How the geomagnetic field vector reverses polarity

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A highly detailed record of both the direction and intensity of the Earth's magnetic field as it reverses has been obtained from a Miocene volcanic sequence. The transitional field is low in intensity and is typically non-axisymmetric. Geomagnetic impulses corresponding to astonishingly high rates of change of the field sometimes occur, suggesting that liquid velocity within the Earth's core increases during geomagnetic reversals.

The Steens Mountain (Oregon) reversed-to-normal polarity transition is probably the most detailed record of a reversal of the geomagnetic field reported from a volcanic sequence. This Miocene reversal occurred 15.5±0.3 Myr ago and can be correlated with the lower boundary of marine magnetic anomaly 5 B2 (ref. 4). We have completed an extensive palaeomagnetic study of the Steens Mountain reversal to obtain a precise, detailed description of fluctuations in absolute palaeointensity of the geomagnetic field as it reverses. In the course of this study, we also obtained a more complete description of the directional changes during this reversal. These directional and palaeointensity data place new major constraints on the reversing Earth's dynamo.

Field and laboratory methods

We collected slightly over 1,000 oriented samples from three almost completely sampled sections, A, B and C, of the upper two-thirds of the Steens Basalt. Sections A and B are located only 1 km apart on Steens Mountain (42.63° N, 241.43° E) and are readily correlated by matching the transitional field directions. Taken together, these two sections span the end of the pre-transitional reversed period, the transition and the post-transitional normal period. Samples from section C (42.18° N, 240.07° E), located 130 km to the south-west of Steens Mountain, are reversed with the exception of those from the top flow, which display a transitional direction also observed on Steens Mountain at the start of the reversal. The main eruptive centre was probably close to Steens Mountain, and the reversed part of Section C is believed to be older than the reversed zones sampled at the bottom of sections A and B, on the basis of the sequence of palaeomagnetic directions. The composite section obtained by combining sections A, B and C is 615 m thick and consists of ~120 distinct lava flows, which are numbered within each section from the top to the bottom.

The palaeodirection of the field was calculated from the remanence direction after either alternating field or thermal cleaning. After grouping successive flows with the same average direction of remanence, the Steens record consists of 55 directional groups (also numbered from the top to the bottom) of which 12 are reversed, 29 are transitional and 14 are normal (Fig. 1).

The absolute palaeointensity of the field was determined using the method of Thellier and Thellier. Although time-consuming, this method is preferable because it relies on experimentally well-established physical laws and a sound theoretical background. In addition, the method allows palaeointensities to be determined without the direct heating of samples to high temperatures required by other methods, which usually result in major magnetochronological changes. We selected 185 samples for palaeointensity investigations with low viscosity index, high Curie point and reversibility (or near-reversibility) of the strongfield magnetization curve versus temperature. These criteria proved to be pertinent. We obtained 157 useable palaeointensity values corresponding to 51 vectorial groups (group of successive flows with the same directions and palaeointensities).

Vectorial description

The transitional state of the geomagnetic field vector may be defined as corresponding to successive vectors of which either the directions or intensities (or both) are outside the range of secular variation observed in the adjacent pre- or post-transitional periods. Using this criterion, the end of the transition corresponds to directional group (DG) 15 whose direction and intensity are both transitional (Fig. 2). The beginning of the reversal was recorded by DG 43, which displays the first transitional palaeointensity (Fig. 2). However, the direction of the field at the same time was only 27° away from that of the reversed dipole (Fig. 1) and may be considered to be within the range of secular variation. Thus, transitional palaeointensities seem to have shortly preceded the transitional directions, which were recorded by the immediately following directional groups. In contrast, normal directions and intensities were recovered simultaneously at the end of the reversal.

Records of secular variation before and after the reversal were used to obtain a crude estimate of the duration of the transition. We assumed that these records are essentially complete because of the high extrusion rate needed to record the field reversal in such detail. A review of archaeomagnetic results shows that the angular rate of change of the virtual geomagnetic pole, when calculated from 2,000 yr BP to the present, is almost the same (6±1° per 100 yr) for areas as widely separated as Europe, North America and Japan. Assuming that this rate can be used for the Miocene, we found that the reversed and normal records in the Steens Basalt correspond to periods of 5,000 and 3,500 years, respectively. The corresponding accumulation rates of flows at Steens Mountain (sections A and B) are the same (43±4 m per 1,000 yr) for the pre- and post-transitional zones, which makes it reasonable to estimate the duration of the reversal from the thickness of the transition zone (190 m). Hence, the transition period lasted ~4,500 yr, with an uncertainty of ~1,000 yr.

