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Evidence suggesting extremely rapid field variation during a geomagnetic reversal

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Large, systematic variations in direction of high-temperature remanence as a function of vertical position occur in a basalt flow from the Miocene volcanic sequence at Steens Mountain, Oregon, that has provided a detailed record of a geomagnetic reversal. These may have been caused by an impulsive change in the transitional field as the flow cooled during the reversal. If this is true, the short time required for the flow to cool by conduction and acquire its thermoremanent magnetization implies astonishingly high rates of change of the geomagnetic field: at least 3° and 300 gammas per day.

1. Introduction

The maximum rate of secular variation in recent times derived from spherical harmonic analysis of globally distributed geomagnetic data is about 150 gammas/yr [1,2]. In the highest resolution paleomagnetic records currently available from sediments, comparably high rates of change of direction of 0.5–2°/yr can be estimated for jumps in magnetic direction of several tens of degrees during geomagnetic excursions [3] and reversals [4,5]. Because of the cut-off in recording resolution imposed by finite deposition rate, nonzero sample size and other factors, however, the actual rates could have been much higher.

Previous publications on the Miocene polarity reversal recorded by basalt flows at Steens Mountain, Oregon, described evidence for two or possibly three episodes of extremely rapid field variation in the geomagnetic field during the transition [6–8]. Such "transitional impulses" were suggested by the occurrence of large gaps in direction of remanent magnetization between successive lava flows that showed no indication of a hiatus in eruptive activity between them. However, the evidence that appeared to be most decisive at the time was the difference found, in two instances at the beginning of the second directional gap, in the direction of remanence between samples thought to belong to the top and middle of the same flow. This was interpreted as demonstrating changes in field direction during cooling and acquisition of primary thermoremanent magnetization (TRM) by these flows. The inferred rates of geomagnetic variation were larger than those quoted above by a factor of 30 or 40.

If real, such impulsive changes in the geomagnetic field have important geophysical implications. However, the samples collected from these flows were not taken with the idea of documenting changes in field direction that may have occurred during their cooling. In this paper we report results from a much more detailed study of another flow, but this time from the first directional gap of the Steens Mountain transition, that we suspected might record another transitional impulse.

2. Sample collection

The lava flow within the first directional gap that is the object of this study is termed B51. It is from the Steens B section, which is 1.5 km south of the Steens A section where, as described above, the flows occur that suggested an extremely rapid

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rate of change for the second gap (see [6, fig. 1 and table 1]). The alternating field cleaned directions of magnetization of specimens taken earlier from flow B51 were highly dispersed, again raising the possibility of rapid field changes [6,7]. However, the samples were too poorly distributed and the number of specimens too few to afford more than a qualitative indication.

In this study we chose a location 25 m south of the previous sampling site, where flow B51 is almost twice as thick and also much less porphyritic. The stratigraphy is straightforward, with no ambiguity in identification of cooling units. The bottom of the flow is fresh and the base sharp, whereas the top 20 cm, although well exposed, is highly vesicular, reddish, and less hard than elsewhere. We drilled seventeen cores in an almost vertical section through the 1.9 m thickness of flow B51, from within 3 cm of the bottom to 15 cm below the top. Owing to the ruggedness of the terrane, the varying orientations and lengths of the cores, and varying thickness of the flow, errors in stratigraphic spacing of successive samples could be as high as several centimeters in some instances, and the uncertainty in position in terms of distance above the base or below the top a little greater.

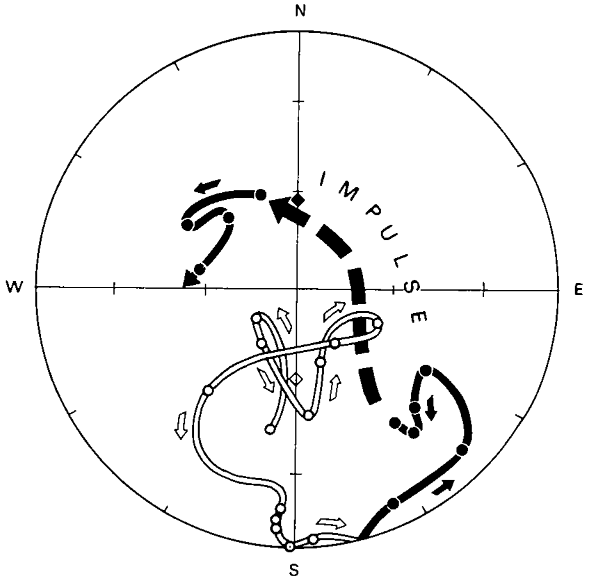

Fig. 1. The first part of the Steens Mountain reversal record [6], a composite from sections A and B showing directions up to the second phase of the transition, including the large directional gap that marks the first geomagnetic impulse [7,8]. Each circle represents a directional average of a group of successive flows that differ insignificantly in direction from one another. Diamonds are the normal and reversed directions for the geocentric axial dipole field at the site. Solid (hollow) symbols denote lower (upper) hemisphere of this equal area projection.

