp et al.*, this issue], one radiocarbon date based on two ashes at 178 m depth [*Beeson et al.*, this issue], and the constraint that the top of the core is approximately zero age. This is intended to provide a crude approximation of paleomagnetic inclination as a function of age down the core. This also aids in estimating the approximate time resolution of the data, although rates of deposition could be highly variable on short timescales. If rates are assumed to be linear, the three intervals described above would have average deposition rates of one lava flow per every 3 kyr from the present to ~40 ka, every 7 kyr from ~40 ka to ~285 ka, and 0.6 kyr from ~285 ka to ~400 ka, respectively. Such variations are expected due to changes in eruptive style from the early shield-building stage of Mauna Kea to a slowdown in growth, followed by a transition to volcanics from Mauna Loa, which is now growing more rapidly than Mauna Kea [*DePaolo and Stolper*, this issue; *Lipman and Moore*, this issue].

To a first order, the paleomagnetic inclination record in the HSDP core shows large, mostly continuous inclination swings, ranging from approximately 0° to 65°. However, there are also short flips of polarity and sudden shifts of inclination away from consistent trends to shallow values. Some of these features are followed by a continuation at the same trend of inclination as before the departure. If this is of geomagnetic origin, it could have very important consequences to our understanding of the relationship between secular variation and excursions of the geomagnetic field. In the following sections we present details of the specific geomagnetic phenomena and discuss the secular variation recorded by the HSDP core.

Geomagnetic Phenomena

Feature A

Beginning with the topmost feature, there is an abrupt change of paleomagnetic inclination at 177 m depth (Figure 4) from a steady trend of high positive inclinations (~45°) in units 30–27 to a very shallow inclination of 0.9° ± 3.2° in unit 23. This unit is a 10-m-thick, massive, aphyric basalt which spans three different core runs. The pattern of inclination variation

