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ACKNOWLEDGEMENTS. We thank V. Courtillot, M. J. Dekkers and J. D. A. Zijderveld for comments on the initial manuscript, D. Gubbins and J. P. Valet for their constructive reviews, and P. J. Verplak for his help in the field and in the laboratory. The research was supported by the Netherlands Foundation for Earth Sciences (AWON) with financial aid from the Netherlands Organization for Scientific Research (NWO).

Link between geomagnetic reversal paths and secular variation of the field over the past 5 Myr

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PALAEOMAGNETIC records provide information about the behaviour of the geomagnetic field during reversals[1,2]. Existing records are incompatible with transitional field configurations that are either entirely dipolar or entirely zonal (dependent only on latitude)[3,4]. Recent compilations[5–8] have indicated that the transitional paths of virtual geomagnetic poles (VGPs) for the past few reversals are located preferentially within two antipodal longitudinal bands, suggesting that simple but non-zonal field configurations dominate during reversals. Here I point out that one of the longitudinal bands coincides with that expected from the reversal of a non-axial-dipole field exactly like that present today; the other requires only a sign change in the non-axial-dipole terms of today's field. Evidence for persistent non-zonal contributions to the field has generally[9–13] (but not always[14,15]) been regarded as not statistically significant in the light of poor data distributions. I show here that a non-zonal bias, similar to that observed in reversal data, is evident in data on secular variation of the field over the past 5 Myr, even after normalization according to site locations. These results suggest that the time-averaged field does indeed contain persistent (but not constant) non-zonal contributions.

Reversal records from a single location are usually plotted in the form of projections of VGP positions, with lines connecting adjacent time horizons. Each VGP position gives the point of intersection with Earth's surface of the axis of the geocentric dipole that would generate the measured palaeomagnetic declination and inclination for a single time horizon at that site[10]. As the geomagnetic field polarity moves from a reversed to normal state, details of the migrations of VGPs from extreme southern to extreme northern latitudes provide a view of the reversal process. The advantage of the VGP transformation is that it removes the geographical dependence of the dipole part of the field: if the field elements of an exclusively dipolar field are measured at any location on the globe, they will all transform into a single VGP position; similarly, for a reversal with exclusively dipolar transitional fields, a single transition path will be obtained regardless of the location from which the observations are drawn (see Fig. 1). It is unlikely that the field is exclusively dipolar during reversals. As with the present-day field, one should expect non-dipole components to be an integral part of the field: such complexities are described by a spherical harmonic expansion, in which the geomagnetic field **B**, at radius r, colatitude θ and longitude ϕ, is written as the gradient of a harmonic potential, Ψ

$$\Psi(r,\theta,\phi) = a\sum_{l=1}^{\infty}\sum_{m=0}^{l}\left(\frac{a}{r}\right)^{l+1}(g_l^m\cos m\phi + h_l^m \sin m\phi) \times P_l^m(\cos\theta) \quad (1)$$

P_l^m are partially normalized Schmidt functions[10] describing the latitudinal variation of the field. At any time the Gauss coefficients, g_l^m and h_l^m, determine the size of spatially varying components of the field that increase in complexity with spherical harmonic degree l. Zonal fields are those for which all Gauss coefficients with $m \neq 0$ are zero; they have no longitudinal variations. For the present normal field the axial-dipole term g_1^0 is overwhelmingly dominant, and the next-largest contributions come from the non-zonal, equatorial dipole terms, g_1^1 and h_1^1. Sampling the 1980 magnetic field at sites distributed worldwide yields VGPs clustered near the north geomagnetic pole, with a tilt away from the Earth's axis and a longitudinal bias reflecting the predominant influence of g_1^1 and h_1^1. As for a dipole field, for an exclusively zonal field there is a simple relationship between VGP positions and the spherical harmonic representation; VGPs from any zonal field are constrained to lie along the great circle containing the site longitude. For example, a zonal quadrupole field superimposed on a geocentric axial dipole will generate VGP positions that lie on the far side of the geographic pole relative to the measurement site. But the presence of non-zonal fields ($m \neq 0$ terms) complicates the issue, as the VGP transformation is nonlinear. In stable polarity times, persistent non-zonal terms may generate VGP positions with non-axisymmetric distributions about the geographic axis.

