Dipole Offset—The Time-Average Palaeomagnetic Field Over the Past 25 Million Years

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Summary

The time-average palaeomagnetic field during Upper Tertiary times has as its source a dipole which is offset $285 \pm 74$ km north of the equatorial plane, but which remains axial. Modification of pole positions, taking the offset source dipole into account, suggests that no significant ($> 1^\circ$) continental drift, polar wandering, or very long-term dipole wobble have been present during the Upper Tertiary.

Four different analyses of the data have shown the dipole offset to be a real phenomenon, not due to peculiarities of the method of calculation.

1. Introduction

In two earlier papers (Paper I by Wilson & Ade-Hall (1970) and Paper II by Wilson (1970)), it was suggested that the time-average palaeomagnetic field over Upper Tertiary, Quaternary and Recent times could be represented by an axial dipole source displaced north of the equatorial plane along the Earth's rotation axis (Fig. 1). The previously held assumption of a centred axial dipole field was questioned. The results presented in I and II seemed inexplicable on grounds of continental drift, or other physical factors than the northward displacement of the dipole source.

The analysis in Paper II was done only on the mean palaeoinclinations of magnetization, and I was even foolish enough to say that it could not be done using pole positions. The present analysis advances beyond Paper II in that

1. Thirteen new mean data have been added to the basic information, bringing it up to 96 data;
2. The analysis of the 96 data is in terms of pole positions, which means that the total information (both palaeomagnetic declinations and inclinations) is put to use, unlike in Paper II;
3. The criterion (Section 4.2) for choosing the best dipole offset distance is a criterion of minimum scatter of pole positions, quite different from Paper II, which dealt with inclinations of magnetization only; and
4. The analysis of results suggests that no Upper Tertiary polar shift is necessary to explain existing results.

2. ‘Far-side’ poles, and dipole offset

In this section I present my own conjectures about how our ideas of the source of the magnetic field are evolving. In subsequent sections these conjectures are tested against the available data.
As shown in Fig. 1 a northward displaced dipole source makes the magnetic inclination, anywhere on the Earth's surface, more negative (i.e. more upwards) than that of a centred axial dipole. This means that if we were to treat the offset dipole field as if it were a centred axial dipole field for the purposes of pole position analysis, each observer would calculate VGP's that were on the far side (Fig. 2) of the geographic pole from the observer (the sample collection site). Each scientist, from his own geographical position, might claim that he had detected, during Upper Tertiary time, long term polar movement because while his data had spanned enough time to average out secular variation and dipole wobble, nevertheless his mean VGP would be significantly different from the geographic pole (Cox & Doell 1964). However, when scientists from all over the world compared their time-average poles, they would find that none of their mean VGP's coincided (as they should if the dipole remained in a fixed tilt over the time of mutual observation). The grand average of all their dipole 'tilts' would be zero, as Opdyke & Henry's (1969) results demonstrated. Then

(1) This would establish experimentally the axially symmetric nature of the palaeomagnetic time-average field;

![Fig. 1. The geometry of the offset dipole produces inclinations which are everywhere more negative (high, dashed lines) than the inclinations of the centred dipole (solid lines).](https://academic.oup.com/gji/article-abstract/22/5/491/667526)
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Calculation of modified pole

FIG. 2. Left, the geometrical parameters used to calculate the colatitude of the VGP for an offset dipole source. $r =$ offset of dipole source along axis of rotation; $R =$ radius of the Earth; $\theta =$ ancient colatitude; $I =$ palaeomagnetic inclination. Right, a diagram to clarify the meaning of quantities mentioned in the text. RH = right handedness of pole as seen from observer's site; FS = far sidedness of pole as seen from observer's site; CSL = common site longitude, or longitude relative to the observer's site, of the pole position; $\theta =$ ancient colatitude of VGP; $D =$ palaeomagnetic declination.

(2) It would also (as far as palaeomagnetic data are concerned) destroy the evidence for a slow polar shift of the pole. We could not agree where the pole was; and

(3) The observers would ultimately be led to hypothesize an axial source which is more complicated than just a centred dipole.

This is the situation which now seems to exist. This paper advances the hypothesis that a northward offset axial dipole explains facts which are inconsistent with a simple dipole tilt. What follows in this paper leads to three different analyses of the data which support this hypothesis.