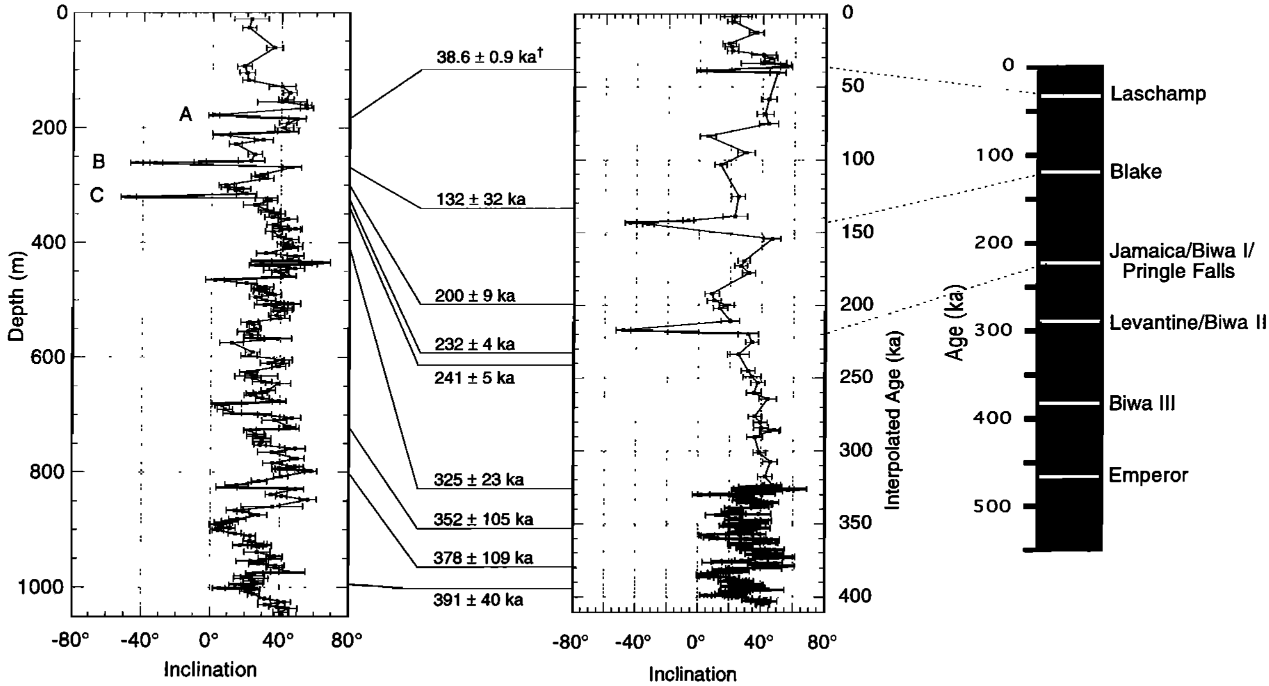

Figure 3. Overall inclination record and interpretation. Mean flow inclinations with $\pm 1\sigma$ error bars calculated from all known uncertainties plotted as a function of (left) depth and (middle) interpolated age. All ages are from *Sharp et al.* [this issue], except for 38.6 ± 0.9 ka from *Beeson et al.* [this issue]. Uncertainty calculations and age interpolations are discussed in the text. Geomagnetic polarity timescale for the past 500 kyr (right) is adapted from *Champion et al.* [1988]. The inclination data are available from the HSDP World Wide Web site (http://expet.gps.caltech.edu/Hawaii_project.html) or the Caltech Paleomagnetics Laboratory site (http://www.gps.caltech.edu/MagLab/).

surrounding unit 23 is one of steadily increasing values from +43.8° ± 6.0° in unit 30 (205.1 m) to +54° ± 3.37° in unit 20 (160.9 m). The jump to shallow inclination in unit 23 is followed by a return to the same trend. There is the possibility that there are substantial changes in the field direction between successive lava flows and that unit 23 is merely "catching" a typical swing of secular variation. However, it would be difficult to achieve the consistent trend of inclination recorded between flows 30 and 20 by randomly sampling a distribution of secular variation with a dispersion equal to that seen in the overall core. If the shallow inclination of unit 23 is the result of "normal" secular variation occurring briefly during an extended time of subdued variation, then this becomes a matter of definition. Shallow inclinations could also result from a large-scale rotation of a block of unit 23 subsequent to cooling. This would produce highly irregular flow contacts, especially at the top of the unit. Examination of the core material shows uniform, gradational flow contacts at both the top and bottom of this unit, indicating that significant block rotation did not occur. The anomalously shallow inclination of unit 23 thus appears to not be a feature of secular variation or block rotation.

Units 24–26, directly underlying unit 23, were not sampled. Unit 25 is a thin (0.3 m) basalt; units 24 and 26 (with an average depth of 178 m) are volcanic ashes and have a weighted average radiocarbon date of 38.6 ± 0.6 ka [*Beeson et al.*, this issue]. This date is also consistent with the island submergence curve of *Lipman and Moore* [this issue]. These data constrain the shallow inclination of unit 23 to have occurred very close in time to the Laschamp event, first discovered by *Bonhommet and Babkine* [1967] and K/Ar dated at 42.9 ± 7.8 ka [*Levi et al.*, 1990]. The sedimentary record of *Levi and Karlin* [1989] from the Gulf of California (7° higher latitude) displays a sudden shift of paleomagnetic inclination from normal steep values to +3° in this time period, which they infer to be correlative with the Laschamp event.

Preliminary paleointensity measurements on HSDP core samples [*Garnier et al.*, this issue] indicate that this feature may be associated with a low geomagnetic field intensity. Low paleointensities have been associated with anamalous paleomagnetic directions in volcanics of this approximate age in Iceland [*Levi et al.*, 1990] and France [*Roperch et al.*, 1988; *Chauvin et al.*, 1989] and in sediments of this age from the western Pacific [*Yamazaki and Ioka*, 1994], to name a few examples. The coincidences of age, preliminary paleointensity determinations, and anomalous inclination behavior led us to interpret this feature as possibly being associated with the Laschamp event.

