New evidence for extraordinarily rapid change of the geomagnetic field during a reversal

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Palaeomagnetic results from lava flows recording a geomagnetic polarity reversal at Steens Mountain, Oregon suggest the occurrence of brief episodes of astonishingly rapid field change of six degrees per day. The evidence is large, systematic variations in the direction of remanent magnetization as a function of the temperature of thermal demagnetization and of vertical position within a single flow, which are most simply explained by the hypothesis that the field was changing direction as the flow cooled.

THE Steens Mountain reversal record, dated radiometrically at 16.2 Myr before present[1], has long held the reputation as the best recording of a polarity transition by lava flows[2]. A detailed study[3–5] found 56 distinguishable flows with stable direction of magnetization intermediate between normal and reversed. Figure 1 shows this record, which can be divided into two parts. In the first, the field moves from stable reversed polarity through transitional directions to temporary normal polarity. In the second, the field retreats from the short-lived episode of normal directions back to intermediate directions that are similar to those attained before, and then successfully completes the transition to normal polarity directions via a different route.

An interesting aspect of the record is the three large gaps, two of which occur in the second part (Fig. 1). Because we did not observe obvious signs at the outcrop of a lapse in eruption rate at any of the gaps, and because flows within two of the gaps yielded anomalously scattered directions for no apparent reason, we suspected originally that the field may have changed unusually rapidly during the time of the gaps[3–5]. Re-study of the flow in the first gap yielded evidence strengthening our suspicion, suggesting that the field may have changed extraordinarily rapidly (3° or 300 nT per day)[6]. However, we could not completely rule out unremoved viscous magnetization as a possible alternative explanation. In this Article we focus on the second gap, recorded in a parallel section 1.5 km to the north, where the field jumped about 80° from westerly to southeasterly declinations (Fig. 1*b*). As we shall show later, viscous contamination is not a tenable explanation for the surprising results we obtained, nor do several other alternative thermal and rock-magnetic hypotheses stand up to scrutiny.

The new section

To carry out this study we moved 250 m north along the cliff from the original section A, tracing two prominent flows A38 and A39 (directional group 21 of Fig. 1) that outcrop continuously, to a place where the underlying flows are particularly well exposed and could be sampled vertically (section D, Fig. 2). There, these flows are laterally continuous on a scale of 100 m, in contrast to some of those in the same stratigraphic position at the original location, which pinch out within a few metres of the sampled sections. Thus some of these flows are probably not precisely the same units as at the original section, although a cover of rubble between the two places prevented us from verifying this directly. Nonetheless, just as was the case at the previous