3. Paleomagnetic results

In Fig. 1 we show the first part of the Steens Mountain transitional record, which is composed of results from both the A and B sections and represented in terms of directional groups—that is, directional averages of groups of successive flows that differ insignificantly from each other. The record tracks quasi-continuously from initially reversed directions to southeasterly and down intermediate directions, from which point it jumps 90 ° to a temporary normal direction that is subsequently abandoned in the second phase of the transition. This first, large directional gap is recorded at both sections. Only at Steens B, however, is there an intervening flow (B51) with highly dispersed directions.

The record of this directional gap is illustrated in Fig. 2 by the direction of stable remanence for Steens B flows only. A group of nine flows with similar directions, the last one being B52, precedes the 90 ° jump to the normal direction of flow B50, which is followed by a group of six flows with more westerly and shallower directions that are indistinguishable from one another. Fig. 2 also shows the directions of high-temperature remanence (that remaining after thermal demagnetization to approximately 500 ° C) for each sample from flow B51, the flow that lies stratigraphically between B52 and B50. A remarkable feature of these directions is that they are streaked out in the gap between the directions of flow B52 and B50.

Before discussing this streaked distribution further, we turn to an example of the evolution of remanent magnetization vector of an individual sample during thermal demagnetization. From room temperature to only 175 ° C the natural remanent magnetization (NRM) of this sample declined by 75%, whereas from 175 ° to 535 ° C it fell much more slowly. The low-temperature component was within 10 ° of the present field direction at Steens Mountain, and thus is presumably viscous in origin (VRM). The large size of this

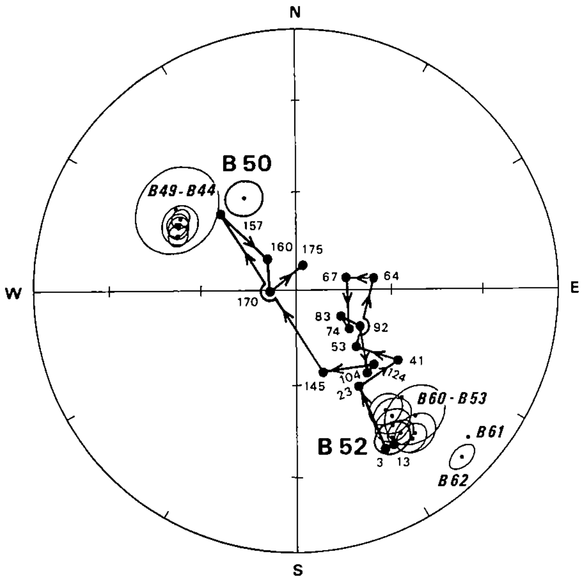

Fig. 2. The first large directional jump during the reversal, as recorded at Steens Mountain section B. Flow-mean directions with their associated 95% confidence limits are shown by small dots. The forward direction of time in the lava flow pile corresponds to decreasing numbers, and the directional jump occurs between flows B52 and B50 (heavy α_{95} circles). Large dots are directions of remanence of samples from the intervening flow B51 after demagnetization to approximately 500 ° C, with heights (in cm) of samples above the base of this 190 cm thick flow indicated alongside and lines with arrows connecting the samples in ascending order. Note that these directions tend to fill in the gap in direction between flows B52 and B50, and that there is a strong serial correlation between vertical position in flow B51 and these directions. See text and Fig. 4 for interpretation.

component relative to its NRM reflects mainly the fact that the earth's field at the time of cooling and initial magnetization of this sample was much weaker than the recent field that produced the VRM.