Feature B

At 261.5 m depth, paleomagnetic inclination changes from +46.4° ± 5.5° in unit 43 to −32.6° ± 3.7° in unit 42 (Figure 4). Unit 43 is an 18.3-m-thick moderately olivine phyric basalt, while unit 42 is a 0.25-m-thick aphyric basalt. Unit 41, directly overlying unit 42, is a 0.25-m-thick weathered ash which was not sampled. Unit 40 is a 1.7-m-thick highly olivine phyric basalt and records a negative inclination of approximately −44° (single sample) which is fully opposite the prereversal value. Moving upward, there is an erosional surface within unit 39 (at 258.8 m depth) including a baked sand layer on top. We obtained a reversed magnetization for a sample just below this contact, suggesting that unit 39 is a compound flow and the bottom of unit 39 is a distinct flow approximately 0.3 m thick (designated in Figure 4 to be unit 39.5). This unit yielded a

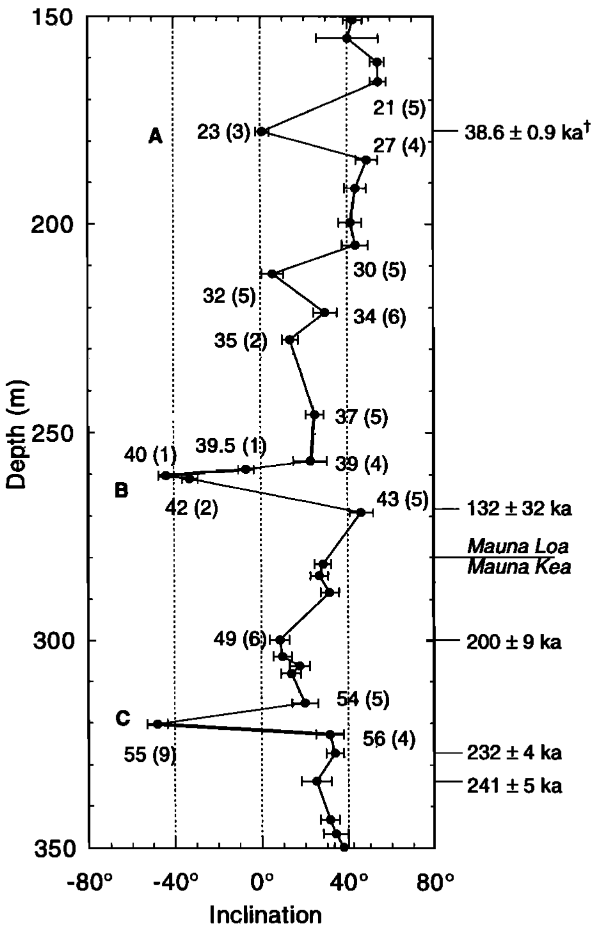

Figure 4. Detail of inclination record from 150 to 350 m depth, spanning inclination features A, B, and C (possibly the Laschamp, Blake, and Jamaica/Biwa I/Pringle Falls events, respectively). Flow unit numbers and the number of paleomagnetic samples from each (in parentheses) are shown for selected units. Ages are discussed in text and in Figure 3. Mauna Loa/Mauna Kea boundary is shown for reference [*Stolper et al.*, this issue].

shallow, negative inclination (−7°), which may be either a transitional direction or the result of partial remagnetization by unit 39 above. Unit 39, a 1-m-thick sparsely olivine phyric basalt, records a positive inclination (22.8° ± 7.8°) immediately above the contact with unit 39.5.

This polarity shift is especially interesting because it falls very close to the boundary between Mauna Kea flows (below) and Mauna Loa flows (above) at ~280 m depth [*Stolper et al.*, this issue]. Beach sands present in unit 38 indicate that these units were deposited very close to sea level. The island submergence curve of *Lipman and Moore* [this issue] provides an approximate upper constraint on the age of this boundary at 95 ka. The lack of adequate potassium in lava flows from this region of the core has hampered dating efforts, although *Sharp et al.* [this issue] have produced an $^{40}Ar/^{39}Ar$ age of 132 ± 32 ka for unit 43 (268.2 m depth, Figure 4).

