Cretaceous, Tertiary and Quaternary Palaeomagnetic Results from Hungary

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(Received 1969 November 12)*

Summary

Forty Tertiary and Quaternary lavas and shallow intrusive bodies have been sampled from four areas of Hungary. At least four oriented cores were taken from each body. The direction of magnetization has been determined for specimens cut from each core using the alternating-field cleaning technique to peak fields of at least 20 millitesla (200 gauss) and when necessary as high as 50 mT (500 gauss). Many of the cores showed a very high stability. Very tight clustering of the directions for the different cores from the same body give a mean value of $\alpha_{95}$ of 3.3°. Normal, reversed and anomalous directions are found and significant deviations of the mean virtual pole positions from the present pole are discussed.

Eleven Cretaceous lavas or shallow intrusive bodies were also sampled in one area in the manner described above except that all the cores had to be magnetically oriented. The results from these Cretaceous samples are generally rather scattered. This scatter may be the result of strong tectonic movements in the Cretaceous area after the bodies were formed, or of the commonly rather decomposed nature of the material from the limited exposure available.

1. Introduction

The opportunity for us to visit Hungary to make a collection of rocks for our palaeomagnetic studies was the result of a visit to Liverpool University by Professor A. Szalay, Director of the Institute for Nuclear Research at Debrecen. The opportunity was welcome because it gave us a chance to add to our collection of Tertiary volcanic rocks and to provide additional information for an analysis of the behaviour of the Tertiary geomagnetic field.

It also enabled us to extend our studies to more acid volcanic rocks than we had previously examined and to sample from Cretaceous volcanic material for the first time.

Four sampling areas, representing a range of age and rock types were chosen. In order of increasing ages these were:

(a) The Balaton Highlands (Bakony) in the west of Hungary (Basalts);
(b) The Zempléni Mountains (Tokaj) in the north-east (Andesites and Rhyolites);
(c) The Matra and Cserhat Mountains in the north (Andesites); and
(d) The Mecsek Mountains in the south (diabase basalts and phonolites).

All the collecting areas lie inside the Alpine–Carpathian arch surrounding the Hungarian Plain. Locations are shown on the map (Fig. 1) and details of the collecting sites, rock types and full reference codes are given in the appendix.

*Received in original form 1969 July 17.
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5. I

16.5°

22.5°

48°

Fig. 1. Outline map of Hungary showing locations of the four collecting areas

2. Ages

No radioactively determined ages are yet available on our material. However, in many cases, palaeontological control provides close age limits. The ages of the units in terms of the Phanerozoic time scale (Geological Society Phanerozoic time scale 1964) are shown in Fig. 2.

The Balaton basalts may range in age from the upper Pliocene to the Pleistocene (1-2 Mega annee) (Anon 1965, 1968) since they lie on the Pliocene (of Hungary) Pannonian clays. The andesites and rhyolites from the Matra Cserhat (12-16 Ma (My)) and Zempléni (9-13 Ma (My)) mountains are supposed to overlap in age (Nairn 1967; Panto, private communication), covering an interval within the Tortonian and Sarmatian sub-divisions of the Miocene. The Komlo (Mecsek) laccolith (C in Fig. 2) is Helvetian (Middle Miocene). The age of unit E003 (Matra) is uncertain; some Hungarian geologists think it may be Eocene (Varga, private communication).

The samples from the Mecsek are from the Hauterivian and Valanginian divisions of the lower Cretaceous (120-130 Ma (My)).

Within these general age groupings the exact stratigraphical (and therefore age) sequence of the units is only known for certain small groups.

3. Sampling

Hungary is a country of very modest relief with its highest point at just over 1000 m. In all the areas visited there is almost continuous vegetation. Exposures are generally poor; they are best in road cuts and quarries but mostly provide only one unit per exposure.

At least four independently oriented cores were obtained from each unit using portable diamond drills, the orientation being determined by geographical sighting where possible.
FIG. 2. Positions of the collection relative to the Phanerozoic Time scale.
(a) The Balaton Highlands (Group A)

The basalts of this region form hills and isolated caps. Some of them may represent vent fillings; others may be flows. Many of the basalts are columnar. All our collecting sites were in quarries and often it was possible to see that there had been little or no tilting since emplacement. In all thirteen cases it was possible to obtain satisfactory geographical orientations.

(b) The Zempléní Mountains (Group D)

Most of the samples were taken from shallow intrusions (‘Sub-Volcanic’). A few were from flows. They are all intermediate to acid (andesite-rhyolite) in composition. Evidence from some of the many boreholes made by the Hungarian Geological Institute in this area suggested that dips are either small or indentifiably original but an apparent tectonic tilt has been measured by ourselves at one of the thirteen sites (D001). Magnetic orientation had to be used for units D001 to D006 owing to bad weather.

(c) The Matra-Cserhat Mountains (Groups E and F)

This is another region of intermediate and acid volcanism, here mainly andesitic. In the central region the local geologists report evidence of hydrothermal alteration of the older rocks. These altered volcanics were avoided by sampling at marginal locations. Younger rocks, the upper andesites, are not altered. It is possible that some of the vulcanicity was submarine as judged from the water deposited tuffs and marine limestones associated with the andesite flows at Samsonhaza (F001 and F002).

There is little general evidence of tectonism; evidence of tilting was found only at Samsonhaza where tilts of between 17° and 20° were measured. In this case we believe the tilting to be post eruptive from the evidence of tilted enclosing sediments although some local geologists think they may be original.

Thirteen units were collected and all orientations were geographical.