The pre-transitional reversed period is characterized by an average palaeointensity of 3.1±0.95 μT (±2σ,d.). This mean is ~30% lower than the expected Miocene field at the site, as calculated from 49 independent palaeointensity data from all over the world, obtained using the Thellier method. We interpret this difference, significant at the 95% confidence level, as resulting from a long-term decrease in the dipole intensity before the reversal. The rather large fluctuations of the field direction before the transition (Fig. 1) support the idea of a relative decrease of the dipole with respect to the non-dipole terms before the reversal. This pre-transitional dipole decrease would have lasted at least 5,000 yr.

In contrast, the intensity of the post-transitional normal field (46.7±20.1 μT) is not significantly different from the expected average Miocene field. However, large and apparently rapid intensity fluctuations are observed during this ~3,500-yr-long record (Fig. 2), which may reflect some instability of the newly re-established dipole.
Fig. 1 The Steens Mountain directional record. Stereographic projection (true angle) of the rotated field direction of the successive directional groups. Directions are rotated by 28.5° about the east-west horizontal axis to bring the dipole field directions coincident with the poles of the projection sphere. The reversal angle varies from 0° (reversed dipole direction) to 180° (normal dipole direction), and corresponds to lines of equal 'latitude' on the projection sphere. Lines of equal 'longitude' correspond to pseudo-declination, which is measured in the 'equatorial' plane from the projection of the north-seeking direction into this plane. A purely axisymmetrical field would have a pseudo-declination equal to 0 or 180°, which corresponds to near-sided or far-sided virtual geomagnetic pole paths, respectively. Directional groups are indicated by a near circular track on most of the circles representing the successive average field directions. With few exceptions (see Fig. 3), 95% confidence semi-angles are only a few degrees and could not be drawn on this diagram. Full circles and solid path are on the hemisphere of the projection sphere which contains the pole of projection (reversal angle 90°, pseudo-declination 150°); empty circles and broken path are on the opposite hemisphere.

The major feature of the Steens Mountain transition is the succession of two distinct phases (Fig. 1). The first phase is a reversed-transitional-normal flip that apparently lasted no more than ~1,500 yr because of the thickness of the recording zone. The second phase is a normal-transitional-normal ‘rebound’ which probably lasted twice as long. The apparently brief period of time between these two phases during which normal dipole-like directions occur is marked by an increase in field intensity back to pre-transitional values (Fig. 2). Thus, we interpret these directions as corresponding to a briefly re-established dipole configuration.

During phases 1 and 2, we found very low values of geomagnetic intensity with several minima close to 5 μT. The average intensity of the typically transitional field vectors, that is, the 18 vectors directed more than 45° away from the unsigned dipole direction, is 10.9 ± 4.9 μT. This is about one-fifth of the intensity of the non-transitional Miocene field. We observe also that the r.m.s. values of the north-south, east-west and vertical components of these transitional vectors are of a comparable order of magnitude with those of the historical non-dipole field at the latitude of the site. Figure 2 shows that there is a fairly regular westward movement of the field vector as the reversal develops, which strongly suggests that at least part of the transitional field is longitudinally drifting.

**Transitional geomagnetic impulses**

Three large directional jumps are observed during the transition (Fig. 1), amounting to ~90° differences between successive pairs of directional groups. This is in marked contrast to most of the Steens Mountain record, where successive angular differences are more often close to ~20°, suggesting a detailed sampling of the transitional field. Although we first interpreted these jumps as a result of some intermission in the eruptive process, further observations suggested that they instead reflect some large and very rapid changes (geomagnetic impulses) of the field. The most convincing evidence comes from the second impulse, which is recorded in section A from flows A46–A43 (DG 24) to A40–A38 (DG 21). Two lava flows, A42 (DG 23) and then A41 (DG 22), erupted at the beginning of this impulse. After magnetic cleaning, the top and middle of both of these flows possess distinctly different directions of magnetization (Fig. 3). Considering the chronology of the flows and their directions of remanence, these differences are not caused by reheating by the overlying flow. Field evidence also eliminates differences resulting from volcanological processes such as filling of lava tubes or rotation of magnetized blocks during eruption.

