Successive palaeomagnetic reversal records from Kauai

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Geomagnetic field reversal is a rapid phenomenon\(^1,2\), perhaps taking only a few thousand years. Knowledge of how the field behaves during these brief and active periods may eventually help to constrain theories of the geodynamo and thus inform us about conditions in the Earth's core. Unfortunately, reliable and detailed palaeomagnetic records of transitional field behaviour are few, almost entirely from Northern Hemisphere sites, and heavily biased toward reversals of the reverse-normal (R–N) sense. We report here new data from basaltic rocks on the island of Kauai, Hawaii, which have recorded successive R–N and N–R field reversals. The sequences of changing field directions for the two reversals are very similar, as would be expected if a standing nondipole component controlled the transitional field. The data are also consistent with zonal flooding models in which the reversal process depends on the sign of the field. Other reversal records, however, cannot be explained by these same models unless the standing field or flooding process changes between some reversals.

Two simple models of the reversing field have been proposed in the past 5 years\(^3,4\). The two involve conceptually different source mechanisms and, in their purest forms, make distinct predictions of transitional field behaviour. Although it is possible that no single process controls transitional fields, we will treat these two models as alternative explanations of palaeomagnetic records of field reversals.

Hoffman's model\(^5,6\) of the reversing field is based on the notion that the reversal process 'floods' through the fluid core from a localized zone or point of initiation. The entire dipole source remains active, but normal and reverse flux is produced simultaneously in different regions. The resulting transitional field depends on how the reversal process propagates through the dipole source. If the reversal initiates at either of the poles or the equatorial zone of the core, essentially axial quadrupolar or octupolar fields, respectively, will predominate during the middle stages of the reversal process. In these purely axisymmetric cases, reversal of the field vector at the Earth’s surface occurs by rotation in the north-south vertical plane; the equivalent virtual geomagnetic pole (VGP) moves along the great circle defined by the geographical poles and the observer's site. Depending on the sense of the reversal, where in the core source region the reversal process initiates, and the hemisphere of the observer, the VGP path for the reversal will be 'near sided' (same longitude as the site) or 'far sided' (180° away).

In contrast to the model of Hoffman, which we will refer to as the flooding model to emphasize its active character, is the standing field model\(^6\). The latter is a special case of the long-held idea that, during reversals, the main dipole field diminishes greatly while at least parts of the nondipole field do not. In particular, the standing field model requires a stationary component of the nondipole field to persist unchanged through dipole reversals. Palaeomagnetic evidence suggests that the dominant part of the nondipole field changes sign with the dipole field\(^7\). Thus, the postulated standing field would have to be in some sense independent of both the dipole and the rest of the nondipole fields.

In the standing field model, the transitional field at any site is the sum of a steady nondipole component plus an axial dipole component that changes only in magnitude and sign. As with simple cases of the flooding model, the equivalent VGP paths are longitudinal great circles. There is, however, no site dependence of path longitude unless the standing nondipole field direction everywhere lies in the north-south vertical plane.

Hoffman\(^8\) has recently proposed a test to distinguish between the flooding and standing field models. The former model predicts that, as long as a reversal is initiated at the same zone in the core each time, successive reversals will be characterized by transitional VGP paths that differ in longitude by 180°. The latter predicts identical VGP paths for successive reversals. Records of back-to-back reversals thus directly test the two models.

On the island of Kauai, Hawaii (22°N), we have collected samples through R–N and N–R transition zones. The thin, shield-building basaltic flows of the Nahali Formation (Fig. 1), which record the R–N reversal, have yielded K–Ar ages ranging from 4.5 to 5.6 Myr (ref. 11). The thicker, caldera-filling flows of the Olokele Formation (Fig. 1) have not been dated, but can be shown on geological grounds\(^12\) to be synchronous with the upper portion of the Nahali sequence. The transition zones in the Nahali and Olokele Formations, however, are at nearly the same elevation. In addition, extensive reconnaissance with a portable fluxgate magnetometer has shown that all Nahali flows exposed above the R–N horizon and all Olokele flows below the N–R horizon are normally magnetized. It is thus very likely that the two transition zones record a back-to-back, R–N–R reversal pair from the early Pliocene.