(d) The Mecsek Mountains (Groups B and C)

This is an area largely of lower Cretaceous submarine basaltic volcanicity. Many of the eruptions formed flows of hyaloclastic and pillow lavas (Bilik 1966). Unfortunately, the Cretaceous rocks of the Mecsek have experienced considerable tectonism, folding and faulting being common. Correction for these effects could not be made with certainty owing to the limited exposures available. Thus lower accuracy and precisions can be expected for this set. Furthermore many of the exposures were in wooded country and we were forced to use magnetic orientation for units B001 to B011. On the other hand the untectonized Tertiary (Miocene) Laccolith at Komló was extensively exposed in a large quarry and geographical orientation was possible.

4. Measurements

The natural remanent magnetization of each core was measured using an astatic magnetometer. Alternating field demagnetization was carried out in steps of 5 mT (= 50 gauss; Anon 1965, 1968) to at least 20 mT (200 gauss). In some cases demagnetization was carried out at higher fields in order to be certain that remanence directional changes were complete.

5. Averaging procedure

A single specimen from each oriented core (sample) is measured and the unit (distinct formation) mean directions have been found in the following way.
The measurement-demagnetization sequence gives a set of at least five directions for each core (independently oriented sample). A consecutive pair of these directions is taken for each core from the unit and the mean direction for the set is found. The procedure is then repeated for all possible combinations of pairs of directions to find which gives the least scatter. The corresponding mean direction is defined as the best direction for the unit. Least scatter is taken to give the largest value of the precision parameter, \( k = (N - 1)/(N - R) \) (Fisher 1953) since this is readily calculated. The calculation has been programmed for the I.B.M. 360/50 computer of the University of Liverpool Physics Department.

This method of averaging is used because frequently we find that the demagnetization curve for individual cores from the same unit are quite different (Fig. 3), and therefore it is not necessarily correct to obtain a mean direction using directions for the same demagnetizing field for each core.

Again it is not necessarily correct to choose the final direction obtained for each core as the best direction for that core because we often find that after converging, the directions diverge again as the result of the addition of significant magnetic moments during the demagnetizing process. (See for instance Irving 1964). With these facts in mind an objective method of choosing the best direction for each core as well for the unit as a whole is needed.

Considering a consecutive pair of directions from each core the point of convergence is found and spurious results are avoided. By taking pairs from all cores at the same time the best overall result is found for the unit. This is a modification of the statistical process suggested by Irving, Stott & Ward (1961) and gives equal weight to each of the independently oriented samples.
In the tables of results (Tables 1–4) the parameter \( N \) is the number of directions taken together and \( R \) is the sum of the \( N \) unit vectors. The actual number of independent cores is \( N/2 \) so this method of calculation gives a value of \( \alpha_{95} \) about 70 per cent \((1/\sqrt{2})\) of that which would normally be reported for \( N/2 \) directions from \( N/2 \) cores. Use of the \( \alpha_{95} \) defined in this way for the unit mean direction is justified by the additional information considered.

6. Results

Of the 51 units collected one, a rhyolite (D003), was too weak to measure on the most sensitive range of the astatic magnetometer \((10 \text{ mm scale deflection } = 10^{-7} \text{ Am}^2 (10^{-4} \text{ e.m.u.}))\). Four others B004, B005 (Cretaceous basalts), D012 (a rhyolite) and E011 (an andesite) gave such scattered results that we have rejected them because there is no clear evidence of a common original direction of magnetization.

(a) The Tertiary samples

The high magnetic stability or 'hardness' of many of the specimens was noteworthy. This characteristic was particularly marked for the more acid rocks, the andesites and rhyolites, for which 28 per cent of the cores had a stability factor, \( S \), greater than 0.8 at 20 mT (200 gauss). This stability factor, defined by Wilson, Haggerty & Watkins (1968) takes into account both intensity and direction during demagnetization. Absence of change in intensity and direction gives a stability factor of unity, a great change in either gives a stability factor approaching zero. Using this parameter, \( S \), we compare the average behaviour of the andesites and rhyolites with the average behaviour of the Balaton basalts and also with a 10 per cent sample \((200 \text{ cores})\) of our collection of Icelandic basalts (Dagley et al. 1967). Fig. 4
shows that the more acid rocks are, on the average, more stable than the basic (basaltic) rocks. This could mean that secondary (viscous) magnetization is a much smaller component relative to the thermoremanence in the acid rocks than in the basic ones and or that the primary magnetization of the basalts is much 'softer' than that of the acid ones so that its magnitude is reduced considerably during the cleaning process.

A high directional stability is demonstrated by the tight clustering of directions obtained after successive steps of the alternating field demagnetization of a single core. In addition the directions obtained for the separately oriented cores from the same rock unit are generally in close agreement; this is illustrated by the low average within unit $\alpha_{95}$ of 3.3°.

The mean direction for all the units are shown in Fig. 5 and listed in Tables 1, 2 and 3. In Fig. 5 the circles are circles of 95 per cent confidence as defined in Section 5 above.

There is considerable variation between the mean directions for the different units. It seems that these differences between the precisely defined mean directions of magnetization cannot be explained in terms of misinterpreted tilts of units since tilts (of any origin) were generally no larger than a few degrees. Even if the 20° tilt of the lavas and interbedded sediments at Samsonhaza (units F001 and F002) has been wrongly interpreted as being of post-eruptive origin, the directions of magnetization of the two units would still be 60° and 80° respectively from the dipole field in the area.

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**Fig. 5.** Mean directions of Tertiary units. Equal area projection, radius of circles equal to $\alpha_{95}$, downward (+ve) inclinations $\Theta$; upward (−ve) inclinations $\bigcirc$.
Table 1

Mean directions of magnetization, virtual pole positions and associated statistics for Balaton Highlands and Komlo laccolith (Tertiary).