The directions of natural remanent magnetization can sometimes be extremely scattered, even antipodal, within a flow interior because of some secondary chemical remanent magnetization developing after the cooling of the flow. In the only such example yet reported, thermal cleaning at high temperature allows the recovery of the direction of primary remanence. In contrast, natural remanent magnetization directions in the interior of both flows A41 and A42 are not extremely scattered before or after magnetic cleaning (Fig. 3). The directions of magnetization of the near-surface samples do not change significantly during either alternating field or thermal cleaning. Most of the blocking temperature ranges of these samples are between 500 and 550 °C, whereas the interior samples display a distribution of blocking temperatures between 20 and 600 °C. However, after destroying some secondary magnetization directed towards the present-day field, directions found at high...
temperatures (~500 °C) in the interior samples are not different from those obtained by alternating field cleaning, and their cleaned directions remain obviously different from those of the near-surface samples (Fig. 3). Thus, the remanence of the interior samples seems to be primary in origin, having been acquired at high temperature during flow cooling.

Therefore, we interpret the distribution of directions observed in flows A42 and A41 as resulting from a geomagnetic impulse occurring during the cooling of these flows. The near-surface directions of flows A42 and A41 yield an average inclination of 45.4°, a declination of 279.5°, with α95 = 3.1°. This direction differs from the interior average directions of flows A42 and A41 by 16 ± 11° and 34 ± 13°, respectively (95% confidence intervals). To estimate the rate of change of the field during the impulse, we need to know the cooling history of the flows. This is only possible for flow A41, which must have acquired its magnetization before being covered by the subsequent flow which has a different magnetization direction. Assuming that the primary remanence was acquired at ~500 °C, and according to temperature measurements in Hawaiian lava lakes14, we find that ~8 months should have elapsed between the time that the top and the middle of this 4-m-thick flow became magnetized. The angular rate of change would have then been ~60°yr⁻¹. The 95% confidence interval given here corresponds only to the uncertainties about directions, neglecting those about the cooling time, which are large but difficult to estimate. Four palaeointensity values were obtained from flows A42 and A41. Their arithmetic average is 7.1 ± 0.9 μT, indicating that this impulse occurred when the field intensity was very low. The corresponding rate of change of the field vector during the impulse would have been 6.7 ± 2.7 μT yr⁻¹.

There is similar, though qualitative, evidence that the first directional jump (Fig. 2) also corresponds to a geomagnetic impulse. The possibility that the third jump also results from an impulse cannot yet be demonstrated.

General characteristics

Comparison of sedimentary records of the Brunhes-Matuyama reversal obtained from various locations on the globe indicates that the transitional field is not dipolar15,16, insofar as the reversing field is faithfully recorded in the rocks studied. To describe the transitional fields in more detail, one has to turn to volcanic rocks, which are much more reliable recorders of both the direction and intensity of the field. Indeed, only volcanic rocks allow the determination of both the 'instantaneous' field direction and absolute palaeointensity. A consideration of the new

Fig. 2 The Steens Mountain vectorial record, showing average inclination, declination and intensity (logarithmic scale) of the geomagnetic field calculated for groups of successive lava flows which do not differ significantly in direction or intensity. a, b, 65 data points, some of which correspond to subdivisions of the directional groups within which intensity varies significantly between successive lava flows. c, 51 data points corresponding to the vectorial groups defined in the text. Group numbers 15 and 43 are indicated by the representative points. Average values are plotted versus thickness from the top of section A (2,950 m), so that time develops from the left to the right on the diagrams. No samples were collected between 410 and 560 m from the top. Error bars in c are s.e.m.; no bar indicates a single intensity determination. Uncertainties about inclination and declination are too small to be represented.

Fig. 3 Lambert equal-area projection of the cleaned directions of remanence of individual samples from lava flows A41 and A42, which erupted during the second geomagnetic impulse, and average directions of some pre- and post-impulse lava flows. Average directions are indicated by crosses with the corresponding α95 circles: solid circles, flows A41 and A42; broken circles, pre- and post-impulse lava flows. The pre-impulse directional path (broken line) is recorded successively by flows A45, A47, A46 to A43 and the tops of flows A44 and A42. Two successive records of the field direction during the impulse are provided by the interiors of flows A42 and A41. The post-impulse field direction is recorded by the overlying lava flows A40 to A38.
data from the Steens Mountain reversal together with other data from transitions recorded in Cenozoic volcanic sequences confirms that transitional fields are low in intensity and suggests that these fields have three other major characteristics: importance of non-zonal terms; occurrence of rapidly damped oscillations; and geomagnetic impulses.

The Steens Mountain data confirm that palaeointensity of the geomagnetic field is low during reversals and suggest that a long-term dipole decrease precedes the transition. We did not find any evidence of the large intensity value thought to occur at the start of the first phase of the transition. To what extent the average intensity of transitional fields found at Steens Mountain (\(\sim 11 \, \mu T\)) is typical is unknown because there are no comparable studies. Note that the average palaeointensity calculated from Cenozoic field reversals and excursions recorded in volcanic sequences from Iceland is only 5.5±3.1 \(\mu T\) (ref. 15), which suggests that average transitional palaeointensities are latitude dependent.