The most widely documented excursion or event near that time is the Blake event. This event has been reported from studies of deep sea sediments [e.g., *Smith and Foster*, 1969; *Creer et al.*, 1980; *Tric et al.*, 1991], lacustrine sediments [*Eardley et al.*, 1973; *Yaskawa*, 1974], and loess deposits [*Zhu et al.*, 1994]. A whole rock K/Ar age of 128 ± 33 ka was obtained by *Champion et al.* [1988] from a basalt flow in New Mexico which displays a transitional paleomagnetic direction and low paleointensity. This age is consistent with those obtained for the Blake event from sedimentary extrapolations of deposition rate, which range from 105 ka [*Ryan*, 1972] to 161 ka [*Aksu*, 1983]. The global nature of the Blake event has been fairly well established, and it appears to have lasted 4–16 kyr based on average sedimentary deposition rates. Using the rough estimates of time resolution described above, the average time between flows which we have sampled is of the order 3–7 kyr. Although the short-term rates of lava deposition could be highly variable, the fact that three to four flows in the HSDP core recorded negative inclinations indicates that the event we observe at 260 m may have lasted for several thousands of years. Due to the strong evidence for reversed directions and the available dating constraints, we correlate this event with the Blake event.

Feature C

At ~320 m depth, inclinations jump from +31.5° ± 6.4° in unit 56 to a fully reversed −48.2° ± 4.6° in unit 55, which is a 5.4-m-thick moderately to highly olivine phyric basalt spanning two core runs (Figure 4). The reversed inclinations of unit 55 are followed by a return to positive inclinations in unit 54. This feature is surrounded by a gradually decreasing trend of positive inclination (Figures 3 and 4) which continues after the jump in unit 55.

Potassium content in this region of the core was much more favorable to $^{40}Ar/^{39}Ar$ dating techniques. This feature is well bracketed by the four dates [*Sharp et al.*, this issue] between 299 m and 416 m shown in Figure 3. Since unit 55 was clearly deposited between two of the dated flows, even the most conservative approach yields the useful constraint of 191–236 ka by taking the extreme limits for the ages immediately above and below. The lava deposition in this interval has resulted in a linear relationship between age and depth (or flow unit) within analytical uncertainty, yielding an estimate for unit 55 of 226 ± 7 ka [*Sharp et al.*, 1995].

Ryan [1972] identified several brief polarity reversals in sedimentary cores from the Caribbean and Mediterranean, one of which he estimated to be ~200 ka old. He named it the Jamaica event and since that time there have been other studies (reviewed by *Champion et al.* [1988]) identifying reversed-polarity rocks of similar age, including the Lake Biwa record of *Yaskawa* [1974]. Recently, *Herrero-Bervera et al.* [1994] have produced multiple records of a reversed-polarity interval which they dated at 218 ± 10 ka and named the Pringle Falls event. This matches the estimated age of feature C within uncertainties. The dates (with associated errors) reported for the published records of events near this time cannot rule out the possibility that there is only one event near 200 ka, and we observe only one event in this period. While our record could have missed other nearby events, it does provide support for at least one global polarity event occurring in the time period 191–236 ka. We will refer to this as the Jamaica/Biwa I/Pringle Falls event.

In order to further characterize this event, we undertook progressive stepwise thermal demagnetizations of samples from near the top of flow unit 55 and the top of flow unit 56. This was done with the goal of finding partial thermal overprints produced by the emplacement of a hot flow unit on top of the already cooled flow. Stepwise demagnetization enables measurement of the relative declination change between the primary magnetization and the partial overprint [*Champion et al.*, 1988], which is important in discerning excursions or polarity events from large swings of secular variation.

For this experiment, seven samples were taken 1.65–2.98 m from the top of flow unit 55 (below an altered zone of rubble), and five samples were taken 0.2–0.5 m from the top of flow unit 56. These samples were thermally demagnetized in ~50°C increments up to 405°C. There was no detectable overprint in unit 56 from reheating by unit 55. For the samples from unit 55, blocking temperatures of the overprint increased from essentially 0°C for the top sample (no overprint) to ~250°C for the lowest sample. The lower four samples yielded overprints sufficient for least squares principal component analysis [*Kirschvink*, 1980] and comparison with primary magnetizations. A representative thermal demagnetization is shown in Figure 2b. The phenomenon of stronger overprinting toward the center of the flow may be related to a change in coercivity of the carriers of remanence as a function of cooling rate, which has been noted previously in Hawaiian basalts [*Doell and Cox*, 1963, 1965]. The top of the flow, which cools more quickly than the middle, is typically finer grained and can result in magnetic domains of higher coercive force. A detailed study of a 30 to 60-m-thick basaltic lava flow in the northwestern United States [*Audunsson and Levi*, 1992] also showed that there can be extensive zonation of magnetic properties in a lava flow with the central section being less magnetically stable than the upper.