3. Data used

The new pole position approach necessitates abandoning the sea-core data used earlier, since sea-core declinations (and therefore pole positions) do not exist. The basic data now consists of Table 1 in Paper II (83 data) plus the 13 new data in Table 1 of the present paper. The starting point of this approach is always to use geographic co-ordinates of the site plus a mean palaeomagnetic direction to re-calculate mean VGP's. The data selection criteria are the same as in Paper II but more stringent than in Paper I. It should again be stressed that each of the 96 mean data is itself to some extent a time-average, although not always a very good one.

4. Three pole position analyses demonstrating offset dipole source

4.1

The first approach is to displace all observers (collection sites) about the rotation axis so that they have a common longitude, taken as zero. Each observer remains at his original latitude, and his observed palaeomagnetic poles are rotated along with
Table 1

Additional data which have been added to those of Paper II for use with this paper. The criteria of acceptance are the same as for Paper II.

Table 1. Numerical references refer to MacElhinny 1969

<table>
<thead>
<tr>
<th>Reference</th>
<th>Place</th>
<th>Age</th>
<th>North America</th>
<th>Mean</th>
<th>Site</th>
<th>Mean pole</th>
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<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>D</td>
<td>I</td>
<td>α₉₅</td>
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<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Lat.</td>
<td>Long.</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Lat.</td>
<td>Long.</td>
<td>(dY, dx or α₉₅)</td>
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<td>Symons 1969a and 1969b</td>
<td>British Columbia, Canada</td>
<td>(2)</td>
<td>356.2</td>
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<td>+51.5</td>
<td>238.6</td>
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<td></td>
<td>84.5</td>
<td>216.5</td>
<td></td>
</tr>
<tr>
<td>Doell 1970</td>
<td>Massif Central, France</td>
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<td>+60.3</td>
<td>3</td>
<td>45.3</td>
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<td>003.1</td>
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<td></td>
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<tr>
<td>Marton &amp; Szalay 1967</td>
<td>Hungary</td>
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<td>+63.9</td>
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<td>+39</td>
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<tr>
<td>Doell 1969</td>
<td>Mauna Loa</td>
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<td>354.8</td>
<td>+24.1</td>
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<td>10–21</td>
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<td>352</td>
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<td>Creer &amp; Valencio 1970</td>
<td>Argentine</td>
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<td>168.8</td>
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<td>Argentine</td>
<td>(1)</td>
<td>006</td>
<td>-60</td>
<td>8</td>
<td>-37.5</td>
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<td>Valencio &amp; Fourcade 1969</td>
<td>Argentine</td>
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<td>290.0</td>
<td>86.6</td>
<td>110.0</td>
<td>(12)</td>
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<td>Argentine</td>
<td></td>
<td>(2)</td>
<td>008</td>
<td>-76</td>
<td>6</td>
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<td>Argentine</td>
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<td>201.1</td>
<td>86.1</td>
<td>54.2</td>
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<td>Argentine</td>
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<td></td>
<td>Argentine and S. Shetland Islands</td>
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<td></td>
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<tr>
<td>Wellman et al. 1969</td>
<td>Australia</td>
<td>(2)</td>
<td>012.4</td>
<td>-53.0</td>
<td>3.7</td>
<td>-30.0</td>
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<tr>
<td></td>
<td>(Nandewar)</td>
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<td>150.3</td>
<td>78.5</td>
<td>264.3</td>
<td>(4, 5)</td>
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<td></td>
<td>New Zealand</td>
<td></td>
<td></td>
<td>34</td>
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<td>Cox 1969</td>
<td>Australia and New Zealand</td>
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<tr>
<td>Qₚ = Recent</td>
<td></td>
<td></td>
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<tr>
<td>Qₚ = Pleistocene</td>
<td></td>
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<td>Tₚ = Pliocene</td>
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</tbody>
</table>

Notes:
- AF = Atlantic Plate
- Tₚ = Miocene
- (1) = Quaternary or Recent
- (2) = Upper Tertiary

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him. This COMMON SITE LONGITUDE method allows us to see simultaneously all of the poles as they are seen by their own observers. Fig. 3 (upper row of diagrams) shows how these common site longitude poles appear when the data are grouped in various ways:

1. 28 Quaternary plus Recent mean data  
2. 68 Upper Tertiary mean data  
3. all 96 mean data  
4. the 72 of the 96 data which resulted from AF demagnetization.