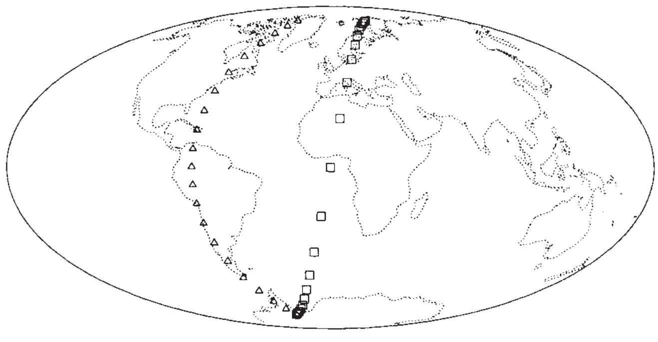

FIG. 1 Transitional VGP paths for reversals simulated from an exclusively dipolar field. Triangles are for reversal during which the equatorial contributions to the dipole remain static throughout and the VGP longitude remains fixed at 70.8° W; squares show a reversal in which the equatorial contributions reverse sign along with the axial part of the dipole, and the VGP longitude migrates from 70.8° W to 109.2° E.

During a reversal, when the axial-dipole part of the field decays in intensity, changes in the relative sizes of non-zonal contributions can considerably alter VGP locations.

A recent compilation[5,6] of 21 records of the Matuyama-Brunhes geomagnetic reversal (dated at 0.78 Myr; ref. 16) showed that the VGP paths had some distinctive features. First, the individual records tended to produce paths confined to fairly narrow longitude bands. This phenomenon has often been observed in sedimentary records, and may originate from either geomagnetism or rock magnetism. If it is geomagnetic then the significant non-axial-dipole contributions to the field (all coefficients in the spherical harmonic expansion except g_1^0) are stable for the duration of the reversal; that is, they are much less variable than the axial dipole. Alternatively, the geomagnetic field variations may be smoothed during the acquisition of remanence (this process may continue for thousands of years after the sediment is deposited) and the result is then some average of the field configuration during and after the reversal[17-19]. Second, when the reversals are considered collectively and the distribution of all the transitional VGPs is plotted as a function of longitude, there are two roughly antipodal bands in which the bulk of the VGPs are concentrated (Fig. 2*a*). Clement[6] modelled three of these reversal paths by a dominant h_3^1 term superimposed on a reversing axial dipole, and suggested that this indicated geographical control of the reversal path. He also noted an apparent correlation between favoured transition paths and concentrations of flux in recent radial field models at the core-mantle boundary[20]; these flux concentrations may be reflected in full polarity palaeopole positions back to 5 Myr (ref. 14), but they do not appear in core-mantle boundary models unless terms of degree $l = 4$ or higher are included. A selective compilation[7,8] of records from reversals spanning the last 11 Myr showed similar confinement of VGP paths and suggested comparatively long time constants for the geographic control. It is possible, however, that these features reflect the geographical location of the sampling sites and inadequate normalization for the different numbers of transitional VGPs in each record[21]. How the number of VGPs in records from different sites should be normalized is not obvious, because the number of transitional VGPs at a given location depends on the predominant transitional field configuration, as well as whatever temporal variability in the sampling is enforced by the recording medium.

An interesting feature of the apparent control of reversal paths by core-mantle boundary conditions is that one of the regions of longitudinal confinement includes the position of the current geomagnetic pole. If the axial-dipole part of today's geomagnetic field decayed and grew back with the opposite polarity, while leaving the rest of the field (the non-axial-dipole part) as it is today, one would see one of the longitudinal bands shown by the reversal data. The longitudinal distribution of VGP data from such a simulated reversal, sampled at 21 equally spaced time points and 788 roughly uniformly distributed points on Earth's surface, is shown in Fig. 2*b*. Reversing the signs of the coefficients of the non-axial-dipole part of the field, and leaving those terms constant during the reversal as before generates an antipodal band. Combining the distributions generated by two such simulated reversals produces a figure like that obtained for the Matuyama-Brunhes transition (Fig. 2*c*). The effect of spatial distribution of reversal sites may be assessed in Fig. 2*d*, where the simulated reversals are sampled at the same geographical locations as the Matuyama-Brunhes data used by Clement[6]; the influence on the resulting VGP longitude distributions is small.