An equal-area diagram showing both components from the four lowest samples in unit 55 is shown in Figure 5. The inclination of the overprint matches that determined from samples of unit 54, within error. Based on these preliminary results, the relative declination change from the primary component to the overprint component is 75.4° ± 10°. This confirms that unit 55 recorded a drastic change in total paleomagnetic direction at ~226 ka. The detailed correlation of this event with published records of the Jamaica/Biwa I/Pringle Falls event will be addressed in a separate paper.

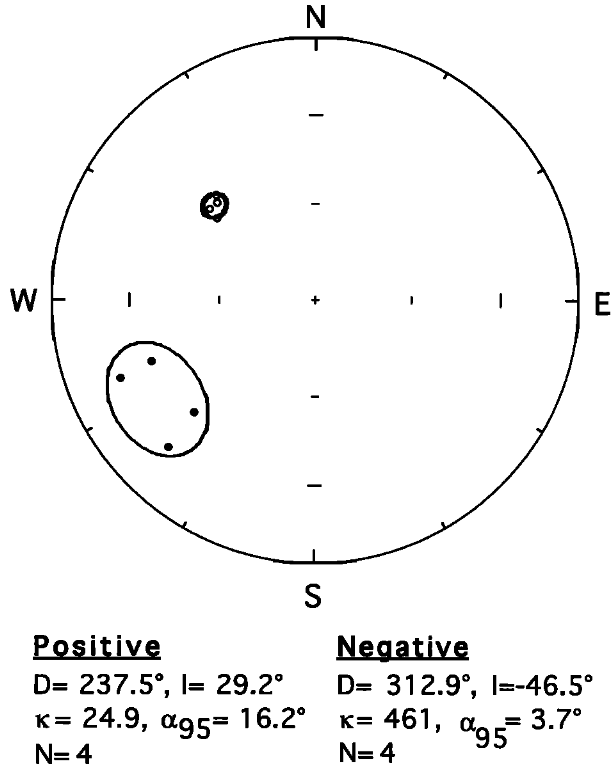

Figure 5. Equal-area diagram showing both overprint directions (solid circles, lower hemisphere projections) and primary directions (open circles, upper hemisphere projections) from samples of unit 55 subjected to stepwise thermal demagnetization (Figure 2b). The α_{95} ellipses for the Fisher means [*Fisher et al.*, 1987] of each component and associated statistics (D, declination east of north; I, inclination, positive downward; κ, precision parameter; N, number of samples) are shown. The relative declination change is 75.4° ± 10°.

Other Shallow Inclination Features

The remainder of the HSDP core below feature C is characterized by a higher rate of lava flow deposition and fewer sudden changes of inclination. Although there are no reversely magnetized samples in this part of the record (Figure 3), there are five instances below feature C where the inclination approaches horizontal: unit 90 at 465 m depth, units 139–141 at ~685 m, unit 168 at 826 m, units 182 and 186 at ~895 m, and unit 214 at 1000 m. The age at the bottom of the core is fairly well constrained to be ~400 ka [*Sharp et al.*, this issue]. These inclinations are within the limits of secular variation and tend to occur within continuous inclination swings, similar to the shallow inclination located at 300 m depth (unit 49, Figure 4) which occurs immediately after feature C and at the end of a long swing of inclination from much higher values (Figure 4). It is possible that one or more of these periods of shallow inclination may be related to previously recorded excursions or events, but without declinations or more precise age control, any attempts to perform such a correlation or to even claim that they are excursional would be highly speculative.