The subdivision was meant to check that the same answer appeared regardless of data grouping. The clear result in all four diagrams is that these common site longitude mean VGP's have a strong tendency to be farside and to the right of the pole as seen by any observer no matter what his longitude. Table 2 gives relevant statistical data for these poles.

Fig. 3 (lower row of diagrams) shows how these poles appear when modified by assuming not a centred, but a northward offset axial dipole to calculate them, as outlined below in Section 4.2. Clearly the far-side nature can be eliminated by relaxing the centred axial dipole assumption, because an offset dipole can bring the poles into closer coincidence with each other and with the geographic pole. The right-hand nature of the poles cannot be eliminated in this way.

Since all four data groupings agree, we need consider only the sum of all 96 data, and say that relative to the average observer anywhere the mean palaeomagnetic pole is 146.3° of longitude to his east and is 3.8° from the geographic pole (86.2° N latitude). It has an ω92 of 1.66° and is 3.2° to the far side (Fig. 2). It is this 3.2° which disappears when the poles are modified by introducing an offset source dipole.

This first approach gives the most "pictorial" assessment of the data.

4.2

The second approach is mathematically the most satisfying and gives a precise estimate of dipole offset. To achieve this one sets up a mathematical method for calculating 'modified' mean VGP's based on the assumption of an offset rather than a centred axial dipole. The amount of dipole offset r km which gives the minimum scatter δ of modified poles, is taken as the optimum offset. The formula developed is based on the relationship

\[ I = \tan^{-1} \left[ 2 \cot \left( \theta + \sin^{-1} \left( \frac{r \sin \theta}{\rho} \right) \right) \right] - \sin^{-1} \left( \frac{r \sin \theta}{\rho} \right) \]

where

\[ \rho = (r^2 + R^2 - 2rR \cos \theta)^{1/2} \]
\[ r = \text{displacement of dipole from Earth's centre} \]
\[ R = \text{Earth's radius} \]
\[ \theta = \text{ancient colatitude relative to mean VGP} \]
\[ I = \text{inclination of the ancient magnetic field (\( +ve \) below horizontal)} \]

Fig. 2 illustrates these quantities.

The only difference from the usual procedure for calculating a VGP is that this relationship between palaeolatitude and palaeoinclination is more complicated and is most easily solved by an iteration method. A FORTRAN IV program is available from the author.

The curves in Fig. 4 show how the scatter of modified poles (both about the geographic pole (\( \delta_g \)) and the mean pole (\( \delta_m \))) varies with dipole offset r. The top row of diagrams in Fig. 5 shows visually the scatter of unmodified poles, and the bottom row shows the minimized scatter of the same poles when modified by the offsets.
Table 2

<table>
<thead>
<tr>
<th>Data group</th>
<th>Mean pole longitude relative to observer</th>
<th>Mean pole latitude</th>
<th>Deviation of mean pole from N. geographic pole</th>
<th>Far-sidedness from observer (see Fig. 2)</th>
<th>∞₉₅</th>
</tr>
</thead>
<tbody>
<tr>
<td>28 Quaternary + Recent mean VGP's</td>
<td>174·4° East</td>
<td>87·9°</td>
<td>2·9°</td>
<td>+2·9°</td>
<td>3·20°</td>
</tr>
<tr>
<td>68 Upper Tertiary mean VGP's</td>
<td>138·7</td>
<td>85·7</td>
<td>4·3</td>
<td>+3·2</td>
<td>1·92</td>
</tr>
<tr>
<td>96 Total data</td>
<td>146·3</td>
<td>86·2</td>
<td>3·8</td>
<td>+3·2</td>
<td>1·66</td>
</tr>
<tr>
<td>72 A.F. demagnetized data (out of total 96)</td>
<td>133·0</td>
<td>86·0</td>
<td>4·0</td>
<td>+2·7</td>
<td>1·88</td>
</tr>
<tr>
<td>10 regional mean poles</td>
<td>147·3</td>
<td>85·4</td>
<td>4·6</td>
<td>+3·9</td>
<td>1·66</td>
</tr>
</tbody>
</table>