Equal-area plots of the flow-averaged palaeomagnetic directions from the two transition zones are shown in Fig. 2. Seven samples per flow were collected, and alternating fields of 100–200 Oe reduced substantially any secondary components of magnetization that were present. We sampled the R–N transition at three widely separated localities (Fig. 1), and the sequence shown in Fig. 2a is based on the simplest correlation of directions from the three sections. We sampled only a single section of the N–R transition because of the thick, horizontal character of the caldera basalts.

Neither transition zone displays an abundance of intermediate field directions. This lack of detail may be interpreted as the result of ill-timed tulls in volcanic activity both times the field was reversing. An alternative hypothesis is that the duration of intermediate field directions was very short. Our observation that contacts between flows were almost never marked by weathered zones or soil horizons supports the latter idea. In addition, the palaeomagnetic results show clearly that the three sections across the Nahali reversal horizon are not identical, and thus that lavas on the flanks of the ancient Kauai volcano were of rather local extent. This pattern is entirely consistent with the modern eruptive style on the big island of Hawaii. Including the
paucity of distinct intermediate directions. These two lines of evidence are mutually consistent, and we tentatively infer that the major change in direction occurred extremely rapidly during both reversals.

In spite of the lack of detail, and regardless of its cause, the pattern of change in field directions is clear for both transitions and is sufficient to apply Hoffman's test. In the R-N transition, the field direction remains southerly while shallowing to nearly horizontal. A single layer with normal polarity occurs among these lower flows. We have examined the anomalous unit and are convinced that it is a flow and not a sill; examples of the latter are easily recognized on Kauai by their distinctive jointing and much greater resistance to weathering. Thus the ancient field apparently underwent a rapid 'flip' in direction during the transition much like those observed in several other detailed records. The shallow southerly directions are followed by a steeply downward directed field vector which subsequently shallows to the expected normal field direction. In the N-R reversal, the same sequence is seen except in reverse; a steep northerly field direction precedes shallow southerly directions. Thus, both reversals are characterized by transitional directions that lie near the north–south vertical plane or, equivalently, by VGP paths that pass near the site.

At first glance, this site dependence is most naturally explained by the zonal flooding model. An awkward complication arises, however, because the R-N and N-R paths are so nearly identical. Their similarity requires the presumed flooding processes for the two reversals to have initiated in opposite regions of the core. More specifically, if the transitional field was predominantly octupolar, as is consistent with the very low field intensities that have been inferred from other transition zones, then flooding for the R-N reversal would have begun at the equator. For the N-R reversal, one is forced to conclude that the reversal somehow initiated simultaneously at both poles. Similarly, quadrupolar transitional field
t require initiation at the south pole for R-N reversals and at the north pole for N-R reversals.

If generally true, systematic behaviour such as just described would mean that the postulated flooding mechanism, and hence the reversal process, depends on the sign of the field. Global palaeomagnetic data suggest that statistically significant and long-lasting differences do exist between the morphology and stability of normal and reversed geomagnetic fields, and thus that asymmetry in the reversal process might be allowed. Such asymmetry, however, is intuitively unappealing and cannot arise directly from the basic dynamo equations.

Theoretical considerations aside, it is important to ask whether the regularities predicted by the flooding models are discernible in the rest of the palaeomagnetic record. Near-sided VGP paths seem to predominate in the R-N reversal records presently available from Northern Hemisphere sites. This characteristic is evident in the R-N reversal from Kauai, supporting the general observation. A pattern in the N-R records, on the other hand, is not yet apparent. Several N-R transition zones from Iceland have been reported; shallow directions with easterly or westerly declinations are common in that VGP paths are not strongly near or far sided. Shallow westerly directions are also found in a detailed N-R transition in volcanic rocks of the Shigarami Formation, Japan. However, this record shows the field tending towards far-sided behaviour. Two N-R records from California, which we will discuss in more detail with respect to the standing field model, are characterized by intermediate directions which are shallow and easterly. The equivalent VGP paths are slightly near sided. A pair of VGP paths from Russian sites, the only N-R data considered in detail in a recent review, are not longitudinally confined, but are generally far sided.