The direction of remanent magnetization changed with progressive thermal demagnetization throughout almost the entire range of unblocking temperatures, as illustrated by the vector component diagram in Fig. 3B. We have omitted points corresponding to temperatures below 300 ° C, choosing this relatively high cut-off to eliminate the possible influence of a "tail" in the distribution of VRM unblocking temperatures. The direction of the component removed during demagnetization changes from north and steeply down to southeast and moderately down as the temperature increases. We can see this more easily in Fig. 3C in terms of vector differences. We see also that the vector difference shifts from a direction nearer to that of the underlying flow B52 at the highest temperatures to a direction closer to that of the overlying flow B50 at lower temperatures. Such a tendency is generally representative of samples from the lower 70% of flow B51, with the exception of the vector differences of the two samples nearest the base, which cluster near the direction of flow B52 at all but the lowest temperatures.

Returning now to the streaked distribution of the high-temperature remanence directions of the

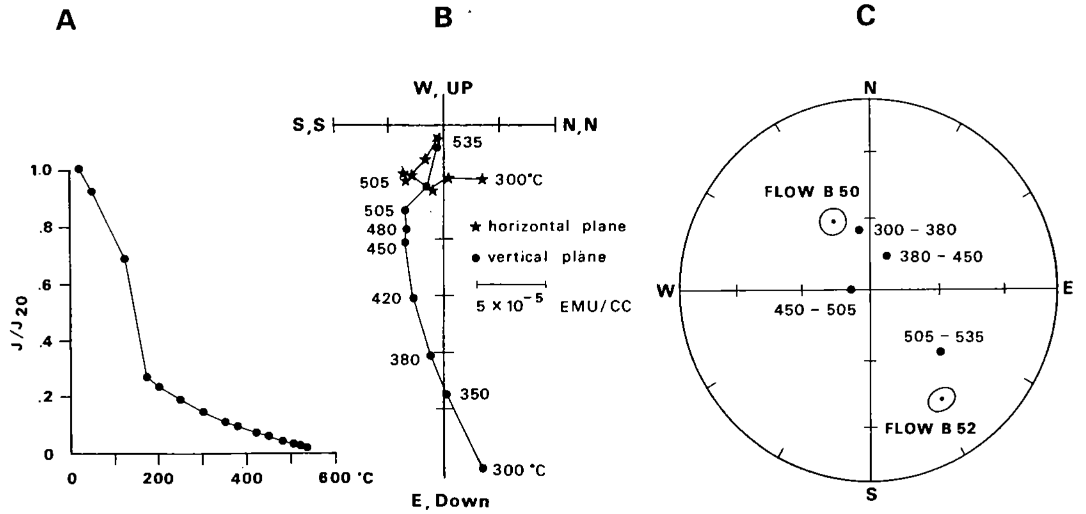

Fig. 3. Thermal demagnetization of a sample from flow B51, 41 cm above its base. A. Fraction of NRM remaining after each thermal demagnetization step; note rapid drop up to 175 ° C corresponding to loss of VRM. B. Vector component diagram [20]. C. Vector difference directions (solid circles), with temperature intervals indicated alongside; note that higher-temperature directions move away from direction of overlying flow (B50) toward that of underlying flow (B52).

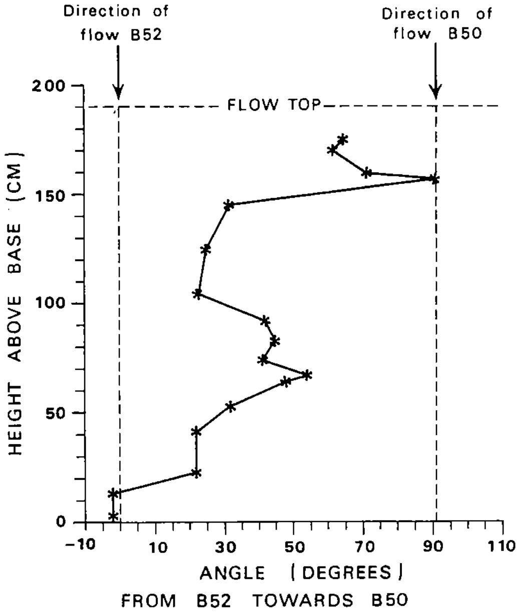

Fig. 4. Angular progression of high-temperature remanence direction of samples of flow B51 away from the underlying (B52) flow direction toward the overlying (B50) flow direction, as a function of their height above its base. The angle in this figure was obtained from Fig. 2 by projecting the direction for each sample onto the great circle containing the B52 and B50 flow directions, and then measuring its angular distance along the great circle from B52 toward B50. The swing toward B50 and then back toward B52 in the lower two-thirds of the flow may be a result of an extremely rapid change in field direction during cooling of B51, whereas the swing toward B50 in the upper part may be caused by baking of B51 by B50.

entire collection of samples (Fig. 2), we draw attention to a strong serial correlation between this direction and vertical position in the flow. Fig. 4 illustrates this relation more clearly in terms of the angular progression of the high-temperature remanence direction as a function of height above the base of the flow. To make this figure we projected this direction for each sample onto the great circle containing the B52 and B50 flow directions, and then measured its angular distance along the great circle from B52 towards B50. Starting at the bottom of flow B51 in Fig. 4 and progressing upwards, the high-temperature remanence direction moves first away from the direction of B52 roughly toward that of B50, then back closer to B52, and finally close to B50. The total range of angular variation is 90°, with individual swings of 30–60°.