<table>
<thead>
<tr>
<th>Code</th>
<th>Location</th>
<th>Lat. °N</th>
<th>Long. °E</th>
<th>N</th>
<th>R</th>
<th>Dm</th>
<th>ETN</th>
<th>I0</th>
<th>δ</th>
<th>ε</th>
<th>k</th>
<th>θ</th>
<th>Polarity</th>
<th>Polat °N</th>
<th>Polong °E</th>
<th>δp °</th>
<th>δm °</th>
<th>Remarks</th>
</tr>
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<tr>
<td>A05-A001</td>
<td>Sarvaly Hill Quarry, Sumegpraga</td>
<td>46.93</td>
<td>17.1</td>
<td>8</td>
<td>7</td>
<td>980</td>
<td>22.8</td>
<td>47.0</td>
<td>4.0</td>
<td>1.4</td>
<td>352</td>
<td>3</td>
<td>N</td>
<td>22</td>
<td>64.2</td>
<td>124.7</td>
<td>2.5</td>
<td>3.8</td>
</tr>
<tr>
<td>A002</td>
<td>Zalaszentod</td>
<td>46.90</td>
<td>17.21</td>
<td>8</td>
<td>7</td>
<td>984</td>
<td>7.5</td>
<td>51.1</td>
<td>3.6</td>
<td>1.3</td>
<td>444</td>
<td>3</td>
<td>N</td>
<td>14</td>
<td>73.8</td>
<td>173.6</td>
<td>2.4</td>
<td>3.6</td>
</tr>
<tr>
<td>A003</td>
<td>Uzsabanya</td>
<td>46.90</td>
<td>17.31</td>
<td>8</td>
<td>7</td>
<td>985</td>
<td>16.4</td>
<td>54.5</td>
<td>3.6</td>
<td>1.3</td>
<td>452</td>
<td>3</td>
<td>N</td>
<td>13</td>
<td>72.9</td>
<td>145.5</td>
<td>2.6</td>
<td>3.7</td>
</tr>
<tr>
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<td>Uzsabanya</td>
<td>46.90</td>
<td>17.31</td>
<td>10</td>
<td>9</td>
<td>989</td>
<td>10.2</td>
<td>51.6</td>
<td>2.7</td>
<td>0.8</td>
<td>818</td>
<td>2</td>
<td>N</td>
<td>14</td>
<td>73.4</td>
<td>165.7</td>
<td>1.6</td>
<td>2.3</td>
</tr>
<tr>
<td>A005</td>
<td>Uzsabanya</td>
<td>46.90</td>
<td>17.31</td>
<td>8</td>
<td>7</td>
<td>969</td>
<td>17.3</td>
<td>56.6</td>
<td>5.1</td>
<td>1.8</td>
<td>225</td>
<td>4</td>
<td>N</td>
<td>12</td>
<td>73.9</td>
<td>138.4</td>
<td>3.9</td>
<td>5.4</td>
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<tr>
<td>A006</td>
<td>Halap Quarry</td>
<td>46.93</td>
<td>17.43</td>
<td>12</td>
<td>11</td>
<td>933</td>
<td>215.4</td>
<td>-50.5</td>
<td>6.1</td>
<td>1.8</td>
<td>163</td>
<td>3</td>
<td>R</td>
<td>157</td>
<td>58.7</td>
<td>124.7</td>
<td>3.1</td>
<td>4.6</td>
</tr>
<tr>
<td>A007</td>
<td>StzGorgy Hill—west side</td>
<td>46.85</td>
<td>17.43</td>
<td>8</td>
<td>7</td>
<td>993</td>
<td>159.0</td>
<td>-53.1</td>
<td>2.3</td>
<td>0.8</td>
<td>1051</td>
<td>2</td>
<td>R</td>
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<td>69.4</td>
<td>255.1</td>
<td>1.6</td>
<td>2.4</td>
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<tr>
<td>A008</td>
<td>StzGorgy Hill—upper flow</td>
<td>46.85</td>
<td>17.43</td>
<td>8</td>
<td>7</td>
<td>989</td>
<td>194.9</td>
<td>-55.6</td>
<td>3.0</td>
<td>1.1</td>
<td>620</td>
<td>2</td>
<td>R</td>
<td>168</td>
<td>74.6</td>
<td>146.1</td>
<td>2.3</td>
<td>3.2</td>
</tr>
<tr>
<td>A009</td>
<td>StzGorgy Hill—second site</td>
<td>46.85</td>
<td>17.43</td>
<td>8</td>
<td>7</td>
<td>966</td>
<td>197.8</td>
<td>-46.9</td>
<td>5.3</td>
<td>1.9</td>
<td>203</td>
<td>4</td>
<td>R</td>
<td>160</td>
<td>66.6</td>
<td>154.5</td>
<td>3.2</td>
<td>5.0</td>
</tr>
<tr>
<td>A010</td>
<td>Gulacs Quarry</td>
<td>46.83</td>
<td>17.50</td>
<td>10</td>
<td>9</td>
<td>993</td>
<td>167.7</td>
<td>-74.5</td>
<td>2.1</td>
<td>0.7</td>
<td>1282</td>
<td>1</td>
<td>R</td>
<td>169</td>
<td>74.1</td>
<td>355.3</td>
<td>2.2</td>
<td>2.4</td>
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Table 1 (continued)