What does this similarity in VGP longitude distributions mean? The low geomagnetic field intensity during reversals makes rocks more susceptible to residual overprinting by the field present now, or by the field present immediately after the reversal. This could certainly account for the path through the Americas, but it is less obvious why there should be an antipodal band for data from a single reversal. The simplistic reversal model used to generate Fig. 2*b* is not adequate either; the twin band at a single time instant requires dominant non-zonal spherical harmonic contributions of degree two or higher[6]. Alternatively, the bimodal distribution for reversal paths may result from inadequate temporal resolution in the sedimentary records, with each mode reflecting a preferred general configuration for the geomagnetic field. If transition between these states occurs sufficiently rapidly, VGPs in both longitude bands could arise during one reversal, and with adequate temporal resolution could be detected at a single site (as sometimes occurs). A global distribution of sites sampling over a long time period would generate VGP longitudes occurring over both the Americas and in the band over Western Australia and East Asia. The present field would provide a snapshot of one preferred configuration. Since AD 1600 the geomagnetic dipole location has migrated

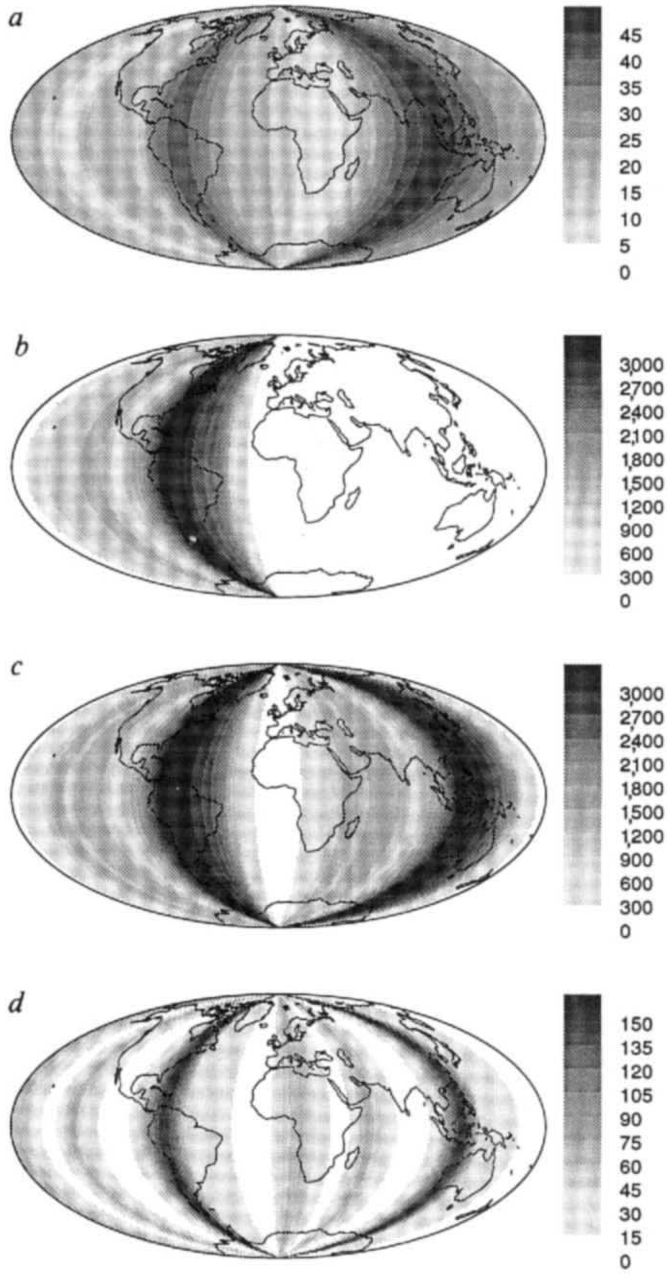

FIG. 2 Longitudinal distributions of VGP positions from (*a*) Matuyama-Brunhes reversal records. (*b*) a reversal simulated from the 1980 field sampled at 788 uniformly distributed sites, (*c*) a twin reversal simulated from the 1980 field distributed sites and (*d*) same as *c* but for those sites for which Matuyama-Brunhes records are available.

from roughly 40° W to 70° W (ref. 10); at 1600 it was still close to (but not exactly over) the peak VGP occurrence in Fig. 2*b*. Some reversal records provide evidence for long-lived preferred VGP locations[22], a result that is compatible with the idea that the time-averaged field has a significant non-zonal component.

