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DISTINCTIVE FIELD BEHAVIOR FOLLOWING GEOMAGNETIC REVERSALS

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Abstract. The paleomagnetism of lava flows from Kauai (Hawaii), erupted about 4 my ago immediately following a geomagnetic reversal, reveals that the post-transitional field had several distinctive characteristics. While the directional dispersion was identical to that displayed by stable field over the past 5 my, the post-transitional field intensity was unusually high. In both these respects, the field at Kauai resembles the one recorded at 15 Ma by lava flows at Steens Mountain in SE Oregon. The two records also differ in an important way: the large intensity oscillations that immediately followed the Steens Mountain reversal are not apparent in the data from Kauai. These results suggest that while the stability of the newly established dipole may vary significantly from one reversal to the next, strong dipolar field and normal directional dispersion may be systematic features of the post-transitional geodynamo. Furthermore, the results lend support to the recent suggestion that the core remains in an unusual state for many tens of kyr following a reversal.

Introduction

It has proven difficult to demonstrate convincingly how the geomagnetic field behaves during polarity transitions. For example, recent debate has centered on whether the field remains dipolar during the transitional interval (see review by Bogue and Merrill [1992]). Progress has been slow because the transitional field is short-lived, weak, and sometimes varies rapidly, so that its details are difficult to observe paleomagnetically. Are there other systematic features of polarity reversals that might be easier to document? One possibility is suggested by the recent work of McFadden and Merrill [1993], who infer that unusual conditions persist in the geodynamo long after a reversal otherwise appears to have reached completion. Using their terminology, the *TT* (total transition) interval may last 45 kyr, roughly 10 times as long as the polarity *D* transition (the interval associated with unusual field directions). If this concept is valid, then it is reasonable to extend the search for systematic, reversal-related field behavior into the immediate post-transitional interval. In this report, we focus on the behavior of the geomagnetic field following the Kauai reverse-to-normal (R-N) geomagnetic reversal [Bogue and Coe, 1982; Bogue and Coe, 1984]. We show that the post-transitional field (i.e., just following the *D* transition) had several distinctive characteristics, the most notable of which is unusually high intensity. This evidence, along with results from other transition zones, supports the concept of an extended transitional interval [McFadden and Merrill, 1993], and further widens the scope of observations that can improve our understanding of the reversal process.

Geologic Background

The oriented rock samples used in this study were collected from superposed 4-5 my old basaltic lava flows exposed on Ohaiula Ridge, near Polihale State Park at the western extreme of Kauai, Hawaii. The thin, seaward-dipping lava flows are part of Kauai's main shield-building sequence, now referred to as the Napali Member of the Waimea Canyon Basalt [Langenheim and Clague, 1987]. The sampled flows, all normally-magnetized, directly overlie a ~460 m thick reverse section [Bogue, 1982]. During fieldwork on Ohaiula Ridge, we apparently oversampled thick cooling units and sets of flows erupted in quick succession. In such cases, we combined sequential units with similar paleodirection and intensity into vector groups (VGs).

Although it has not proved possible to determine reliable radiometric ages from lavas of the Napali Member, it is very likely that many were erupted during one of the three short reversed subchrons within chron 3n. The basis for this inference is a radiometric age (3.95±0.05 Ma; Clague and Dalrymple, 1988) from high in the caldera-filling flows (the Olokele Member) that stratigraphically overlie the Napali Member. The upper part of the Olokele Member is reversely magnetized [Bogue, 1982] and so probably formed during chron 2Ar (3.553-4.033 Ma; Cande and Kent, 1992). It therefore seems likely that the reverse section in the Napali Member formed in one of the three immediately preceding reverse polarity intervals, sometime between 4.134 and 4.812 Ma [Cande and Kent, 1992]. If these correlations are correct, then the time represented by the reverse section in the Napali Member is between 118 kyr and 179 kyr. A straightforward estimate of the time represented by the post-transitional record at Ohaiula Ridge (~140 m of section) is therefore 36 kyr to 54 kyr.