<table>
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<tr>
<th>Site</th>
<th>Mean A001–A005</th>
<th>Mean A006–A013</th>
<th>Mean A001–A013</th>
<th>A05–C001</th>
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<tr>
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<td></td>
<td></td>
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</tr>
<tr>
<td>A011 Gulacs Quarry</td>
<td>46.83</td>
<td>17.50</td>
<td>8</td>
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<tr>
<td>A012 Badacsony</td>
<td>46.80</td>
<td>17.50</td>
<td>8</td>
<td>7.990</td>
</tr>
<tr>
<td>A013 Hajagos Quarry</td>
<td>46.88</td>
<td>17.53</td>
<td>32</td>
<td>31.832</td>
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<tr>
<td>A015 Komlo Quarry</td>
<td>46.1</td>
<td>18.3</td>
<td>18</td>
<td>17.941</td>
</tr>
</tbody>
</table>

\[N = \text{number of directions averaged. For unit mean directions } N \text{ is twice number of cores collected at each site (see text); for group means } N \text{ is number of units.}\]

\[R = \text{length of resultant of } N \text{ unit vectors.}\]

\[D = \text{mean declination of remanent magnetization (ETN).}\]

\[I = \text{mean inclination of remanent magnetization (+ve down).}\]

\[\delta = \cos^{-1} \left( R/N \right) \text{ Angular standard deviation (Wilson 1959).}\]

\[\varepsilon = \delta/\sqrt{N} \text{ angular standard deviation of mean (Wilson 1959).}\]

\[k = \text{estimate of precision parameter (Fisher 1953).}\]

\[\alpha = \text{semi-angle of cone of 95 per cent confidence for mean direction (Fisher 1953).}\]

\[\gamma = \text{angle between mean direction and dipole field.}\]

\[\delta p, \delta m = \text{semi-axes of oval of confidence for virtual pole position.}\]
### Table 2

Mean directions of magnetization virtual pole positions and associated statistics for Zempléni Mountains (Tertiary). *Nairn’s (1969) results in parenthesis.*

<table>
<thead>
<tr>
<th>Code</th>
<th>Location</th>
<th>Lat. °N</th>
<th>Long. °E</th>
<th>N</th>
<th>R</th>
<th>$D_0$</th>
<th>$I_0$ down</th>
<th>$\delta$ °</th>
<th>$\varepsilon$ °</th>
<th>$k$</th>
<th>$\sigma_95$ °</th>
<th>Polarity</th>
<th>Polat °</th>
<th>Polong °</th>
<th>$\delta p$ °</th>
<th>$\delta m$ °</th>
<th>Remarks</th>
</tr>
</thead>
<tbody>
<tr>
<td>A05</td>
<td>Saskutberc near Mogyoroska</td>
<td>48.4</td>
<td>21.6</td>
<td>10</td>
<td>9-9</td>
<td>164.2</td>
<td>-62.1</td>
<td>8.0</td>
<td>2.5</td>
<td>91.4</td>
<td>5</td>
<td>R</td>
<td>164</td>
<td>77.9</td>
<td>273.0</td>
<td>6</td>
<td>7</td>
</tr>
<tr>
<td>D002</td>
<td>Satorhegy Quarry near Satoraljaujhely</td>
<td>48.4</td>
<td>21.6</td>
<td>12</td>
<td>11-9</td>
<td>160.0</td>
<td>-59.6</td>
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<td>0.8</td>
<td>812</td>
<td>2</td>
<td>R</td>
<td>169</td>
<td>73.7</td>
<td>269.8</td>
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<td>2</td>
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<tr>
<td>D003</td>
<td>Somlyod Quarry</td>
<td>48.4</td>
<td>21.6</td>
<td>8</td>
<td>7-9</td>
<td>337.3</td>
<td>65.1</td>
<td>8.2</td>
<td>2.9</td>
<td>85</td>
<td>6</td>
<td>N</td>
<td>9</td>
<td>74.8</td>
<td>295.4</td>
<td>8</td>
<td>10</td>
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<tr>
<td>D004</td>
<td>Senyo Valley</td>
<td>48.4</td>
<td>21.6</td>
<td>10</td>
<td>9-9</td>
<td>345.6</td>
<td>68.7</td>
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<td>1.6</td>
<td>239</td>
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<td>Senyo Valley</td>
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<td>21.6</td>
<td>8</td>
<td>7-9</td>
<td>310.5</td>
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<td>78</td>
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<td>22</td>
<td>55.2</td>
<td>301.1</td>
<td>7</td>
<td>10</td>
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<tr>
<td>D006</td>
<td>Pivrtok, north of Fuzer</td>
<td>48.4</td>
<td>21.6</td>
<td>10</td>
<td>9-9</td>
<td>122.2</td>
<td>-17.3</td>
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<td>1.1</td>
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<td>2</td>
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<tr>
<td>D007</td>
<td>Tolvajhegy, east of Fuzer</td>
<td>48.4</td>
<td>21.6</td>
<td>8</td>
<td>7-9</td>
<td>213.4</td>
<td>-62.2</td>
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<td>0.3</td>
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<td>99.7</td>
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<td>D008</td>
<td>Erdobenye</td>
<td>48.4</td>
<td>21.6</td>
<td>12</td>
<td>11-9</td>
<td>138.8</td>
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<td>40.5</td>
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<td>R</td>
<td>163</td>
<td>54.6</td>
<td>277.9</td>
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<td>9</td>
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<tr>
<td>D009</td>
<td>Sulyom Hill, near Abaujszanto</td>
<td>48.4</td>
<td>21.6</td>
<td>8</td>
<td>7-9</td>
<td>32.0</td>
<td>61.3</td>
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Mean $D_0$--$D_013$ all treated normal
(D003, D012 no data D007 not included)

| Units | 10 | 9-6591 | 352.5 | 66.3 | 15.0 | 4.7 | 26.4 | 9.6 | 85.00 | 298.6 | 13 | 16 |

*Units: 10°, 9° 6591°, 352.5°, 66.3°, 15.0°, 4.7°, 26.4°, 9.6°, 85.00°, 298.6°, 13°, 16°.*

*Remarks: Too weak to measure.*
### Table 3

Mean directions of magnetization, virtual pole positions and associated statistics for Matra and Cserhat Mountains (Tertiary). Key as for Table 1.