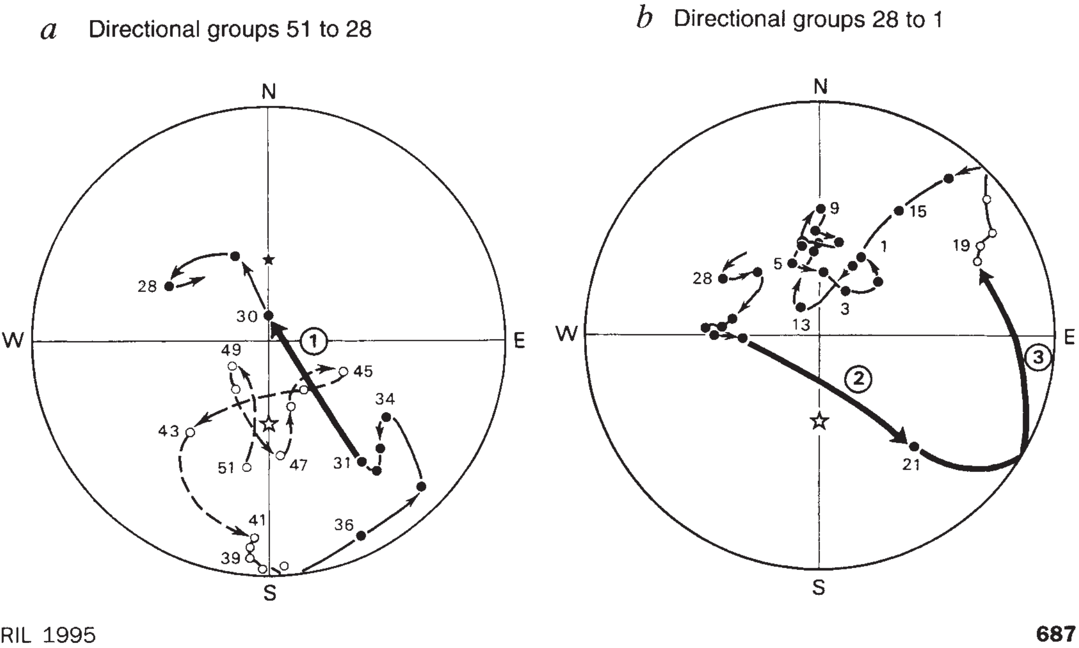


FIG. 1 The Steens Mountain directional record showing the three large jumps or gaps (encircled numbers). The projection is equal area, and each point is a directional group that represents one to nine consecutive flows with indistinguishable directions. Stars denote normal and reversed geocentric axial dipole directions. Filled (open) symbols are plotted on the lower (upper) hemisphere. *a*, First part of record: field direction moves from stable reversed to transitional to temporary normal. *b*, Second part of record: field direction moves from temporary normal to transitional to stable normal.

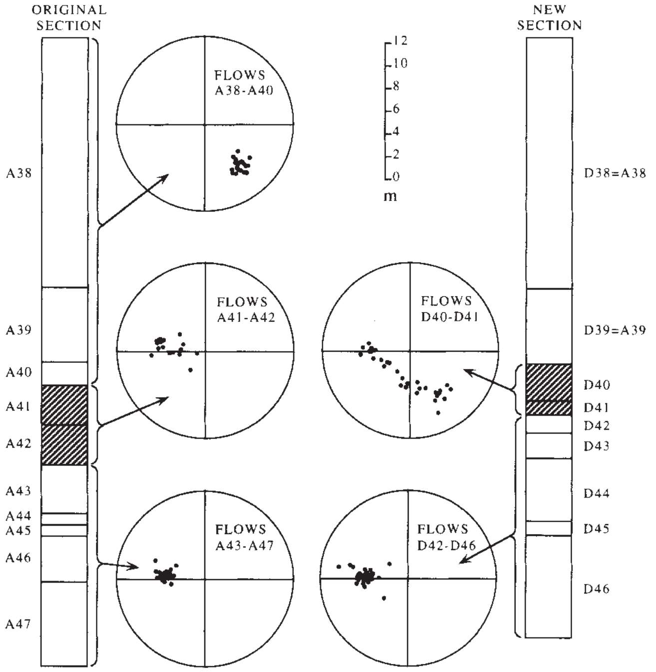


FIG. 2 Natural remanence directions after thermal demagnetization to 500 °C of samples from flows within the directional gap (shaded), which display anomalous scattering, and from pre-jump and post-jump flows. At the new section, where each flow was sampled along a vertical profile, flow D41 and D40 directions smear out all the way between the directions of the underlying and overlying flows. At the original section[3], where horizontal coverage was stressed more than vertical sampling, flow A42 and A41 directions are nonetheless significantly smeared, with Fisher[38] precision parameter $k=29$ as compared to $k=196$ and $k=156$ for the pre- and post-jump flows below and above, respectively.

locality, the two flows D41 and D40 immediately underlying the prominent marker flows A39 and A38 fall within the same directional gap and display anomalously scattered directions of high-temperature remanence, which smear out between the tightly clustered directions of the flows immediately below and above (Fig. 2). Moreover, in contrast to samples from their margins and from other flows, many samples from the interior of flows D41 and D40 fail to reach a stable endpoint during thermal demagnetization; instead, their directions tend to rotate from southerly towards westerly declinations as the temperature progressed beyond 300 °C (Fig. 3*a*).

Even more remarkable, however, is the systematic variation of direction of high-temperature remanence of samples within flows D41 and D40 as a function of their vertical position (Fig. 3*b*). From bottom to top in the lower two-thirds of flow D41, the direction moves from near that of underlying flow D42 (pre-jump direction) about 60° towards that of the overlying flow A39 (post-jump direction), and then back to the flow D42 direction again. The swing in direction is corroborated in sections 2 m to the south and north, which overlap the bottom and top of the principal section. A similar but smaller swing occurs in the lower one-third of flow D40, but above that all samples exhibit stable endpoint directions that are close to those of the overlying flow.