Two observations from Ohaiula Ridge, however, suggest that the above figures may grossly overestimate the length of the interval. As shown in Figure 1, the sequence of virtual geomagnetic poles (VGPs) from the section exhibits a fair degree of serial correlation, as if many of the VGs were erupted in steady succession without long hiatuses. Furthermore, the total amount of field variation is quite modest: the flows record only one large swing of the field away from its expected axial dipole orientation. Judging by the Holocene secular variation (SV) in

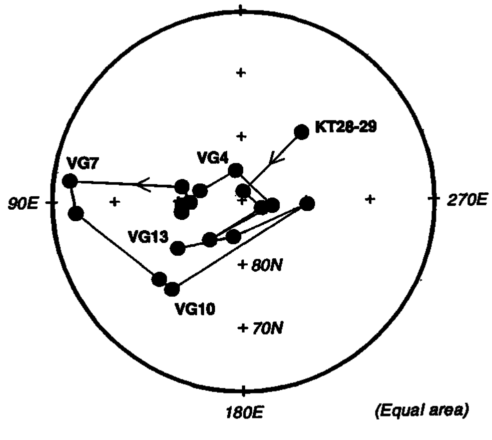

Fig. 1. Post-transitional VGPs at high northern latitudes, calculated for a site at the Hawaiian hotspot (19N, 205E).

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Table 1. Paleomagnetic data from the post-transitional section.

Flows/VG	Dec	Inc	N_d	α_{95}	F_{wm}	N_f	+(-)%	VDM
28/13	346.9	37.4	5	4.3	--	--	--	--
27/12	356.1	41.0	5	3.9	49.9	4	6(7)	10.6
26/11	009.8	41.1	5	1.5	--	--	--	--
25/10	342.3	44.2	5	3.9	--	--	--	--
24/9	341.4	41.1	5	3.2	--		--	--
18-23(22)/8	335.4	16.0	5	3.6	35.8	4	27(18)	09.0
17/7	337.2	06.9	5	3.9	--	--	--	--
16/6	352.3	24.6	5	5.5	--	--	--	--
14-15/5d	352.3	29.2	10	1.8	48.3	4	9(14)	11.3
13/5c	350.3	30.3	5	1.8	44.7	3	17(5)	10.4
10-12/5b	351.0	28.9	15	1.7	50.4	10	17(13)	11.8
6-9(7)/5a	354.6	27.7	5	2.1	31.1	4	1(2)	07.4
4-5(4)/4	001.2	27.1	5	1.6	48.1	3	8(7)	11.4
3/3	004.3	38.5	5	3.7	66.6	3	1(2)	14.5
2/2	353.0	38.8	5	4.0	53.6	2	3(4)	11.6
1/1	002.5	38.0	5	4.4	60.4	3	7(6)	13.2
*KT30-32(30,32)	000.9	32.7	13	0.9	44.4	4	1(1)	10.1
*KT28-29	013.4	24.6	13	1.6	37.5	6	6(9)	09.1

Subset of flows providing paleodirection and intensity estimate for each VG are shown in parentheses. * indicates data from Bogue and Coe [1984]. East declination (Dec) and downward inclination (Inc) of mean of N_d samples; α_{95}: radius of 95% confidence about mean. F_{wm}: VG-mean paleointensity for N_f samples weighted by quality factor Q [Coe et al., 1978]. +% and -% express the percentage range of sample paleointensities about F_{wm} for each VG. VDM is the virtual dipole moment (x10^{22} Am) for a site at the Hawaiian hotspot (19N, 205E).

Hawaii [Holcomb et al., 1986], the Kauai post-transitional record appears to represent several kyr rather than several tens of kyr of geomagnetic field behavior. Even this general inference is somewhat uncertain since there is evidence that the Holocene SV is not typical of the last 5 my [Holcomb et al., 1986]. We therefore tentatively interpret the paleomagnetism of the Ohaiula Ridge section to record field behavior during an interval of 10 kyr or less immediately following the Kauai R-N transition. For comparison, the post-transitional record obtained from the 15 my old basalt flows at Steens Mountain, Oregon [Mankinen et al., 1985; Prevot et al., 1985], may represent some 3.5 kyr of field behavior, an estimate based solely on the amount of SV recorded by the flows.