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<th>I₀ down</th>
<th>δ</th>
<th>ε</th>
<th>k</th>
<th>a₀₉₅</th>
<th>Polarity</th>
<th>γ</th>
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<th>Polong °E</th>
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<td>37-932</td>
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</tbody>
</table>
In the case of units A007, A008 and A009 slipping of the massive basalt on the lower incompetent Pannonian sand may have occurred (Jugovics, private communication). Unfortunately, exposure at this locality was insufficient to measure the rotation, if any, caused by the supposed landslipping.

At Hajagos quarry (A013) the attitude of the columns varied greatly so we sampled from several different parts of the quarry including a fan shaped arrangement of columns in the more regularly columnar basalt. Our aim was to try to decide between the alternative initial cooling and tectonic mechanism for the formation of the fan and the varying attitudes of the columns. Fig. 6 shows that directions from cores taken from different parts of the quarry are much more widely dispersed if the arrangement is assumed to be of tectonic origin (with the column inclinations taken as measures of tilts) than if it is assumed to be an initial cooling feature. Therefore we believe that no movement has occurred since magnetization.

The four units (D007, E003, F001 and F002) are outstanding in that their mean directions of magnetization much more than 40° from the present dipole field ($D = 0°$, $I = +65°$ (down)) (Tables 1–3). Within each unit the clustering and stability are good and it seems that these rocks record genuine directions of the geomagnetic field intermediate between Normal and Reversed. Units F001 and F002 are particularly interesting being two thick andesitic flows separated by a calcareous
water deposited tuff with the lower flow lying on a fossiliferous marl. The mean
directions for each of F001 and F002 are found from 19 and 23 separately oriented
cores respectively and it is possible that they provide a partial record of a single
transition between polarities near the boundary between the Helvetian and Tortonian
divisions of the Miocene (~15 Ma (My)).

All the other 33 unit mean directions are within 24° of the present dipole field.
The overall mean direction for these Tertiary units, $D = 2.2^\circ$, $I = + 61.0^\circ$ (down)
($\alpha_{95} = 4.8^\circ$, between-unit dispersion conventionally defined—equal weight to each
unit) is not significantly different from the direction of the present dipole field.

Mean pole positions have been calculated for the groups from each area.
(Tables 1–3, Fig. 10). The poles for groups A and D lie within the angle of 95 per
cent confidence of the present North pole while E lies just outside this range. C
represents only 1 unit. The virtual pole position for the whole of these sets is at
84.4° N 182.1° E ($\delta p = 6^\circ$; $\delta m = 7^\circ$).

**Fig. 7. Tentative magnetic polarity sequence for the Tertiary units.**
Mean directions of magnetization, virtual pole positions and associated statistics for the Mecsek Mountains (Cretaceous). Key as for Table 1. Values in brackets are without correction for tilt.

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<th>(I_0) down</th>
<th>(\delta) °</th>
<th>(\epsilon) °</th>
<th>(k)</th>
<th>Polarity</th>
<th>(\gamma) °</th>
<th>Polat °N</th>
<th>Polong °E</th>
<th>(\delta_p) °</th>
<th>(\delta_m) °</th>
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<td>Kvesteto Quarry near Hosszuhe teteny</td>
<td>46.1</td>
<td>18.3</td>
<td>8</td>
<td>7</td>
<td>914</td>
<td>20.5</td>
<td>34.0</td>
<td>8.4</td>
<td>3.0</td>
<td>8.1</td>
<td>6</td>
<td>A</td>
<td>33</td>
<td>57.8</td>
<td>159.9</td>
<td>4.0</td>
</tr>
<tr>
<td></td>
<td></td>
<td>(50.2)</td>
<td>(71.8)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>N</td>
<td>19</td>
<td>57.7</td>
<td>70.5</td>
<td>10</td>
</tr>
<tr>
<td>B010</td>
<td>Dezso Rezso</td>
<td>46.1</td>
<td>18.3</td>
<td>8</td>
<td>7</td>
<td>773</td>
<td>316.3</td>
<td>54.1</td>
<td>13.7</td>
<td>4.8</td>
<td>31</td>
<td>10</td>
<td>N</td>
<td>24</td>
<td>55.3</td>
<td>284.8</td>
<td>10</td>
</tr>
<tr>
<td></td>
<td></td>
<td>(9.4)</td>
<td>(69.7)</td>
<td></td>
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<td></td>
<td></td>
<td></td>
<td></td>
<td>N</td>
<td>6</td>
<td>80.5</td>
<td>54.2</td>
<td>15</td>
</tr>
<tr>
<td>B011</td>
<td>Dezso Rezso</td>
<td>46.1</td>
<td>18.3</td>
<td>8</td>
<td>7</td>
<td>948</td>
<td>306.8</td>
<td>48.5</td>
<td>6.5</td>
<td>2.3</td>
<td>135</td>
<td>5</td>
<td>N</td>
<td>32</td>
<td>45.7</td>
<td>285.5</td>
<td>4</td>
</tr>
<tr>
<td></td>
<td></td>
<td>(345.2)</td>
<td>(70.8)</td>
<td></td>
<td></td>
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<td></td>
<td></td>
<td></td>
<td>N</td>
<td>9</td>
<td>77.0</td>
<td>337.7</td>
<td>7</td>
</tr>
</tbody>
</table>

| Mean B001-B011 all treated as normal Tilt | Units | 11 | 9  | 550  | 333.7 | 46.7 | 29.8 | 9.0 | 6.9 | 18.7 | 62.5 | 256.2 | 16 | 24 |
|                                           | No Tilt | 10 | 074 | 43.3 | 79.2 | 23.7 | 7.1 | 10.8 | 14.6 | 58.6 | 46.3 | 26 | 28 |
A tentative polarity sequence is shown in Fig. 7 for the Miocene units (D, E and F) based on a probable stratigraphical order (Panto, private communication). The sequence of units from group A is not known.