The importance of non-zonal components during the Steens Mountain reversal can be qualitatively understood from Fig. 1. Only sectorial or tesseral spherical harmonics can account for any deflection of the field direction from the north–south vertical plane (corresponding to pseudodeclination of 0° or 180° in Fig. 1). The second phase of the transition, which is also the longest, exhibits the directions that are the farthest from the geographical meridian. Considering the transition as a whole, the vector density of typically transitional directions (that is, >45° away from the unsigned dipole direction) is at a maximum for angular deviations between 30 and 40° from the geographical meridian (Fig. 4). Thus, most of the Steens Mountain transition is not axisymmetrical, which is a general characteristic of Cenozoic reversals (Fig. 4). As well as the Steens Mountain reversal, data from the 71 directional groups in Fig. 4 correspond to transitions recorded by volcanic sequences in North America\(^{16,20}\), Iceland\(^{21,22}\), Japan\(^{23}\) and Africa\(^{24}\). Vector density is at a maximum for angular deviations between 40 and 70° from the geographical meridian, in marked contrast to the distribution of non-transitional field directions which would have typically displayed a maximum for a deviation of zero. The observed distribution indicates that, on average, east–west (non-zonal) components of transitional fields are at least as important as the components lying within the geographical meridian. As the latter components are a combination of zonal and non-zonal terms, this suggests that zonal and non-zonal components of transitional fields are of the same order of magnitude.

Thus, during polarity transitions, the geomagnetic field not only loses its dipolar morphology but also its axisymmetry. Similarly, the present-day non-dipole field does not show any predominance of zonal terms. The absence of a purely zonal morphology for transitional fields is compatible with the suggestion that the frozen-flux approximation is valid during reversals\(^{25}\). However, this agreement does not imply that flux diffusion is negligible over the full time of a reversal. In particular, the beginning of the Steens Mountain reversal, which seems to be only moderately non-zonal (Fig. 1), could result from ohmic decay within a geodynamo temporarily inoperative as a consequence of the axial symmetry\(^{26}\).

The notion that the transitional state of the geodynamo corresponds to an oscillating field was proposed by Braginsky\(^{27}\). In contrast, more recent models suggest that the field reverses in a progressive way, through either some spreading of the reversal over the core surface\(^{12,28}\) or by reversible energy transfer from the dipole to non-dipole terms\(^{29}\). The entire directional path observed during the Steens Mountain transition can be interpreted as corresponding to a rapidly damped oscillation of the field. Although other records of reversals by volcanic rocks are not as detailed as the Steens Mountain record, examples have been reported in which the field reverses polarity and then comes back to its initial polarity before reversing again, even in such incomplete records\(^{19,30}\). Such observations favour models of the geodynamo that allow a highly damped oscillatory state of the geomagnetic field during reversals.

The geomagnetic impulses occurring during the Steens Mountain transition can be considered as impulses of the first order time-derivative of the field. They may be interpreted as large and possibly global changes of the field configuration with time constants of the order of 1–2 yr. By comparison, we note that the same order of magnitude has been proposed recently for the smoothing time of the 1969 impulse resulting from filtering by the mantle\(^{31}\). The rates of change of the field components during the Steens Mountain transitional impulses would have been very large. For the second impulse, the rates of change of the three components would have been between 15 and 50 times larger than the maximum rates calculated for the historical non-dipole field\(^{32}\).

Obviously diffusion of field lines cannot explain such rapid changes; even for harmonic degrees as large as 10, the decay time is still equal to a few hundred years\(^{33}\). Larger-degree harmonics with decay times of the order of a few years require implausibly large fields at the core–mantle boundary. Under the frozen-flux approximation, however, the transitional geomagnetic impulses can be accounted for by a large increase in fluid velocity at the core surface. This suggests an increase in the level of turbulence within the liquid core during reversals. This increase in kinetic energy can be of thermal origin, resulting from too steep a thermal gradient within the core for a convective regime to be preserved\(^{34}\). Alternatively, this increase can result from a decrease in magnetic energy. We have shown that, on average, the intensity of the geomagnetic field at the Earth's surface reduces to one-fifth of its normal value during the Steens Mountain polarity transition. If the field intensity within the core also decreases during reversals, the liquid can become more unstable as part of the magnetic energy is transferred into kinetic energy\(^{35}\).

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