Paleomagnetic Directions

Partial alternating field demagnetization with peak field strengths in the range 10mT to 40mT effectively isolated the primary thermoremanent magnetizations of the flows. As can be seen in Table 1, the VG directions are determined very precisely, with the average α_{95} [Fisher, 1953] being 3.0°. Table 1 includes two results from the Kukui Trail site [Bogue and Coe, 1984], located about 11 km east of Ohaiula Ridge, where the same post-transitional section is exposed. The direction for KT28-29, which directly overlies reversely-magnetized flows at the Kukui Trail site, is shallower and more easterly than any of those from low in the section at Ohaiula Ridge. This characteristic plus its intermediate paleointensity suggest that KT28-29 stratigraphically underlies VG1 (the lowest normally-magnetized flow at Ohaiula Ridge). Correlation of KT30-32 is more equivocal; its direction and intensity suggest a stratigraphic position between KT28-29 and the lowest Ohaiula unit (VG1) or a higher one near VG4. We have used the lower of these two options in Table 1 and the figures, but emphasize that the conclusions of the study do not depend critically on our choice.

In spite of having just reversed polarity, the geomagnetic field recorded by the Ohaiula Ridge section appears to display ordinary directional dispersion (see Figure 1). Care must be taken when interpreting this observation since the VGPs are serially correlated and their mean (with α_{95}=5.0°) lies 6.3° from the spin axis; it is quite possible that the lavas have not fully sampled the ancient SV. Nevertheless, we parameterize the dispersion by giving each VG unit weight and calculating the angular standard deviation (S) of VGPs from the spin axis [e.g.; McFadden et al., 1988]. For the post-transitional section at Kauai, S=13.4°, a value that is within 0.1° of that expected from model G (fit to paleomagnetic data from post-5 Ma volcanic rocks) of McFadden et al. [1988]. Provided our estimate is within a few degrees of the true value, the directional dispersion following the Kauai R-N resembles that which followed the Steens Mountain R-N [Mankinen et al., 1985; Prevot et al., 1985] about 11 my earlier. There, the observed scatter of VGPs (recalculated to be comparable to the result from Kauai) is 17.0°, just 2.6° below that expected from Model G [for the interval 5 Ma to 22.5 Ma; McFadden et al., 1991]. At Steens Mountain, however, ordinary post-transitional dispersion contrasts sharply with the unusually large directional variation (S=24.8°) displayed by the field just prior to reversing. Current work on a pre-transitional section from Kauai will allow a more complete comparison of these two reversals.

Ancient Field Intensities

In order to infer ancient field intensities from our samples, we used the familiar Thelliers' [Thellier and Thellier, 1959; Coe, 1967] stepwise double-heating experiment with modifications that help make apparent certain forms of thermally-induced magnetochemical alteration [Coe et al., 1978] of the rock specimens. This undesirable alteration manifests itself as a chemical remanent magnetization (CRM) aligned parallel to the low (35μT) field applied at various times during the paleointensity experiment. We monitored the growth of this CRM in each specimen and 1) determined the paleointensity only from a blocking temperature (T_b) interval below the T at which the CRM first exceeds 15% the remaining natural remanent magnetization (NRM) of the specimen and 2) corrected for the small amount of CRM that is present in remanence components used to calculate the paleointensity. Full details of our experimental method will be reported elsewhere.

The results of the double-heating paleointensity experiments are shown on diagrams like those in Figure 2. Each point on the plots corresponds to a pair of heating-cooling cycles to the same temperature: the NRM remaining after cooling in very low (<8nT) field versus the partial thermoremanent magnetization (TRM) acquired by cooling in a 35μT field. Ideally, these points will form a straight line whose slope provides a measure of the ancient field intensity. In practice, however, the line is straight only over a central portion of the T_b distribution, with secondary magnetizations and thermally-induced alterations typically spoiling the low-T_b and high-T_b segments respectively. All samples were heated (in air) from room T to near 600°C. For the 40 samples that yielded usable paleointensities, however, the average linear segment spanned only 191.5° (corresponding to an average of 37.0% the sample's NRM). To calculate flow-mean paleointensities (see Table 1), we have used a weighting factor [Coe et al., 1978] which expresses our preference for segments on NRM-TRM plots that span a large fraction of the specimen's NRM and have points that are both highly linear and evenly distributed along the length of the line. All line segments were defined by at least 5 points.