If such a bias exists, then one would also expect it in the average field configuration derived from palaeosecular variation (PSV) data. Figure 3*a* shows a histogram of the longitudinal distribution of VGP positions for PSV data for the past 5 Myr. Each position is an average result for several samples from a lava flow. There are 2,244 globally distributed data from 88 studies (see refs 23, 24). In Fig. 3*a* they have not been corrected for plate motions, because in many cases the reported ages are not exact enough to provide accurate corrections over such a short time span. The effect of such motions was shown to be negligible by adjusting all the data sites to their positions 5 Myr ago and repeating the analysis. Using lava flow data minimizes the effects of time-averaging during remanence acquisition. Most studies of the time-averaged field[8–15] have used palaeomagnetic pole positions[10] (not VGPs) drawn from both sediments and basalts; these are averages of VGP directions, designed to remove the effects of secular variation. The most striking feature of the plot is that the PSV VGP distributions have a structure similar to that seen in the Matuyama–Brunhes reversal data and in the simulated twin reversal: they are most concentrated in two antipodal longitude bands. The regions are broader than those for the present-day field, or for the reversal, an effect that would be readily accounted for by noise in the palaeomagnetic data and a better temporal average of the secular variation. The longitudinal distribution of sites around the world is non-uniform: there are no data from sites between 99° W and 27.2° W or 77.5° E and 119.5° E (Fig. 3*b*). To compensate for this, I normalized contributions to the histogram of VGP longitudes so that equivalent weight was given to longitudinal regions of width 45°, except for the bin between 90° W and 45° W, which contains no data. The effects of this normalization are small (dashed line on Fig. 3*a*). Although the normalization cannot entirely compensate for the uneven data distribution, the lack of correlation between the VGP distribution of Fig. 3*a* and site distribution in Fig. 3*b* does argue strongly against a zonal field configuration. The VGP longitudes for the PSV data are obviously not well modelled by a uniform distribution; both Kuiper's V_N statistic and the Kolmogorov–Smirnov statistic D_N (ref. 25) give significance levels well below 1%.