Rapid-field-change hypothesis

A simple hypothesis to explain these results is that when flow D41 was cooling through its magnetic blocking temperatures, the geomagnetic field was moving from the pre-jump direction recorded by flow D42 towards that of the post-jump direction recorded by flow A39. This accounts very naturally for the change in remanence direction away from that of the overlying flow towards that of the underlying flow during progressive thermal demagnetization of individual samples (Fig. 3*a*). It also explains the observed variation in direction of high-temperature remanence with vertical position in the flow (Fig. 3*b*), because the more slowly cooled interior of flow D41 records directions that are further from that of the underlying flow.

The similar but less pronounced swing shown in the lower part of flow D40, which picks up approximately where that in flow D41 leaves off, suggests that it was erupted shortly after D41 was emplaced, probably even before D41 had completely cooled. The samples higher in D40 appear to have been remagnetized by the overlying flow A39, because they all maintain directions close to those of A39 at every demagnetization step above 350 °C. They also exhibit titanomagnetite-granulation textures in polished thin section under reflecting light that are characteristic of hydrothermal alteration[7]. This texture is absent in the lower third of D40 and all of D41, suggesting that flow D40 may have protected D41 from being remagnetized by the hydrothermal action of the much thicker A39.

Experimental observations of cooling basaltic lava on the island of Hawaii demonstrate that simple conductive calculations can describe the evolution of temperature with time reasonably well, especially when an effective thermal diffusivity of $k = 6 \times 10^{-7}$ m^2 s^{-1} is used to take account of average vesicularity and other second-order factors[8]. The characteristic cooling time for a thin sheet of constant thickness and thermal diffusivity held at constant temperature at its boundaries is $t=a^2/k$, where a is half the thickness[9]. For flow D41, which is 1.3 m thick, this gives only 8 days, suggesting an astonishingly fast rate of change of field direction of the order of 10° per day. This rapid change apparently did not occur as a result of vanishingly low geomagnetic intensity during the directional jump. Palaeointensity experiments conducted previously[5] yielded estimates of the transitional field intensity that decrease from 10 to 7 μT for the three pre-jump flows, remain at 7 μT for the two anomalous flows in the jump (samples from the quickly chilled flow margins), and increase from 4 to 13 μT for the three post-jump flows overlying the jump. Thus the ancient field strength during the cooling of anomalous flow D41 was probably about 7 μT, which would require a rate of change of total field around 1 μT per day to account for the directional rate.

Alternative hypotheses

This rate is so extraordinary, of the order of 1,000 times faster than that directly observed in secular variation of the geomagnetic field[10], that we are obliged to consider carefully any alternative hypotheses that might account for our results. These are of two general classes: thermal (that is, simple baking or multiple cooling units) and rock magnetic (that is, anisotropic remanence acquisition, viscous contamination or chemical remagnetization).

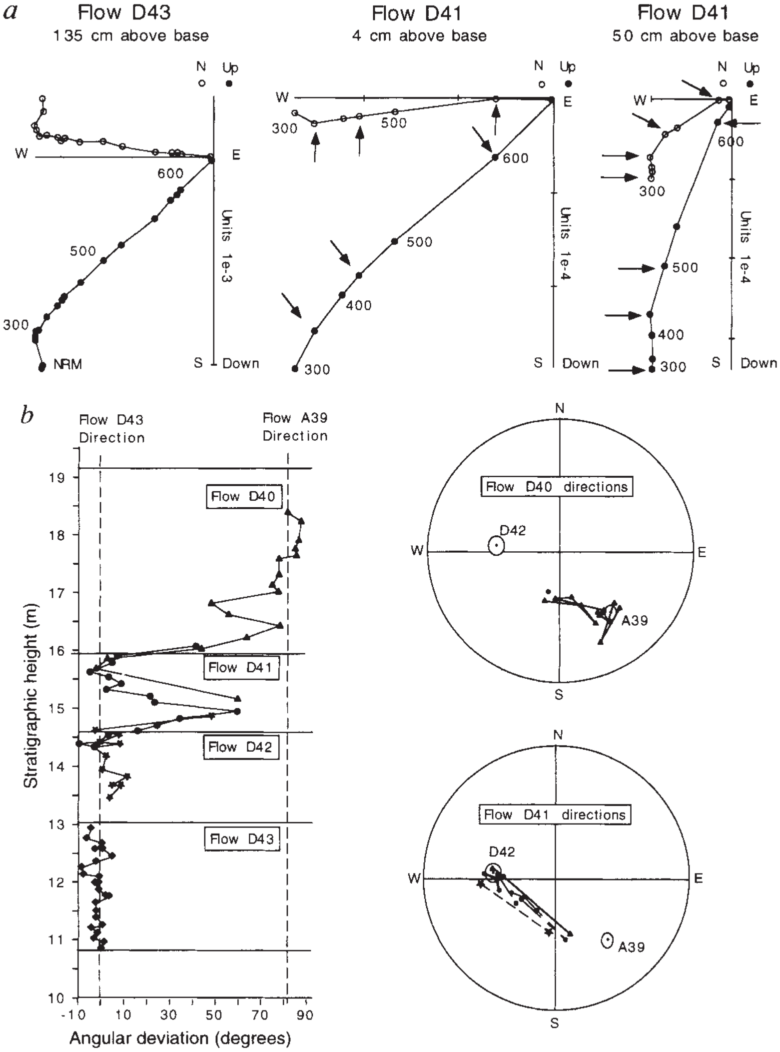
Baking. Hypotheses involving simple baking by the overlying flow are beset by serious difficulties. Thermal demagnetization experiments show that only the upper two samples of flow D41 were significantly remagnetized by the overlying flows, exhibiting appreciable angular deviations of remanence between 300 and 500 °C from the pre-jump towards the post-jump direction. Beyond 500 °C thermal demagnetization, the directions of the six upper samples are very similar to the pre-jump direction, which implies that the upper 60 cm of the flow was not reheated above that temperature. Below 60 cm, the directions display the peak in angular deviation with depth (Fig. 3*b*) that gives rise to the rapid-field-change hypothesis. For this signature to have been caused instead by baking, the middle part of the flow would have to have been reheated to higher temperature than the upper 60 cm, which is of course unrealistic.