(b). The Cretaceous samples

The results from the Cretaceous samples shown in Table 4 and Fig. 8 are less precise than those from the Tertiary. We have used the information provided by the local geologist (Bilik, private communication), together, where possible, with our own estimates, to make corrections for the tectonic movements. However any correction for tilt will only alter the unit mean direction and not the within unit scatter because in each case all cores were drilled in the same rock mass. It could however affect the between unit scatter so we have considered the possibility that magnetization took place after tectonic tilting. The between unit scatter is less when no correction is made for tilting. If it is correct to assume that the directions of the units should be similar then there is some possibility that magnetization occurred after tilting.

It is possible that both the within unit and between unit scatter may be due, in part at least, to the difficulties associated with magnetic orientation. Of the eleven units studied only the results for B004 and B005 appear to deserve complete rejection on the grounds of a very large within unit scatter of directions (angular standard deviations 34.8° and 48.8° respectively).

![Fig. 8. Mean directions of Cretaceous units. Equal area projection, radius of circles equal to \( a_{5/5} \), downward (+ve) inclinations \( \bigotimes \); upward (−ve) inclinations \( \bigcirc \). Full circles\( \bigotimes \) indicate mean directions only for rejected units, B004 B005.](https://academic.oup.com/gji/article-abstract/20/1/65/604044)
If all five cores are considered for B008 the direction is anomalous (more than 40° from the present dipole field direction) and the scatter is large. However the large scatter arises from two cores with poor internal consistency and directions very different from the other three. These last three are sufficiently coherent to suggest that the polarity is reversed. Mean directions based on these three cores are included in Table 4.

Virtual pole positions are shown in Fig. 10(b).

The geological succession is known quite well and Fig. 9 shows the measured polarities in chronological order.

7. Discussion

(a) Tertiary

To date there has been very little palaeomagnetic work done in Hungary. Marton, Szemeredy & Voros (1964) and Marton & Szalay (1967) have recently carried out a study in the Balaton area and Nairn (private communication) has sampled in the Zempléni mountains as an extension of his work in the neighbouring region in Czechoslovakia (Nairn 1966, 1967). Some of his sites are the same as some of ours.

Marton, et al. (1964) reported measurements of samples from the Tatika group of hills. Their results show considerable dispersion although they have used alternating field cleaning techniques. Their mean direction \( D = 130°, I = +71.5° \) (down), \( \alpha_95 = 5.8° \); pole 78° N 54.8° E differs from our results for A001–A005 (see Table 1) which are from the same area.
More specific locations are given by Marton & Szalay (1967) and although we cannot be certain that the exact sites correspond, three locations within the Tatika group are identical (Uzsabanya, Sarvalyhegy and Zalaszantod). Their mean direction is $D = 8.8^\circ$, $I = +58.7^\circ$ (down), $\alpha_{95} = 6.5^\circ$ with a pole at $80^\circ$ N $152.5^\circ$ E and is quite close to our mean direction for A001–A005 (see Table 1).

Marton and Szalay also collected at Halap, Szentgyorgyhegy, Gulacs and Badacsony so their units could correspond to A006, A007–A009, A010–A011 and A012 respectively.

Their Halap results ($D = 187^\circ$, $I = -56.3^\circ$ (up)) differ from ours by $18^\circ$ ($26^\circ$ in declination); our samples were from the lower level and they may have collected from a different unit. The exact site at Szentgyorgyhegy is not given by Marton but their result agrees quite well with our first site on the Western side, A007. The Gulacs results are also in quite good agreement with A010 which was from the upper flow. Their Badacsony results ($D = 153.1^\circ$, $I = -74.5^\circ$ (up)) differ by $9^\circ$ ($30^\circ$ in declination).

One possible explanation of these differences could be in the different methods of specimen orientation at the collecting site; all our cores from these sites were geographically oriented.

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**Fig. 10 (a)** Mean Virtual (North) Geomagnetic pole positions for groups of Tertiary units Equal area projection with present North. Geographic Pole at centre. Open circles, $\bigcirc$, in Northern Hemisphere; full circles, $\bullet$ in Southern Hemisphere.
As far as can be certain without having been present at the same occasion four of our units (D002, D004, D006 and D009) have also been collected by Nairn and three more (D007, D008 and D013) probably correspond to units of his collection.

The results for D002 and D006 agree quite closely (the directions differing by 3° and 11° respectively). Our result for D004 is some 20° steeper than Nairn’s. Nairn’s specimens from D009 were too weak to give satisfactory directions but show the same (reversed) polarity as ours. D007 and D008 also give similar results to the (probable) corresponding units of Nairn’s collection (differing by 17° and 6.5° respectively). In particular it is noteworthy that the anomalous direction of D007 is confirmed.

Nairn’s results from the Czechoslovakian extension of the Zemplén hegység (Nairn 1967) show similar features to our Hungarian results. In Czechoslovakia the rock types are andesites and rhyolites from the Upper Tortonian and Sarmatian sub-divisions of the Miocene. They show a similar between unit spread of directions with both relatively stable and unstable rocks, some of which are very weakly magnetized.

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**Fig. 10 (b)** Virtual (North) Geomagnetic pole positions for individual Cretaceous units. (i) Equal area projection with present North Geographic pole at centre. Open circles in Northern Hemisphere.
Nairn has put forward a tentative polarity sequence but without absolute ages it is not profitable to try to correlate it with ours. Heirtzler's interpretation (Heirtzler et al. 1968) of the oceanic magnetic anomaly patterns suggests that there have been about 10 normal and 10 reversed polarity intervals in the period between 9–16 Ma (My). Thus unless the age of a unit is known quite accurately and precisely the polarity is not a great help in placing a unit in the geological time scale.