Mean data for poles referred to a COMMON SITE LONGITUDE, for a centred axial dipole source. 'Far-sidedness' is the angle through which the pole must be brought, towards the observer, to lie on his 90° or 270° longitude line, (Fig. 2).
Fig. 3. Common site longitude representation. The top row of diagrams contains mean virtual geomagnetic poles as seen by all observers who have been placed on a common line of longitude, taken as zero. For each of the four subdivisions of the data, the poles clearly tend to lie on the far side of the geographic pole. The bottom row of diagrams contains the same basic data except that the poles have been modified to be those due to a source dipole with offset $r$ km, chosen to minimize the scatter of poles. This pulls the poles towards the observer until there is no net far-side effect.
Fig. 4. Original site longitude representation. The top row of diagrams contains the usual pole positions, seen by each observer at his own site, and assuming a centred dipole. The bottom row of diagrams shows how a northwards offset $r$ km of the axial dipole reduces the scatter below that seen in the top row and makes the data peak better near the centre of the projection.
Dipole offset

printed on each diagram. These results are summarized in Table 3. The dipole
offsets lie between 235 and 310 km northwards depending on the grouping of the
data. The agreement between groups is good, so that we may concentrate attention
on the total 96 giving a best offset of

\[ r = 285 \pm 74 \text{ km} \]

(the 74 km is one standard error of the mean).

In the case of all 96 data, the scatters \( \Delta_p = 8.99^\circ, \Delta_m = 8.94^\circ \) for the unmodified
poles reduce to \( \delta_p = 8.12^\circ, \delta_m = 8.07^\circ \) for the modified poles with minimum scatter.
The reduction of scatter seems too small compared with 3.2° of 'far-sidedness' in
Section 4.1, until we remember that this scatter reduction is independent of other
sources (experimental error and incompletely averaged ancient field variations). This

![Graphs showing dipole offset results](https://academic.oup.com/gji/article-abstract/22/5/491/667526)

**Fig. 5.** Four plots of calculations showing how the scatter of the poles about the
geographic pole (\( \delta_p \)) or the mean pole (\( \delta_m \)) can be minimized by an optimum offset
\( r \) km of the axial dipole.
Table 3

Unmodified VGP calculations (modified)

<table>
<thead>
<tr>
<th>Data group</th>
<th>Mean longitude</th>
<th>Mean latitude</th>
<th>$\Delta m^\circ$ ((\delta_m))</th>
<th>$\Delta p^\circ$ ((\delta_p))</th>
<th>$\alpha_{95}^\circ$</th>
<th>$\alpha_{p95}^\circ$</th>
<th>Dipole offset for minimized scatter of modified VGP's</th>
<th>Dipole offset calculated by different method in Paper II</th>
<th>Scatter reduction (\delta_{\text{reduced}} = (\delta^2 - \delta'^2)^{\frac{1}{2}}) about mean pole</th>
<th>Scatter reduction about geographic pole</th>
</tr>
</thead>
<tbody>
<tr>
<td>28 Quaternary + Recent data</td>
<td>343.0 (339.8)</td>
<td>88.2 (89.2)</td>
<td>8.80 (8.30)</td>
<td>8.97 (8.34)</td>
<td>3.32 (3.14)</td>
<td>3.40 (3.16)</td>
<td>235 $\pm$ 130 km*</td>
<td>191 $\pm$ 38 km</td>
<td>2.94</td>
<td>3.32</td>
</tr>
<tr>
<td>68 Upper Tertiary data</td>
<td>134.5 (90.9)</td>
<td>88.2 (88.5)</td>
<td>8.78 (7.87)</td>
<td>9.00 (8.01)</td>
<td>2.12 (1.90)</td>
<td>2.18 (1.94)</td>
<td>310 $\pm$ 90</td>
<td>306 $\pm$ 41 km</td>
<td>3.90</td>
<td>4.10</td>
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<td>96 total data</td>
<td>120.4 (85.2)</td>
<td>89.0 (89.0)</td>
<td>8.94 (8.07)</td>
<td>8.99 (8.12)</td>
<td>1.82 (1.64)</td>
<td>1.84 (1.66)</td>
<td>285 $\pm$ 74</td>
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<td>3.86</td>
<td>3.86</td>
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<tr>
<td>72 A.F. demagnetized data (from total 96)</td>
<td>119.4 (68.5)</td>
<td>88.8 (89.3)</td>
<td>8.89 (8.22)</td>
<td>8.97 (8.25)</td>
<td>2.10 (1.94)</td>
<td>2.12 (1.94)</td>
<td>260 $\pm$ 90</td>
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<td>3.38</td>
<td>3.53</td>
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<tr>
<td>10 regional means</td>
<td>166.2 (165.8)</td>
<td>88.9 (89.5)</td>
<td>5.16 (3.39)</td>
<td>5.27 (3.43)</td>
<td>3.26 (2.14)</td>
<td>3.34 (2.16)</td>
<td>280 $\pm$ 60</td>
<td></td>
<td>3.89</td>
<td>4.00</td>
</tr>
</tbody>
</table>