Multiple cooling units. More flexibility is afforded by the hypothesis that flow D41 was erupted as more than one cooling unit. To account for the directional signature of flow D41, any later-erupted unit would have to intrude the first horizontally, thereby delaying cooling of the interior relative to the margins. Examples of such behaviour are known from observations of modern eruptions, but unless intrusion occurs before most of the first unit has crystallized the two units do not weld at their boundaries and the compound nature of the flow is apparent (G. P. L. Walker, personal communication). No internal boundaries of this kind are present in any section of flow D41 that we have examined, suggesting that if any such intrusion occurred, it was when the interior of the first unit of D41 was well above the solidus temperature. Thus most of the two units would still have cooled as one through the remanence blocking range. This conclusion is reinforced by microscopic examination of polished thin sections of samples in flow D41 for indications of relative cooling rate. The average maximum size of titanomagnetite crystals shows a simple trend, with its maximum in the central part (Fig. 4*a*). Moreover, the proportion of dendritic titanomagnetite, indicative of degree of undercooling, is maximal (near 100%) at the top and bottom boundaries and decreases progressively inwards.

Magnetic anisotropy. Preferred orientation of magnetic minerals and their easy axes of magnetization can deflect the direction of thermoremanence away from the ambient field[11,12]. To cause the large deviations of remanence directions, however, this mineral fabric would have to be exceptionally strong in the interior and weakened progressively toward the boundaries. On the contrary, the fabric of flow D41 is extremely weak throughout and inconsistent in orientation: susceptibility anisotropy is small (<0.5%) and bears no relation to the angular deviation of remanence. Furthermore, thermoremanent magnetization imparted in the course of palaeointensity experiments[5] to four samples of the anomalous flows from the original section deviated from the applied field by no more than a few degrees.

Viscous contamination. Our experience with Steens and other basaltic lavas is that the viscous overprint impressed by the present normal polarity Brunhes epoch is effectively eliminated

FIG. 3 *a*, Vector component diagrams illustrating how the direction of natural remanent magnetization (NRM) of samples from the interior of flow D41 (right) rotates from southerly toward westerly declinations during progressive thermal demagnetization above 300 °C, whereas that from samples near the margins (centre) and from lower flows (left) decay straight towards the origin with constant direction. Points are the projection of the remanence vector on the horizontal (open circles) and N–S vertical (filled circles) planes, and the numbers beside them are demagnetization temperatures in °C. Arrows denote unblocking temperature intervals used in the conductive cooling computation[16] summarized in the text. *b*, Angular deviation of remanence after thermal demagnetization to 500 °C as a function of vertical position of samples in flows through the second directional jump (left); equal-area projections showing the full direction of samples from flows D41 and D40 after demagnetization to 500 °C (right). Angular deviation for each sample is the angle measured from the pre-jump direction (D42) toward the post-jump direction (A39) after projecting its direction onto the plane containing the flow D42 and A39 mean directions. Different symbols denote different vertical profiles within a horizontal distance of 10 m. Note the large swing in direction in flow D41 towards and away from A39 and the smaller such swing in flow D40.