4. Interpretation

The highly unusual distribution of the direction of remanent magnetization within flow B51, as well as its systematic movement during thermal demagnetization of a single sample, demands an explanation. The large variation of high-temperature remanence with position in the flow is very unlikely due to measurement error; the moments are relatively large, about 0.002 emu on average, comprising on average 35% of the remanence with unblocking temperature higher than 300°C. Three simple possibilities occur to us to explain the results: (1) baking by the overlying flow; (2) incompletely removed VRM; (3) rapid variation of the geomagnetic field direction during cooling and acquisition of primary remanence.

Baking provides a first-order explanation for the largest angular deviations exhibited by the four highest samples (Figs. 2 and 4). We expect reheating by the overlying flow B50, which is also about 2 m thick, to produce a secondary TRM component parallel to that recorded by B50 that would fall off rapidly with depth in flow B51. (We do not understand why the directions of high-temperature remanence of the top three samples are not as close to the direction of B50 as is that of the fourth highest sample. Perhaps it has to do with alteration of the flow, which is visible at the top.) Secondary TRM caused by reheating cannot, however, explain the variation in direction of the other samples (Fig. 4), with the possible exception of the fifth highest sample. In particular, the trend away from the direction of B50 with increasing height shown by samples between 67 and 104 cm from the bottom in flow B51 (Figs. 2 and 4) is the opposite of what would be expected by this hypothesis.

VRM acquired in the normal field of the last 0.7 My, if not completely removed by demagnetization, could produce streaking of the remanence direction something like that shown in Fig. 2. Indeed, the samples do have a large viscous component, but the sharp break in slope of the demagnetization curve that is so prominent in Fig. 3A suggests that almost all the VRM resides in unblocking temperatures less than 175°C. Thermal demagnetization on 185 specimens from about 73 Steens Mountain lava flows, carried out in the course of paleointensity experiments [8], also supports this view. Moreover, the streaked directions that we must explain reside in remanence with even higher unblocking temperatures (above 500 ° C), and display a correlation with vertical position in the flow that is not easily accounted for by this hypothesis.

If, shortly after emplacement of flow B51, the geomagnetic field direction were changing rapidly from the direction of flow B52 roughly toward that of B50, we can explain the paleomagnetic data quite naturally. The systematic variation of high-temperature remanence direction with vertical position in the lower 70% of the flow (Figs. 2 and 4) would be expected because cooling proceeds from the top and bottom margins inward. In particular, the relative maximum in angular deviation toward the direction of B50 would occur at a position below the midpoint of flow B51 (see Fig. 4) because more heat is lost through the top than the bottom. The primary record of the more quickly chilled margins has been obliterated at the top by baking, as discussed above, but at the base the two lowest samples exhibit invariant high-temperature remanence directions indiscernible from that of the underlying flow. This would require that the rapid change in field direction began after the base of the flow had cooled to 500 ° C. In a different vein, the streaking of remanence directions in individual samples (e.g., Fig. 3C), characterized by directions of higher temperature remanence closer to that of the underlying flow than those of lower temperature remanence, is also just what would be expected by the rapid field variation hypothesis.

Assuming that flow B51 really did record a part of the directional jump, we can use cooling models to estimate the rate of variation of the field. A very simple model (e.g. [9]) suffices to calculate a reasonable value of the cooling time of basaltic sheets, as shown by Shaw et al. [10] using actual temperature measurements from the island of Hawaii. Suppose that at time zero a thin sheet of constant thickness and thermal diffusivity is emplaced at its melting temperature on a thick pile of material of identical diffusivity and uniform ambient temperature. The upper surface of the sheet is held constant at the ambient temperature, latent heat of crystallization is neglected, and cooling is by conduction only. Choosing a diffusivity of 0.006 cm^2/s, which was the average value used successfully by Shaw et al. [10], we find that the entire sheet would cool to 500 ° C or below in about 15 days. This is 16 times shorter than the previously estimated time for cooling of the Steens A flow from which was obtained the rate of change of the field during the second transitional impulse [6,8]. The lesser thickness of flow B51 accounts for a factor of 4 in the discrepancy. The remaining factor of 4 derives from approximations made previously that the heat lost through the base does not appreciably alter the cooling rate at the center of the flow and that the center cools the slowest.