* The larger error $\pm$ 130 km compared with only $\pm$ 38 in Paper II, is partly due to the present deletion of the sea-core data from the earlier data set, and partly due to the different method of calculation.

$m$ Subscript referring to calculations about mean poles.

$p$ Subscript referring to calculations about geographic poles.

$\Delta$ Standard deviation of usual VGP's prior to modification.

$\delta$ Standard deviation of modified VGP's due to offset dipole.
orthogonality of sources of scatter means that the offset dipole has eliminated an
amount of scatter.

\[ \delta_{\text{reduced}} = (\Delta_p^2 - \delta_p^2)^\dagger = 3.86^\circ \]

or

\[ (\Delta_m^2 - \delta_m^2)^\dagger = 3.85^\circ \]

about the geographic pole or mean pole respectively. These numbers are in reasonable
agreement with the 3.2° of Section 4.1.

4.3

The third approach is to try to reduce experimental error and inadequately
averaged ancient field variation by taking regional means of the data. For our
purposes this means finding a regional mean geographic location and a mean direction
of magnetization, so as to be able to calculate a series of regional mean modified
poles for scatter minimization purposes. These averaging processes entail certain
small inaccuracies but the result is nevertheless useful as a condensed illustration of
the observations.

There are now ten geographical regions providing sufficient numbers of mean
poles to be considered separately. In Paper II there were only eight. The two new
regions are

1. Argentina (3 mean poles) plus the South Shetland Islands (1 mean pole)
2. E. Australia (3 mean poles) plus New Zealand (1 mean pole).

Some others of the 13 new data have also been added to the previously defined eight
regions.

Fig. 6(a) shows that all the ten regional unmodified poles (black dots) are far-side
(on average 3.9° far-side), using the COMMON SITE LONGITUDE representation
of Section 4.1. The probability of ten poles falling randomly to one side like this is
1/1024, and since each pole is the mean of a great deal of data, the likelihood of an
accidental result seems extremely remote. A dipole displacement of 280±60 km
modified the poles to become the open circle in the same diagram, which agrees well
with the 285±74 km of Section 4.2.

Fig. 6(b) shows how the scatter of the modified poles is reduced by the 280 km
displacement. A centred dipole puts seven out of ten poles more than 4° from the
geographic pole. Eight of the ten modified poles are inside this range. The scatter
is reduced by

\[ \delta_{\text{reduced}} = (\Delta_p^2 - \delta_p^2)^\dagger = 4.00^\circ \]

or

\[ (\Delta_m^2 - \delta_m^2)^\dagger = 3.87^\circ \]

5. Further consideration of the data

It is clear from Fig. 6(a) that eight out of ten regional observers, looking towards
the geographic pole, see their own regional mean modified poles between 3 and 4
degrees to the right of the geographic pole as well as being far-side. Since the observers
are in reality well spread out longitudinally, so are their poles (Fig. 6(b)). No time
average multipole field, and in particular no polar wander could produce a consistent
world-wide 'right-hand' result of this kind, which is linked with the mean eastward
declation discussed in Paper II. The results here reveal however that the two
regional poles, for the southern U.S.S.R. and for the Argentine plus South Shetland
Islands, have poles lying to the left. It may be therefore that an overall world average
will eventually show that this effect does not exist. Otherwise it remains as difficult
to explain as in Paper II.
6. Conclusion and discussion