Figure 3 shows the variation of the ancient field intensity during and after the Kauai R-N transition. The minimum field

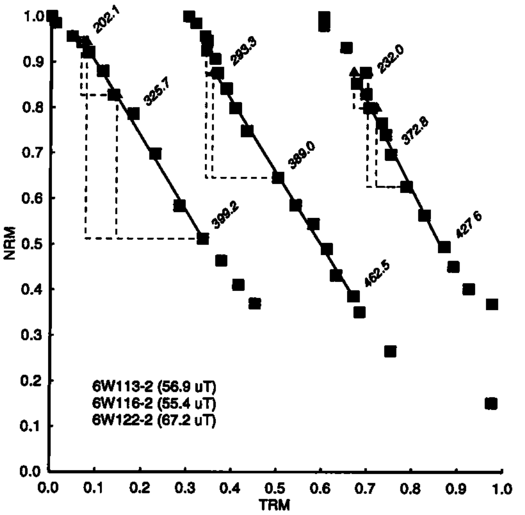

Fig. 2. NRM-TRM diagrams from post-transitional flows recording high paleointensities. Black squares and connecting line denote the linear segment used to determine the ancient field intensity; labels indicate the maximum temperature reached in the two heating cycles for each datum. Dashed lines and triangles show "PTRM checks" (Coe et al., 1978). TRM values for 6W116-2 and 6W122-2 are offset for clarity.

strength recorded during the reversal was 10.1μT [Bogue and Coe, 1984], approximately 28% the field present today at Kauai. From this low, a sequence of eight VGs records an apparently steady, 659% increase in the ancient field strength. Paleointensities from the first two post-transitional units (from the Kukui Trail site) are comparable to the modern field and to the post-5 Ma dipole average [McFadden and McElhinny, 1982]. The three NRM-TRM diagrams in Figure 2, all of relatively high quality, are from two of the next three units that occur upsection (i.e., the lowest flows from the section at Ohaiula Ridge). If the corresponding VG-mean paleointensities are expressed as virtual dipole moments (VDMs; see Figure 4), both exceed the standard deviation of post-5 Ma VDMs and the highest exceeds more than 90% of post-5 Ma VDMs [McFadden and McElhinny, 1982]. Furthermore, these high paleointensities are associated with VGPs that lie within 10° of the spin axis. This evidence suggests that the geodynamo was generating unusually strong dipole field just after entering its normal-polarity state. Following this maximum, the field dropped in strength by over 50%, recovered half this decrease, and then exhibited lower-amplitude variation.

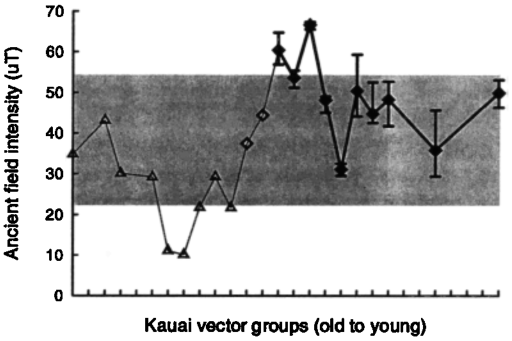

Fig. 3. Field intensity during and after the Kauai R-N transition. Open symbols from Bogue and Coe [1984]; triangles represent transitional data. Error bars show the range of sample values about the weighted mean paleointensity. Shading indicates the range of field strengths (at the latitude of the Hawaiian hotspot) corresponding to the paleomagnetically determined post-5 Ma dipole average (± standard deviation) of McFadden and McElhinny [1982]. The present-day field in Kauai is 36 μT.