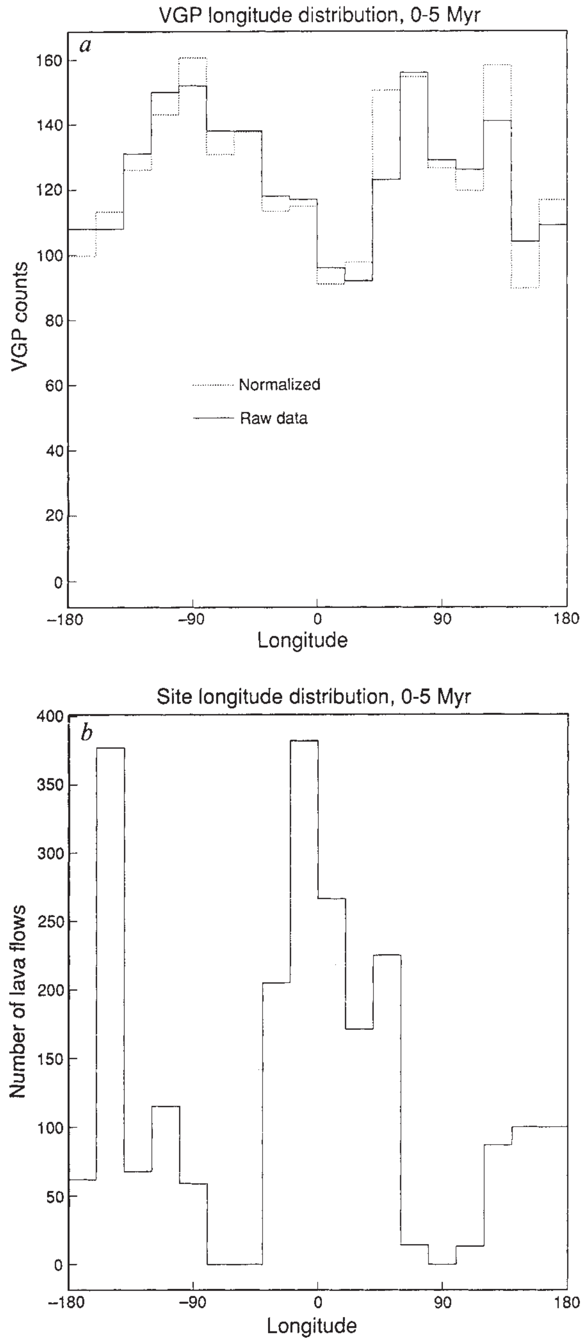

FIG. 3 *a*, Histogram of VGP longitudes for globally distributed palaeosecular variation data from lava flows spanning the past 5 Myr. Solid line is for the raw data, dashed line is normalized for site distributions. *b*, Histogram of site distributions as a function of longitude (20° bins) for the data in *a*.

The PSV data support the idea of preferred longitude bands in the VGP distributions. The details of this distribution are liable to change as more data becomes available, but it is clear that the zonal models mostly used in determining the average geomagnetic field configuration over the past 5 Myr are inadequate, and we need to look for models that show the minimum necessary departure from the geocentric axial dipole field, including longitudinally varying spatial components. The time constants for such non-zonal contributions have traditionally been thought to be short, because of westward drift velocities and also because at some sites palaeomagnetic directions become on average those of an axial dipole in only a few thousand years; but short time constants do not preclude the existence of a bias in the average field. The bias in VGP longitudes is unlikely to be seen in the standard checks[10,13] for residual equatorial dipole contributions, g_1^1 and h_1^1, because the pair of bands observed is not well modelled by an $l = 1$ term. Such analyses have not been done for terms of higher degree. Global palaeosecular variation from lake sediments and archaeomagnetic sites could also be used to obtain better resolution than is possible with either reversal or PSV data. These span several thousand to tens of thousands of years and would provide a useful test of these ideas for prehistoric times. □

Received 24 February; accepted 15 June 1992.

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ACKNOWLEDGEMENTS. I thank C. Johnson and R. Parker for discussions, and the NSF for financial support.

Post-Jurassic mammal-like reptile from the Palaeocene

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MAMMAL-LIKE reptiles of the Order Therapsida document the emergence of mammals from more primitive synapsids[1] and are of unique zoological and palaeontological interest on that account[2]. Therapsids, first appearing in the Early Permian[3], were thought to become extinct in the Middle Jurassic[4,5], soon after the Late Triassic origin of mammals[6]. Here, however, we report the discovery of a therapsid from the late Palaeocene, 100 million years younger[7] than the youngest previous occurrence of the order. This discovery nearly doubles the stratigraphic range of therapsids and furnishes their first record from the Cenozoic. The documenting fossils, an incomplete dentary containing three teeth, and four isolated teeth from other, conspecific individuals (Fig. 1), are from the Paskapoo Formation, at Cochrane, Alberta, Canada, from beds yielding a diverse mammalian fauna of early Tiffanian age[8]. These specimens are catalogued in the collections of the University of Alberta Laboratory for Vertebrate Paleontology (UALVP) and provide the basis for a new taxon, as named and described below.

Class Reptilia

Subclass Synapsida

Order Therapsida

Suborder Cynodontia

Chronoperatidae fam. nov.

Type genus *Chronoperates* gen. nov.

Chronoperates paradoxus gen. et sp. nov.

Etymology. *Chronos* (Greek): time; *perates* (Greek): wanderer, in reference to the geochronologic gap between this taxon and other known therapsids; *paradoxus* (Latin): contrary to expectations.

Holotype. UALVP 32358, left dentary having the three posteriormost teeth, two empty alveoli preceding these, and an incomplete coronoid process.