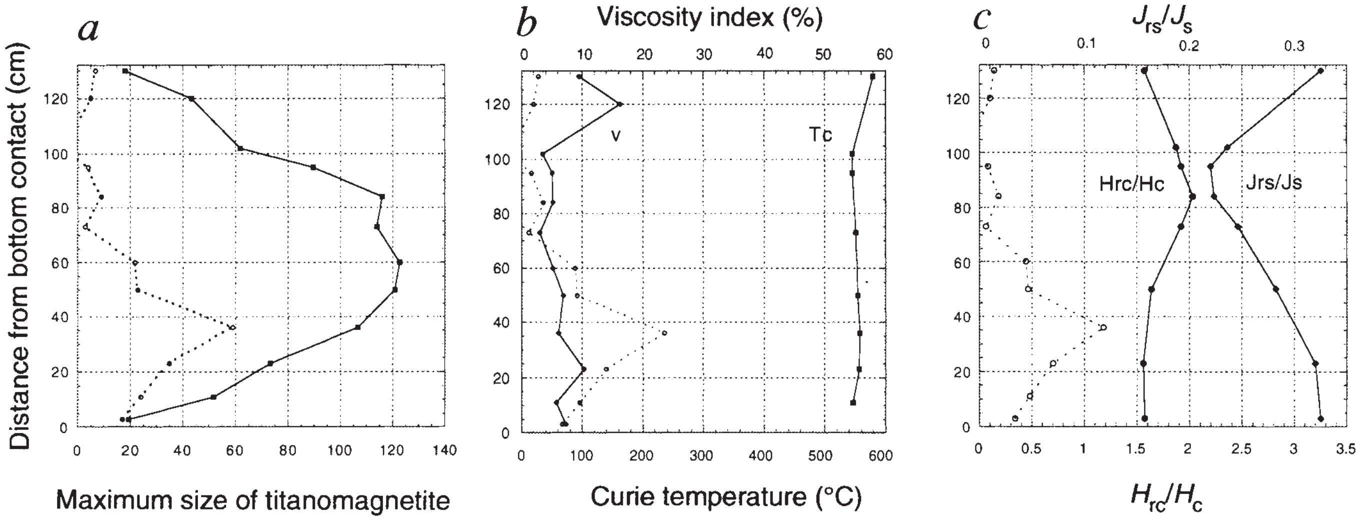


FIG. 4 Magnetic properties of samples (solid lines) through the critical flow D41 as a function of vertical distance above the bottom contact. Angular deviation of remanence (see Fig. 3*b*) also shown (dotted line) for reference. *a*, Average maximum grain size (μm) of titanomagnetite crystals (not size of remanence-carrying magnetite particles—see text). *b*, Curie point T_c and viscosity coefficient *V*. *c*, Hysteresis parameter ratios indicative of magnetic grain size (J_{rs}/J_s = saturation remanence/saturation magnetization; H_{rc}/H_c = remanent coercivity/coercivity).

after demagnetization at temperatures ranging between 150 and 300 °C. The overlying flow direction and that of the normal axial dipole field are far apart in the second jump, making it implausible that Brunhes viscous remanence could play any role in the observed pattern of directions in flow D41. To test the possibility that a more ancient unremoved viscous component (imparted by thermal enhancement of magnetic viscosity after the thick overlying flows A39 and A38 were emplaced) could explain the vertical distribution of remanence direction in flow D41, we measured the viscosity index, defined as the ratio of viscous remanence acquired in the ambient field in approximately two weeks to the stable natural remanent magnetization. It is low throughout the flow (generally <10%) and not correlated with the angular deviation of remanence (Fig. 4*b*), indicating once again that viscous remanence is not a viable explanation.

Chemical remanence. A similar but less easily discounted class of hypotheses is that a moderate rise in temperature or hydrothermal activity accompanying the emplacement of post-jump flows A39 and A38 might have caused some kind of partial chemical remagnetization of flow D41. Because chemical alteration can produce remanence with unblocking temperatures much higher than the temperature at which it occurs[12], a chemical remagnetization could have unblocking temperatures that strongly overlap those of the original thermoremanence. But as there is no *a priori* reason why such effects should be peaked at the centre of a 0.7-m zone of lava in the lower half of the flow rather than increasing steadily upwards or being concentrated along unit boundaries or cracks at the top and bottom, this interpretation needs to be supported by mineralogical observations or rock-magnetic data to be convincing.