More convincing evidence of far-sided N-R behaviour has been found in back-to-back transition zones of Miocene age from Crete. The VGP path for the N-R reversal follows a

Fig. 2 a, Equal-area plot of flow-averaged directions from the R-N transition zone. Results from three sites in the Napali Formation are combined. Indicates downward (upward) directed magnetization vectors. Connecting lines and arrows show the stratigraphic order from oldest to youngest flows. Centre of plot marked by a plus sign, and ticks indicate 10° intervals. The axial dipole direction (asterisk) is shown for comparison. b, Directions from the N-R transition zone in the Olokele Formation.

and that from the Olokele Formation on Kauai represent our best examples of site-dependent N-R paths, yet the former is far sided and the latter near sided. Thus, the N-R data as a whole display no coherent trend and, moreover, the two most clearcut records conflict directly. This evidence suggests that, at least for the N-R transitions, the flooding mechanism varies considerably from one reversal to the next.

The similarity of the N-R and R-N reversal records from Kauai is easily explained by the standing field model. Reversals in the early Pliocene were quite frequent, and the Kauai data require a standing field that persisted for only a few hundred thousand years. Results from two California localities suggest that a standing field may persist for a much longer period. Volcanic rocks from Clear Lake, California, record intermediate directions from two N-R reversals that occurred several hundred thousand years before the Matuyama–Brunhes transition. The VGP equivalent to these directions fall right on the Matuyama–Brunhes R-N transition path that Hillhouse and Cox found at Lake Tencapa, also in California. Even more remarkable is a detailed record of the Gauss–Matuyama transition in dry lake sediments from Searles Valley, California. This reversal, 1.6 Myr earlier still and N-R, also repeats the Lake Tencapa path. Note that these three VGP paths are not strongly near or far sided, the VPGs passing almost 90° to the east of the site. Such a grossly non-axisymmetric field behaviour, nearly identical for reversals of both senses, can arise only in very special cases of the generalized flooding model. Thus, the California results more strongly support the standing field model than do the Kauai data. More significantly, the ages of the three sites in California imply that the standing field, if that is what controlled the transitional fields, remained unchanged for several millions of years.

The back-to-back reversal records from Crete again provide conflicting evidence. The VGP paths from these two reversals differ from one another by 135°. Marine sediments such as those now exposed on Crete may not record changing field directions as faithfully as rapidly deposited lake sediments or volcanic rocks. Nevertheless, it is difficult to dismiss the general features of these reversal records, especially the significant longitudinal separation of the VGP paths. Unless the standing field can occasionally change between reversals or be masked by other effects (floding processes?) the results from Crete cannot be dismissed lightly.
An additional problem is that the concept of standing fields has no clear independent basis. Yukutake and Tachinaka\(^3\) mathematically divided the historic nondipole field into standing and drifting parts. The analysis provided a better description of secular variation, but the separation of the field into two parts is arbitrary; it allows but is not strong evidence for an actual standing field. Moreover, analysis of historical field behaviour is not sufficient to demonstrate that a field component can last for millions of years as required by the model; such evidence must come from palaeomagnetism. The ‘standing fields’ that emerge from analyses of global palaeomagnetic data\(^9\) are by definition statistical; that is, they represent long-term properties of the time-averaged geomagnetic field. Standing fields of the sort needed for the reversal model are again allowed, but in no way proven, by analysis of the time-averaged field. In short, no standing nondipole field capable of controlling transitional fields has been observed, palaeomagnetically or otherwise, except by inference in some of the transition zone data.

In conclusion, the similarity of VGP paths in back-to-back reversal records from Kauai and in several records from California favours the standing field model, according to the test proposed by Hoffman\(^10\). Conversely, the large latitudinal separation of VGP paths in back-to-back reversal records from Crete and the predominance of near-sided VGP paths in the available R-N records from the Northern Hemisphere favour the zonal flooding model. However, unless the standing field or flooding process can change, at least occasionally, from reversal to reversal, neither model can explain all of the available transition data. It may thus be too simple to assume that a single type of transitional field is always present during reversals. Furthermore, palaeointensity data we are currently analysing for the Kauai R-N reversal suggests that more complex versions of these mechanisms may be required to model even a single reversal. These results will be discussed elsewhere.

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