If the lowest two samples (3–13 cm above the base of flow B51) cooled to 500 ° C instantaneously, then the 45 ° difference in remanence direction between them and the five interior samples (64–92 cm above the base) would have been recorded within 15 days. This period is undoubtedly an overestimate because the basal 13 cm would not have cooled instantaneously. Nonetheless, even this conservative figure of 15 days corresponds to an astonishingly rapid rate of variation of the geomagnetic field direction of 3° per day. There are few paleointensity estimates in this part of the section, but values of 0.06 Oe from flow B54 below and 0.15 Oe from flow A60 above the directional jump show that the field was weak. Using the lower value of 0.06 Oe the minimum estimate of the vector change during cooling of flow B51 is 4500 gammas at an average rate of at least 300 gammas/day.

The rapidity and large amplitude of geomagnetic variation that we infer from the remanence directions in flow B51, even when regarded as an impulse during a polarity transition, truly strains the imagination, prompting us to search for alternative, rock magnetic explanations beyond the two most obvious possibilities that we dismissed above. By addition of complicating factors involving chemical changes, both the baking and the unremoved VRM hypotheses can be stretched to explain the thermal demagnetization data. Chemical changes throughout the body of flow B51 during emplacement of the overlying flow B52—for instance, as might be brought about by pervasive hot fluids—could produce a CRM parallel to the direction of B52 whose unblocking temperature spectrum strongly overlapped that of the primary TRM. In a similar vein, chemical changes occurring in the laboratory during thermal demagnetization—for instance, by oxidation of titanomagnetite—could raise the unblocking temperature of VRM acquired during the Brunhes normal epoch. In either case, the secondary remanence might then be impossible to separate cleanly from the primary TRM by thermal demagnetization and could produce a streaked distribution of directions similar to that in Fig. 2. Both hypotheses, however, require special pleading to explain the relationship between the high-temperature remanence direction and vertical position in the flow. Nonetheless, we are currently conducting an investigation into the magnetic properties and mineralogy of these samples to double-check these and other alternatives. We will report the results of these studies fully when they are concluded, but so far we have not found convincing evidence for any such hypotheses.

Thus, the balance of evidence now in hand weighs in favor of rapid geomagnetic field variation. The question then arises whether the source of this variation was inside or outside of the earth. The rate of change (at least 300 gammas/day) is much greater than the secular variation of the internal field observed in modern times. On the other hand, the amplitude of the change that occurred between the eruption of flows B52 and B50 (at least 8000 gammas) is much greater than most external field variations, although it is possible that enhanced external activity might accompany the decrease in dipole field intensity that takes place during polarity reversals. The coherent progression of the change in direction from one close to those recorded by the underlying nine flows towards those recorded by the overlying seven flows, however, is difficult to rationalize with external field variations, unless the external field played more than a transient role during the polarity inversion.

5. Conclusions

We think that the most probable explanation of the anomalous remanence directions of flow B51 is the occurrence of a large and extremely rapid change in the geomagnetic field during cooling of the flow, and that this change most likely originated in the core. This interpretation must remain tentative until our investigation is completely finished, but, if true, it has important implications for the reversal process and the state of the earth's interior. Detailed discussion of the implications would be premature, but we would like to make a couple of comments at this time. Firstly, inasmuch as recent analyses of secular variation suggest fluid velocities near the core–mantle boundary as high as a few tens of kilometers per year [11,16], the very rapid change indicated by our data could imply much higher velocities of the order of 1 km/hr. Secondly, for such a high-frequency signal to reach the surface of the earth, the upper bound on electrical conductivity models of the mantle would have to be 4–5 times lower than that permitted by recent analyses of the "geomagnetic jerk" of 1969-70 [17]. Determinations of electrical conductivity at very high pressures and temperatures in a diamond-anvil cell by Li and Jeanloz [18] show that this upper bound could be easily satisfied by a lower mantle composed of (Mg,Fe)SiO_3 perovskite phase, with or without magnesiowüstite, but not by a D″ layer at the base of the mantle greatly enriched in iron, as might be the case if the core had reacted with the mantle [19].

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