Despite considerable effort, we have found no such evidence to support this hypothesis. A detailed account of our observations and magnetic experiments will be published elsewhere, but we summarize here the most important results. In thin section under the petrographical microscope, flow D41 appears to be a common basalt, rich in plagioclase and olivine. Olivine is partially altered to iddingsite. Titanomagnetite grains are subdivided by lamellae of the usual trellis type, typical of deuteric oxidation (that is, oxidation during original cooling) at high temperature. Thermomagnetic curves in low field indicate single Curie points close to 555 °C and are reversible within 10–15%. This is consistent with the impression, gained by microscope observations, of a simple magnetic mineralogy dominated by iron-rich titanomagnetite. There is no significant variation of Curie point with vertical position in the flow (Fig. 4*b*). About 5% of the natural remanence has blocking temperatures above 600 °C, signalling the presence of titanohaematite, which is also a typical product of deuteric oxidation.

Magnetic hysteresis parameters should also provide clues whether magnetochemical changes occurred that could have caused the angular deviations in flow D41. In particular, the ratios of saturation remanence to saturation magnetization and remanent coercivity to coercivity (Fig. 4*c*) are very useful indicators of effective magnetic grain size. They demonstrate that the magnetic grains in flow D41 are pseudo-single-domain or interacting single-domain, not multidomain[13]. They are smallest at the top and bottom and reach a maximum 85 cm above the base, well above the anomalous angular deviations of direction and somewhat above the height at which the largest titanomagnetite grain size was observed microscopically. There is no contradiction with this latter observation, because the lamellae produced by the deuteric oxidation/exsolution process subdivide the titanomagnetite host grains. Thus the effective magnetic grain size is controlled by this process, rather than by the overall size of the titanomagnetite grain. It is important as well to emphasize that for magnetite grains like ours having J_{rs}/J_s (saturation remanence/saturation magnetization) ratios larger than 0.2, the blocking and unblocking temperatures of any partial thermoremanent magnetization (PTRM) are the same[14]. Even after allowance for the difference in rate of cooling in nature and rate of heating in the laboratory[15], for such fine-grained particles the blocking temperature in nature of a given PTRM cannot be much larger than the unblocking temperature in the laboratory.

To sum up, we have failed to unearth any variation in composition, phase or grain size of magnetic minerals as a function of vertical position that would suggest that magnetochemical changes occurred preferentially in the lower third of flow D41 during the emplacement of post-jump flows A39 and A38. Although this negative result does not prove that the anomalous deviations in remanence directions we found there could not have been caused by some chemical mechanism, as yet unknown and for which we can find no clue, this is obviously not a satisfying explanation. Moreover, as described above, we did find both microscopic and magnetic evidence for magnetochemical alteration of the upper 60% of flow D40 by the overlying flow or

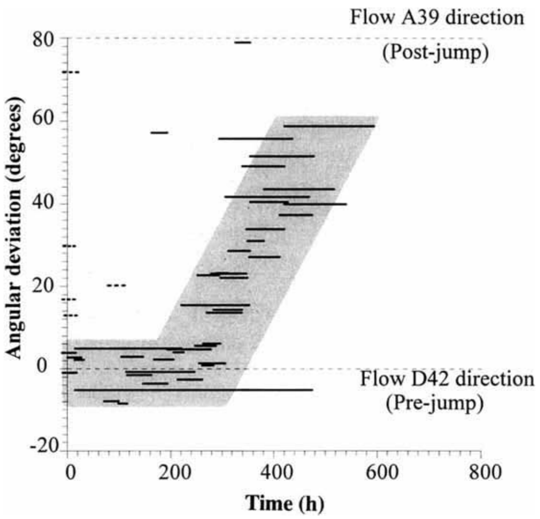


FIG. 5 Conductive cooling analysis by Camps *et al.*[16] of the palaeomagnetic data reported here, assuming the rapid-field-change hypothesis. The analysis yields a rate of change of geomagnetic field of 6 ± 2° per day, as suggested by shading (see text). Angular deviation of direction obtained by thermal demagnetization of samples from flow D41, measured from the underlying (D42) flow direction toward the overlying (A39) flow direction, is plotted as a function of time elapsed since beginning of cooling (see text). Each bar indicates the time interval during which each direction of magnetization was blocked. Dashed bars correspond to samples near the flow top that were reheated by the overlying flow. (Figure adapted from ref. 16.)