We conclude that the second approximation to the sources of the time average palaeomagnetic field during the past 25 My is that of an axial dipole displaced $287 \pm 74$ km northwards from the equatorial plane. The subdivided estimates in Table 3 agree well with the earlier values. The problem has now been approached in four different ways including the palaeoinclination method of Paper II. It can therefore be said that the result is no accident of the method of calculation. The non-centred nature of the source introduces an average error of $3^\circ$ to $4^\circ$ in the usual pole position estimates, placing the pole always too far away from the observer. This source of dispersion may be eliminated by the recalculation of modified VGP's based on a non-centred dipole.

When this source of scatter has been eliminated, the remaining scatter of all 96 Upper Tertiary, Quaternary and Recent modified mean VGP's is about $8.1^\circ$, which probably represents a combination of inadequately averaged ancient field variations.
Dipole offset

and experimental error. The scatter of the ten regional mean modified poles is only 3.4° which represents a considerable elimination of these sources of scatter.

The offset dipole hypothesis seems to eliminate the need for, and to be incompatible with, simple polar shift during Upper Tertiary times. This, in conjunction with the papers of Cox & Doell (1964), Doell & Cox (1965), Doell (1969), Cox (1969), seems to be leading to the following phenomena associated with the behaviour of the geomagnetic field, in order of increasing period:

(a) Secular variation with periods of the order of several hundred years;
(b) Dipole wobble with periods of the order of several thousand or even a few ten thousand years;
(c) Reversals of the main field, aperiodic but happening on average every 200,000 years; and
(d) Dipole offset, which has persisted quite constant over the past 10 or 20 My at least. I believe that this concept can replace the random walk of the pole suggested by Cox & Doell (1964, page 2264) since a tilted dipole is no longer in existence when looked at from the new point of view. Their suggestion was entirely reasonable when poles were viewed from their Pacific area only (Alaska, Hawaii and later New Zealand have very similar longitudes, Galapagos is about 70° of longitude from these three). But in view of the results in this paper from a complete range of longitudes, no single polar movement or dipole tilt will suffice to explain the far-side effect. An offset dipole does explain the results to date fairly well.

The dipole offset is anomalous in that while (a), (b) and (c) have progressively larger amplitudes as their characteristic times increase, the dipole offset, which has persisted much longer, is an effect with only about 4° amplitude and is smaller than any of the other effects.

It also seems that while secular variation, dipole wobble and reversals are connected with the instability of the field generation mechanism, the statistically permanent dipole offset is more likely to be directly connected with the north–south asymmetries of the core–mantle interface as suggested by Cox (1969) and in Paper II.

Wells (1969) and Verhoogen & Wells (1970) have analysed Quaternary (46 sites) and Late (Upper) Tertiary (30 sites) by using a spherical harmonic technique. They showed that the best fit was obtained by a centred dipole + quadrupole + octupole, for Quaternary sites, but they felt that the errors involved made the difference from a simple centred dipole rather uncertain. The analyses in this paper, and in Paper II, differ from Verhoogen and Wells' in mathematical approach and in selection of the best data by objective means. It would appear that Verhoogen and Wells have perhaps accepted all available Quaternary data. Their typical $g_{2}/g_{1}$ value (-0.016) was about one sixth of the value derived from results in this paper (see Paper II)

$$\frac{g_{2}}{g_{1}} = \frac{2 \times \text{offset of dipole}}{\text{radius of the Earth}} = -0.089$$

while their octupole component $g_{3}$ is quite large. If it becomes desirable to incorporate an octupole component then the simple representation by an offset dipole will have become obsolete. It is true that the offset dipole contains an inherent octupole component $g_{3}$, but its magnitude relative to $g_{2}$ is fixed since ($r$ = dipole offset, $R$ = radius of the Earth)

$$\frac{g_{3}}{g_{2}} = \frac{-3r}{2R}$$
which is about $-0.08$ for $r/R = 1/20$ as in our case. This forces the octupole component to remain small, so that any unusually large octupole would necessitate abandoning the offset dipole model. The results of our own researches to date do not suggest that this will become necessary, but the offset dipole does have its limitations which are perhaps compensated by its pictorial clarity.

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