Secular Variation

Much has been written concerning the hypothesis of a lack of nondipole geomagnetic field components in the central Pacific region [*Doell and Cox*, 1971, 1972; *McWilliams et al.*, 1982; *Peng and King*, 1992; *Mankinen and Champion*, 1993]. This has not been extended back in time more than ~15 kyr due to the paucity of older data sequences. Although the HSDP core data are inclination only, they may be used to address several important questions regarding secular variation and nondipole field components in general. The mean inclination for all flows, excluding those with reversed inclinations, is 30.9° as calculated according to *McFadden and Reid* [1982] for inclination-only data, with an α_{95} radius of 2.27°. This is significantly lower than the 35.6° expected from a geocentric axial dipole and consistent with a time-averaged field including an axial quadrupolar (g_2^0) component [*Wilson*, 1970, 1971].

The dispersion of the inclination data about the mean is 12.5°, which agrees with the dispersion of inclination dispersion data for 0–5 Ma from global secular variation databases [e.g., *Quidelleur et al.*, 1994] and the predictions of simple secular variation models [e.g., *Constable and Parker*, 1988; *Quidelleur and Courtillot*, 1995]. Hence there is a significant nondipole field contribution when averaging over the past ~400 kyr. However, the inclination data (Figure 3) show considerable variation in their mean and dispersion over timescales of ~10–50 kyr. This may indicate that there are large variations in the amount of nondipole contribution to the geomagnetic field, or possibly even variations in the dipole component, over these timescales.

The data show a pattern of inclination swings which result in a series of repeating shallow inclination values below 400 m depth (Figure 3). This pattern appears to be a feature of secular variation with a periodicity of the order ~10–50 kyr. Typical secular variation has periodicities less than ~10 kyr [*Courtillot and Lemouel*, 1988]. Geomagnetic field variations on a longer timescale were recently reported by *Yamazaki and Ioka* [1994], who found inclination variations of several degrees amplitude with a periodicity of 40–50 kyr in sedimentary inclination records from the western Pacific. They suggest that orbital forcing may be the ultimate source of their long-term inclination variations. This follows the work of *Negrini et al.* [1988], who performed a spectral analysis of sedimentary paleomagnetic records from the northwest United States and found peaks with periodicities close to those of orbital parameters. In sediments, however, there is the possibility that fluctuations of inclination with this periodicity may be the result of periodic changes in lithology which affect the degree of compaction-induced inclination shallowing. The record from the HSDP core demonstrates the existence of a real component of secular variation with a period greater than 10 kyr, because there are no known processes other than the geomagnetic field which could affect volcanic records of paleomagnetic inclination in such a periodic manner. A spectral analysis of the HSDP inclination record is required in order to address this question in more detail.

One of the most intriguing aspects of the HSDP inclination data is how short-term variations of the geomagnetic field appear to be superimposed upon long-term trends. For example, the inclination jump in unit 55 (feature C, Figures 3 and 4) occurs during a steady decrease in inclination which persists for at least ~50 kyr around this feature. Although not as pronounced, there is also a consistent trend surrounding the large inclination shift recorded by unit 23 (feature A, Figures 3 and 4). These observations indicate that short-term deviations of the geomagnetic field from stable polarity states may not necessarily be related to more subtle, long-term variations.

Summary

The paleomagnetic inclination record obtained from the pilot core of the Hawaii Scientific Drilling Project is the longest continuous volcanic record of geomagnetic field inclination yet reported. This record contains two brief inclination reversals which we tentatively correlate with the Blake and Jamaica/Biwa I/Pringle Falls events and an anomalous inclination which may associated with the Laschamp event. These are the first records of these events to be found in the central Pacific region and provide evidence that they are global features rather than localized perturbations of the geomagnetic field. Long-term variations of the geomagnetic field are recorded in the HSDP core and are significant when conservative estimates of the known uncertainties are included. Two of the sudden inclination shifts (the Jamaica/Biwa I/Pringle Falls and the possible Laschamp records) appear to be superimposed upon these long-term trends. This might suggest that sudden changes of geomagnetic field direction (e.g., excursions or events) and long-term secular variation are caused by two separate processes that produce geomagnetic field variations at different timescales.

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