Rocks of the same Tortonian–Sarmatian age from Central Slovakia (Nairn & Karolus 1965, Nairn 1966) give similar between unit scatter to our Hungarian material.

Other palaeomagnetic results from Czechoslovakia include those of Krs for the 2nd phase vulcanicity (Upper Tortonian) and 3rd phase (Upper Pliocene–Pleistocene). He reports mean directions after alternating field cleaning of $D = 13^\circ$, $I = +63\cdot1^\circ$ (down) ($\alpha_{95} = 9\cdot2^\circ$) and $D' = 10\cdot9^\circ$, $I = +72\cdot9^\circ$ (down) ($\alpha_{95} = 8\cdot8^\circ$) respectively which are to be compared with the results for our sections D, E and F and A.

Kruczyk reports some measurements on upper Tertiary andesites at Wzar, Poland (49\cdot4° N, 20\cdot3° E) which give a direction of $D = 197\cdot6^\circ$, $I = -80^\circ$ (up) ($\alpha_{95} = 7\cdot6^\circ$) and a pole position of 67\cdot3° N 35\cdot5° E ($\delta p = 14^\circ$, $\delta m = 11^\circ$). Of Kruczyk's 64 samples

![Fig. 10 (b) (ii) Equal area projection with present South Geographic pole at centre. Full circles ●, in Southern Hemisphere.](https://academic.oup.com/gji/article-abstract/20/1/65/604044)
Peter Dagley and J. M. Ade-Hall

56 gave a reversed NRM direction. Only 17 of the samples were tested for stability and 16 of these were used to define the mean direction. It is not clear how many different units were involved nor what the stability tests were. No mention is made of thermal or alternating-field demagnetization and the value of $a_{95}$ is large considering the number of specimens unless individual specimens are from separate units.

It can be seen from Fig. 10 that omitting the anomalous units the pole positions for each of our groups do not lie far away from the present pole and are within the oval of 95 per cent confidence. However they do seem to fall on the side of the geographic pole away from the collecting area. This feature has already been noted by Wilson (private communication) for other areas in Europe and Asia.

(b) Cretaceous

Recently Helsley & Steiner (1969) have summarized Cretaceous palaeomagnetic data. They suggest that there may have been long periods of Normal polarity and only a few short intervals of reversed polarity. During the Valanginian and Hauterivian (130–118 Ma (My)) stages of our collection their summary gives a transition from reversed to normal at around 129 Ma (My) then no further change in polarity until much younger ages. Our work would appear to give a normal-reversed-normal sequence with the younger transition coming somewhere near the Valanginian–Hauterivian boundary at 124 Ma (My). If this is so then there is an additional Reversed period just prior to this time not shown in Helsley and Steiner's Diagram. A much greater density of data will be needed before a polarity sequence for the Cretaceous can be produced with any certainty.

Acknowledgments

This work would not have been possible without the support and co-operation given to us by our Hungarian colleagues.

We would like to thank Professor A. Szalay, Director, and Dr Adam Kovach of the Institute of Nuclear Research, Debrecen for organising our stay in Hungary and helping with the collecting, Dr G. Kertai, Director, Drs G. Panto, J. Varga, L. Jugovics and I. Bilik of the Hungarian Geological Institute, Budapest for providing all the necessary geological information and guidance in the field. We must apologize to them for any mis-spelling of the Hungarian place names which we have committed.

We are also indebted to The Royal Society for providing travel funds. Dr A. E. M. Nairn kindly sent us a copy of his results from the Zemplénihegyseg before publication.

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Sample numbering

The complete reference code used by this department specifies for each core the geological age, geographic location, group label, unit and core number. In this collection Tertiary cores are prefixed A05, Cretaceous core B05. The full code for the first unit list below is therefore A05A001.

Notes on sampling sites

Balaton area; all basalt units of Tertiary to Quarternary age, (prefix A05).

A001 South west face of upper level in Sarvaly Hill Quarry near Sumegpraga (46-93° N; 17-1° E). Maximum tilt 3° in any direction and considered to be original. Thickness greater than 10m.
Small quarry at Kovaci hegy near Zalaszantod village (46-90° N; 17-21° E). Tilt less than 2° in any direction; jointing within flow close to horizontal. Thickness 10m as exposed.

Middle columnar flow at Uzsabanya (46-90° N; 17-31° E). No tilt distinguishable, thickness approx 8m.

Lower Flaggy flow at Uzsabanya, No tilt; thickness greater than 6m.

Regular columnar basalt from lower level of Halap Quarry (46-93° N; 17-43° E). No detectable tilt; thickness 10m as exposed.

Columnar basalt from small quarry half way up west side of Stz. Gyorgy Hill (46-85° N; 17-43° E). No good evidence for origin of tilt of columns—has probably slipped.

Flaggy basalt, upper flow at second site on Stz Gyorgy Hill. Jointing planes dip 15° at 80° EMN—unit probably slipped; thickness 10m as exposed.

Lower columnar basalt at second site on Stz. Gyorgy Hill, probably slipped; thickness 20 m as exposed.

Uppermost basalt in quarry on north face of Gulacs Quarry (46-83° N; 17-5° E). Tilt less than 5° to South as judged from jointing; thickness 20m as exposed.

Lower Columnar basalt in north face Gulacs Quarry. Jointing dips 44° at 140° EMN and flow may be faulted.

Badacsony Quarry (46-80° N; 17-5° E). Tilt less than 4° in any direction measured on jointing; thickness 30 m as exposed.

Columnar basalt from Hajagos Quarry (46.88° N; 17-53° E). Irregularity in columns shown to be original by fold test; thickness 20 m as exposed.

Mecsek Mountains (Lower Cretaceous; prefix B05).

Single outcrop of alkaline diabase pillow lava in Janosi Great Valley near Janosi Puszta (46-1° N; 18-3° E). Fourth and highest flow (\(\Omega K_1 V_4\)) of Valanginian. Enclosing sediments dip 45° at 315° EMN.