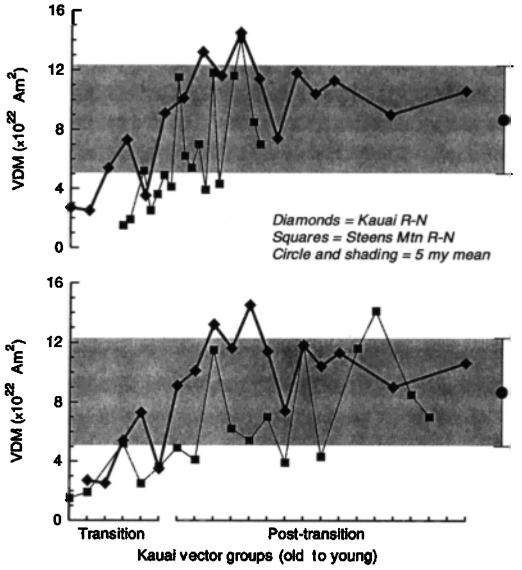

Fig. 4. The intensity recovery for the Steens Mountain and Kauai R-N reversals. Shading as in Figure 3, but for VDMs.

Discussion

Steens Mountain provides the only other detailed record of the variation of absolute geomagnetic field intensity following a polarity reversal. It is difficult to compare these data to those from Kauai because so little is known about the time elapsed between eruptions at either volcano. Nevertheless, the lower part of Figure 4 shows how the two records look after: 1) including transitional data from both records back to the transitional field minima; 2) grouping flows that have very similar paleomagnetic direction or direction and intensity (if available); and 3) aligning the two sequences by correlating the first non-transitional flow-groups from the two localities. The lower half of the figure shows a direct comparison of the two sequences, as if they represent approximately the same amount of time. The upper half shows the comparison with the paleointensity maxima also correlated, as if the Ohaiula Ridge record represents approximately twice as much time as does Steens Mountain. Although straightforward, these two approaches ignore many complications such as the real possibility that the transitional interval is not globally synchronous.

Keeping in mind that the time intervals between VGs are not at all uniform, what can be learned from the comparison in Figure 4? One striking difference between the two records is the amplitude of the intensity variation. Following the return of axial dipole directions, the intensity at Steens Mountain displays two large oscillations before finally rising to its maximum. At Kauai, there is no sign of low VDMs in the post-transitional interval, and the rise to maximum intensity appears nearly monotonic. Prevot et al. [1985] speculated that large intensity oscillations may reflect the instability of the newly established dipole. If so, then the new data from Kauai suggest that this property of the post-transitional dynamo can vary substantially from reversal to reversal.

Perhaps the most striking similarity between the two records is that they both exhibit unusually high VDMs, greater than 14×10^{22} Am^2, in the immediate post-transitional interval. At Steens Mountain, the highest field strengths appear high in the post-transitional section, which as a whole represents about 3.5 kyr of field behavior. At Kauai, where a longer interval of post-transitional field behavior may be recorded, the maximum strength appears low in the section. In both cases therefore, the evidence suggests that the high field intensities lag the first nontransitional directions by less than 10 kyr. Other hints of strong post-transitional field have been reported from volcanic rocks [Hoffman et al., 1989] and deep-sea sediments (J.-P. Valet, pers. comm). It is also interesting that a recent theoretical model [Olson and Hagee, 1990] shows the field intensity at a maximum right after reversal, gradually decreasing afterwards.

Taken as a whole, these observations lead us to hypothesize that a strong post-transitional dipolar field, exhibiting normal directional dispersion, is a systematic feature of geomagnetic reversals. Additional studies of the post-transitional interval will of course be needed to establish a firmer basis for this proposition. It seems clear, however, that such study might provide strong support for McFadden and Merrill's [1993] claim that the geodynamo remains in an unusual state for 45 kyr after the polarity D transition. Their analysis, based on statistical properties of the geomagnetic polarity timescale, reveals that some property of the post-transitional geodynamo inhibits subsequent polarity reversals through the TT interval. They suggest that the inhibition may be associated with the decay of chemical boundary-layer instabilities that play a role in triggering reversals. Alternatively, the inhibition may arise from the evolving conditions that exist in the outer core as magnetic diffusion helps equilibrate the geodynamo in its new stable state [McFadden and Merrill, 1993]. We speculate that the distinctive post-transitional field behavior documented in Kauai and other localities may directly manifest the unusual core properties that inhibit the onset of reversals during the TT interval. Following McFadden and Merrill [1993], it is very plausible that the post-transition geodynamo evolves in such a way that the inhibition is strongest at first and decreases with time. If so, then it is not particularly surprising that the episodes of unusually strong dipole field seem to occur early in the TT intervals following the Kauai and Steens Mountain D transitions.

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