flows. This alteration decreased in intensity downward, as would be expected, and did not affect the lower part of D40 or any of D41. Finally, we point out that flow B51 in the first directional gap, for which we reported earlier[6] a similar pattern of angular deviation to D41 in the lower half (though not in the upper half because baking was much more pronounced—see Fig. 4 in ref. 6), has quite different magnetic properties from flow D41. Its magnetic mineralogy is more complex, with most samples exhibiting low-, intermediate- and high-temperature Curie points, and its magnetic grain size and magnetic viscosity are considerably larger. Therefore, it is unlikely that one rock-magnetic explanation could account for the vertical distribution of directions in both flows, whereas the single hypothesis that the geomagnetic field direction was changing extremely rapidly as they cooled can do so very naturally.

Conductive cooling calculations

For these reasons we return to the hypothesis of rapid field change during cooling to enquire whether it can explain quantitatively the thermal demagnetization results from flow D41. A calculation using the analytical error function solution[9] for conductive cooling of a thin lava sheet emplaced instantaneously at 1,140 °C on a thick pile of already-cooled lava, and with its upper surface held at constant ambient temperature, predicts that the sample in flow D41 taking the longest time to cool to 500 °C (about 6 days) would be the one which displays the largest angular deviation in Fig. 3*b*. This agrees with the rapid-field-change hypothesis. Numerical computation employing a more realistic model, which allows for temperature-dependent diffusivity, latent heat of crystallization released over a range of temperatures, and variable vesicularity with depth in flow D41, shows for a range of cases that the last sample to cool to 500 °C would be either that with the largest angular deviation or the next lower sample, and that the cooling time would be between 6 and 16 days (ref. 16). Figure 5 shows a fit of this model to well defined remanent directions of PTRM in flow D41 for unblocking intervals above 300 °C. One to four (on average, three) PTRMs from all samples in the three vertical profiles through the flow are included. The model assumes that as the flow cooled, each element of PTRM faithfully recorded the instantaneous field direction, and, as discussed above, that the blocking temperatures for each element are equal to their unblocking temperatures during thermal demagnetization. The time elapsed from when the flow began to cool until it cooled through the upper and lower blocking temperature of each PTRM is calculated and plotted against the angular deviation of PTRM direction. Thus the total magnetic recording interval plotted is the span of time over which various samples in flow D41 were cooling through magnetic blocking temperatures between 680 and 300 °C.

The general trend in Fig. 5 is consistent with a simple model in which the field remained stationary during the first half of the magnetic recording interval and then moved from the pre-jump towards the post-jump direction at a rate of 6 ± 2° per day. The fit to the data is reasonably good. Only seven PTRMs lie off the general trend. Five of those are shown as dashed bars in Fig. 5 because they are from samples in the upper 22 cm of the flow that were clearly remagnetized by baking, as discussed earlier, and so can be excluded. This is probably the case for the sixth, which is the lowest-temperature PTRM from the next sample down, still only 30 cm below the top. We have no explanation for the seventh outlier, which is the 525–575 °C PTRM from the sample deep within the flow that shows the peak in angular deviation in Fig. 3*b*.

There are two main aspects of our data that cannot be fitted by the idealized cooling models we have employed. The first, just mentioned, is the sharply peaked form of the angular deviation as a function of vertical position (Fig. 3*b*). We cannot dismiss it as an artefact due to a single outlying point because it is corroborated by two other samples from partially overlapping sections. The second aspect is the quantitative relationship of the angular deviations in the lower third of flow D40 to those in D41. The magnetic data suggest that D40 cooled quicker, and baked the top of D41 less, than the simple models predict. Previous workers have also noted the surprisingly small extent to which lava flows have reheated those underlying them[17]. This indicates that the assumption of cooling proceeding from an initially uniform temperature throughout the flow just after emplacement must be significantly incorrect. Such would be the case if appreciable heat were lost during the process of emplacement, as more sophisticated modelling indicates[18], or if a later pulse of magma were injected into a previous flow unit erupted shortly before, as mentioned briefly above. Indeed, the slight changes in slope of the maximum-grain-size curve (Fig. 4*a*) around 25 and 100 cm above the base of flow D41 could conceivably be a result of such a two-stage emplacement process. These complications notwithstanding, the general compatibility of thermal demagnetization data for flow D41 with the simple conductive cooling model is an argument in support of the rapid-field-change hypothesis.