Alkaline diabase lava from lowest group (\(\Omega K_1 H_4\)) of Hauterivian series 250 m SE of Janosi Puszta well and 200 m down valley from B001. Tilt as for B001.

Sixth flow in Hauterivian succession, Janosi Great Valley. Tilt as for B001.

Dolerite sill (\(\Omega K_1 V_2\)) in Marevari valley (46-1° N; 18-3° E) in Bajocian limestones and marls. Enclosing sediments dip 51° at 310° EMN; thickness 3-5 m.

Pillow in pillow lava, below hyaloclastic top, from Valanginian (\(\Omega K_1 V_2\)) in middle Marevari valley. Dip as for B004.

Basalt flow from third stage of Valanginian (\(\Omega K_1 V_3\)) exposed in middle Marevari valley. Dip as for B004.

Alkaline diabase pillow lava of Hauterivian series (\(\Omega K_1 H_4\)) exposed at western edge of swimming pool in Marevari. Dip as for B004.

Alkaline dolerite sill (\(\Omega K_1 V_2\)) of Valanginian exposed near Hosszûhetény (46-1° N; 18-3° E). Dip of jointing 42° at 5° EMN.

Phonolite intrusion at Kovesteto quarry near Hosszûhetény (46-1° N; 18-3° E). Equated on petrological grounds with second stage of Valanginian vulcanicity (\(\Omega K_1 V_2\)).

Valanginian alkaline diabase pillow lavas (\(\Omega K_1 V_2\)) from middle part of Dezso Rezso valley (46-1° N; 18-3° E). Limestones below dip 30° at 280° EMN.
B011 As B010; it is not clear whether or not B010 and B011 are different flows.

Mecsek Mountains (Tertiary; prefix A05)

C001 Andesite laccolith exposed in Komlo quarry (46.1° N; 18.3° E) believed to be of lower Helvetian age. Dip less than 2° in any direction.

Zempléni (Tokaj) Mountains (Tertiary; prefix A05)

D001 Uppermost Sarmatian andesite flow. Tilt about 5° 225° EMN at Saskutberc (48.4° N; 21.6° E), near Mogyoroska.

D002 Upper Tortonian dacite from Satorhegy quarry, near Satoraljaujhely (48.4° N; 21.6° E). Tectonic effects small.

D003 Rhyolite from Somlyød quarry (48.36° N; 21.6° E), near Karolyfalva. Upper Tortonian age; tectonic effects small.

D004 A Sub-volcanic andesite, supposed lower Sarmatian exposure in Senyo valley (48.4° N; 21.6° E).

D005 Green welded tuff.

D006 Red Rhyolite

Both D005 and D006 are lower Sarmatian in age. Exposed in Senyo Valley, east of Telkibanya (48.4° N; 21.6° E).

D007 A dacite which bakes lower Sarmatian at Pivotka, north of Fuzer (48.4° N; 21.6° E).

D008 A rhyolite containing inclusions of dacite D007; Probably upper Sarmatian. Tolvalhegy, Fuzer, (48.4° N, 21.6° E).

D009 Andesite laccolith baking lower Sarmatian at Erdőbénya (48.4° N; 21.6° E).

D010, D011, D012, Top, middle and lower rhyolites near summit track on Sulyom hill near Abaujszanto (48.4° N; 21.6° E); D010 is the youngest formation in Western Tokaj. Drill records for boreholes show no apparent dip in sediments below rhyolites.

D013 A pyroxene dacite from Kopasz, Takaj (48.4° N; 21.6° E). Post lower Sarmatian with apparently no tectonism.

Matra-Cserhat (Tertiary; prefix A05)

E001 Upper Tortonian andesite, lower flow at south-east foot of Piszkets-teto (47.91° N; 19.95° E). No tectonic tilt.

E002 Upper Tortonian andesite, upper flow at same site as E001 (47.91° N; 19.9° E).

E003 Andesite dyke like body baking sandstones at Nagy-ko near Recsk (47.93° N; 20.1° E). Age not known but could be Eocene.

E004 An andesite of supposedly upper Tortonian age. Contains inclusions of material of same type as E002 and so probably younger, Csakanyko quarry (47.88° N; 20.1° E).

E005 One of three andesite flows in Füledugo quarry (Bolya Hill Centre) near Gyöngyőstarjan (47.47° N; 19.5° E). Tilt 7° at 0° ETN.

E006 Andesite at Harsas creek near Szucsí (47.8° N; 20.1° E) flow 3 of Harsas centre.

E007 Lower andesite flow at same site as E006; Flow 2 of Harsas centre.

E008 Rhyolite at Mülato-hegy (57.8° N; 20.1° E); no dip.

E009 Andesite from Kopasz-hegy Great Quarry (47.8° N; 20.1° E). Flow 3 of Kopasz-hegy centre.

E010 Upper andesite flow from Kopasz-hegy great quarry flow 4 of this centre. Probably no tectonic tilt.
E011 Andesite from quarry S.S.E. of Szurdokpuspoki (47°8' N; 20°1' E). 10th or 11th flow of Muzsla centre.

F001 Lower andesite Samsonhaza (47°98' N; 19°8' E). Tilt 17°5' at 80° EMN; about 10 m thick.

F002 Upper andesite flow same site at F001. About 8·5 m thick; tilt 19°5' at 78° EMN.

References


Note added in the proof

The latitude and longitude of the virtual poles given in Tables 1, 2 and 3 correspond to the intersection of the dipole axis with the Northern Hemisphere. The virtual (North) Geomagnetic Pole is of course in the Southern Hemisphere for the reversely magnetized Tertiary samples and is found by changing the sign of the latitude and subtracting 180° from the longitude.