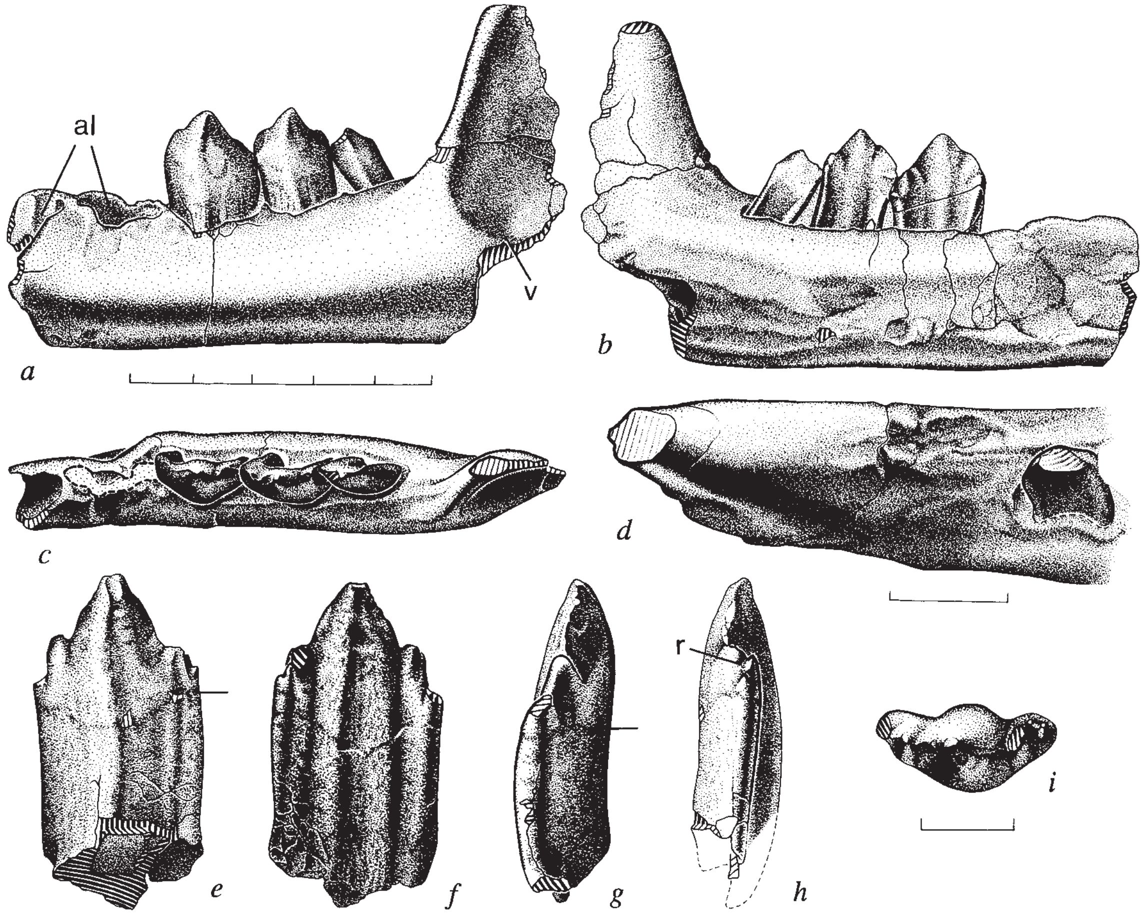

FIG. 1 UALVP 32358 (holotype), incomplete left dentary, *Chronoperates paradoxus* gen. et sp. nov., Cochrane 2 locality[8], late Palaeocene, Alberta: *a*, labial view; *b*, lingual view; *c*, occlusal view; *d*, dorsal view of scar for coronoid bone behind posteriormost tooth. UALVP 32359, isolated lower left molariform tooth (distalmost extent of root missing): *e*, labial; *f*, lingual; *g*, anterior; *h*, posterior; and *i*, occlusal views. al, Alveoli; v, ventral rim of masseteric fossa; r, posterior recess for receipt of next, more posterior tooth. Horizontal bar in *e* and *g* points to irregular line marking ventral extent of enamel. Scale bar divisions, 1 mm (*a*–*c* drawn to same scale; *e*–*i* drawn to same scale).