Broader implications of rapid field change

If this hypothesis is correct, it may imply that rapid jumps of field direction occur many times during reversal of polarity. If only three occurred during the reversal recorded at Steens Mountain, corresponding to the three gaps labelled in Fig. 1, and if it took several thousand years to complete, as believed to be the cases for this reversal[3] and for reversals in general[19,20], the probability of one of the 56 transitional lava flows cooling through its magnetic blocking range during one of these jumps is a few tenths of a per cent. The Steens Mountain section records two such occurrences. Thus it would either have to be an exceptionally rare recording, or many other rapid changes of field direction occurred that were not recorded. Perhaps there were extended intervals when the field jumped repeatedly, either randomly or in an oscillatory manner, or perhaps many isolated jumps occurred. Because of the fragmentary nature of lava flow records and the decade or longer time resolution of sedimentary records, these possibilities are difficult to prove or disprove.

Whether such rapid jumps of the geomagnetic field might be generated externally is an open question. It has been suggested that during the reversal recorded at Steens Mountain, when the internally generated field was weak, enhanced external field activity due, for example, to greater penetration of charged particles from the Sun[21] might somehow cause the jumps. Although attractive because of their ability to produce rapid field change, a difficulty inherent in all such external mechanisms is that the fast swing in direction occurred between relatively stable beginning and ending directions. In other words, at the second directional gap, the field must have maintained the pre- and post-jump directions for several tens of weeks at a minimum, enough time for two flows spanning 28 m and five flows spanning 18 m (Fig. 2) to be erupted and cool. It is hard to understand how such long-lived directions anchored to the Earth could be produced by the external field, and even harder to imagine how the external and internal fields could work in concert to produce the jump in direction.

On the other hand, one must ask whether magnetic screening due to the electrical conductivity of the mantle would permit such a rapid field change to be observed at the surface if it were generated internally. The conductivity of rocks near the surface is so low that their screening is negligible, but electromagnetic-induction studies have long suggested that conductivity increases significantly with depth in the mantle[22,23]. Several recent studies suggest that this increase may occur at the phase transition at 660 km depth, reaching an average value of the order of $1\ \mathrm{S\ m^{-1}}$ in the lower mantle[24–27], which is lower by a factor of 10–1,000 than believed earlier. Laboratory measurements of conductivity of presumed lower-mantle minerals at high pressure and temperature are consistent with these low estimates[28] or are even lower[29,30]. For such a mantle conductivity profile ($0\ \mathrm{S\ m^{-1}}$ above 660 km depth, and $1\ \mathrm{S\ m^{-1}}$ below), we calculate that the characteristic smoothing time[31,32] for an impulsive change in magnetic field of spherical harmonic degree 1 and 6 at the core–mantle boundary is 20 and 6 days, respectively. We consider that a degree of more than one is more realistic because such rapid changes at greatly diminished field intensity suggest a local, non-dipolar source. Thus the rates of change inferred from our data are not incompatible with present estimates of mantle conductivity. Moreover, it is widely held that mantle conductivity is laterally heterogeneous on a large scale[33–37], which would allow such rapid signals to be observed at the Earth's surface above regions of low conductivity even if the average were considerably greater than $1\ \mathrm{S\ m^{-1}}$.

Concluding remarks

The large-amplitude directional deviations of remanent magnetization within single lava flows reported here, and their unusual dependence on both vertical position and unblocking temperature, are unique in our experience. Their occurrence in two flows at two different locations and stratigraphic positions where large jumps occur in the Steens Mountain record is probably not coincidental. Putting aside for the moment that field changes 1,000 times more rapid than observed for the modern field are implied, the hypothesis that the reversing field changed several tens of degrees in direction during the cooling of these flows is by far the most natural and satisfying explanation of our observations. Even though such extraordinary rates of change are inescapable under this hypothesis, it still seems preferable to any rock-magnetic explanation that we can imagine, each of which proves to be severely contrived when examined closely and tested with measurements of magnetic properties.

This is not to suppose that geomagnetic reversals take place much more quickly than the several thousand years currently supposed, but rather to suggest that polarity transitions may be punctuated by episodes of extraordinarily rapid field change. An internal origin is not excluded by recent estimates of mantle conductivity, whereas an external mechanism cannot easily account for the relatively long-standing pre- and post-jump directions. Thus such rapid signals may well originate in the outermost core. □

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