Origin of the Magnetization of the Wichita Mountains Granites, Oklahoma

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Summary

The magnetization of the Cambrian Wichita Mountains basement complex consists of several components, two of which are shown to be significant. The residual primary remanence is associated with the original titanomagnetite and the dominant secondary component is carried by minerals of the ilmenite-haematite series. The latter has been acquired at temperatures up to 300 °C as a result of the regional hydrothermal alteration during late Palaeozoic. The secondary remanence is of thermochemical origin and carries a memory of a variable ambient field direction which may be modelled as a resultant of the geomagnetic field direction contemporaneous with the hydrothermal process and of the direction of the magnetostatic field of the primary titanomagnetite. Although the destruction of the original presumably Cambrian remanence has been extreme, in a few cases its direction appears to have been recovered. The results are complicated by the possibility of a self-reversal of secondary remanence as well as geomagnetic field reversal. An issue unresolved by the investigation relates to the possibility of generation of magnetite by heat treatment of rock material in the laboratory. It is generally concluded that it is difficult to recover the original cooling thermoremanence direction in an igneous intrusion which has been subjected later in its life to extreme conditions of hydrothermal alteration.

1. Introduction

The palaeomagnetic data for Cambrian rocks of North America are scarce and the results contradictory despite the work that has been done since the publication of the results of Collinson & Runcorn (1960). An investigation of the Lamotte sandstone in Missouri (Al-Khafaji & Vincenz 1971) suggested that some North American early Palaeozoic rocks have been remagnetized during the late Palaeozoic, but a study of an Ordovician limestone of New York State (McElhinny & Opdyke 1973) showed that this formation has not been remagnetized. More recently McElhinny, Giddings & Embleton (1974) presented justified arguments against the hypothesis of widespread late Palaeozoic remagnetization originally proposed by Creer (1968). Most of these studies as well as the earlier ones (Day & Runcorn 1955; Howell & Martinez 1957)

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were performed exclusively on sediments and the results yielded two groups of palaeomagnetic poles, one representing the late Palaeozoic or Mesozoic geomagnetic field and the other supposedly giving the direction of the Cambrian field. Black (1964) and Symons (1967) obtained intermediate pole positions.

The first attempt to study igneous rocks was made by Yaskawa, Vincenz & Giya (1966) who investigated the Cambrian basement complex of Wichita Mountains in Oklahoma and concluded that, despite their high magnetic stability, these rocks were not suitable for palaeomagnetic studies. Subsequent more refined measurements conducted by Ku et al. (1967) gave palaeomagnetic poles closely coinciding with those for the North American Carboniferous. A more detailed investigation of the Wichita Mountains granites was undertaken by Spall (1968) who obtained two distinctly different palaeopoles. One, based on data from specimens cleaned by alternating field demagnetization, was close to the Permo-Carboniferous North American poles, while the other, obtained after thermal cleaning of equivalent specimens, was close to the late Cambrian poles of Howell & Martinez or Al-Khafaji & Vincenz. Subsequent studies (Spall 1970) did not wholly support the above results and suggested the possibility of self-reversal. Further studies of early Palaeozoic igneous rocks were made by Larson & Mutschler (1971) who investigated Cambrian and Ordovician intrusives of Colorado and concluded that they were magnetized in the same direction as most of the late Palaeozoic rocks of North America.

These varied and contradictory results demand an explanation which must of necessity introduce the question of the origin of the magnetization of the Wichita Mountains complex. The present investigation has been undertaken to find an answer

![Igneous geology sketch map of Wichita Mountains](https://academic.oup.com/gji/article-abstract/42/1/21/712355/121712355)
to this question and is not necessarily intended to yield any specific information about the direction of Palaeozoic geomagnetic field.

2. Geological setting of the area

The Cambrian basement rocks in Southwestern Oklahoma crop out sporadically over an area of about 6000 square kilometres (Fig. 1). They comprise three rock types: the Wichita granites, the Carlton Rhyolites, and the Raggedy Mountain gabbros (Ham, Denison & Merritt 1964). The former two groups have been dated radiometrically at 525±25 My, while the gabbros have been assigned an age of 535±30 My (Tilton, Wetherill & Davis 1962). The rocks consist of intrusions (mainly sills and irregular plutons) or stratiform flows all of which have been block-faulted. According to Ham et al. (1964) the structural evolution of the Wichita Mountains province took place in several stages. The deposition of clastic sediments on the floor of Precambrian basement was followed by injection of plutons of gabbroic magma accompanied by extrusion of basalts and spilites. The Wichita region was then subjected to faulting, one feature of which was the formation of a central horst bounded by high angle normal faults. This uplift was followed by erosion of the gabbro and the eroded surface was then covered by a widespread blanket of rhyolites, followed by injection of the slightly younger granites which now form over 50 per cent of the surface exposures of the Wichita Mountains igneous province. In the late Cambrian, as a result of subsidence, the area was covered with sediments and sedimentation continued into the late Palaeozoic. The contact between the rhyolites and the overlying sediments, where observable, is however unconformable. In the Wichita block, the sill configuration of granites indicates that they were intruded into the contact between the gabbros and the still warm rhyolites. But the rhyolites overlying the granites, though 2–3 km thick, were almost completely eroded before the deposition of Cambrian sandstones (Ham et al. 1964).

The second and final uplift of the Wichita Mountains province took place in the Pennsylvanian, the subsequent erosion exposing the igneous basement consisting of granites, rhyolites, and gabbros which are differentiated into anorthosites, gabbros proper and diorites.

A dominant feature of the Wichita block was the uplift and subsequent almost total erosion of the rhyolites and complete erosion of sediments deposited during the periods of subsidence. The uplift was accompanied by down-warping on the north and south sides of the horst. The late Palaeozoic orogeny caused the central Wichita block to be only slightly tilted to its present position of a very gentle south dip. The wide and very gentle northward plunging and N–S striking anticline comprising the Wichita block was probably generated before the deposition of late Cambrian sediments. The Wichita Mountains essentially comprise the top of the anticline and the block-faulting without rotation has been associated with up and down movements only. Thus, the main granite and gabbro outcrops have virtually undergone no tectonic dislocation since Middle Cambrian and should be structurally suitable for palaeomagnetic investigations. The rhyolites north of Meer's fault (Fig. 1) have, on the other hand, been tilted through about 45° towards NE and would require a tilt correction to make them suitable for palaeomagnetic study.

Of special interest are the mineralogical characteristics of the rocks under investigation and the degree to which they have been altered. Ham et al. (1964) give a detailed description of these characteristics. All three units have been subjected to alteration beyond the stage of devitrification and new minerals have been introduced. Two types of alteration are present. One is contemporaneous with the extrusion, i.e. deuteric (high temperature) or, in the case of rhyolites, late deuteric, associated with the intrusion of slightly younger granites. In the granites the feldspars are clouded
and finely-disseminated haematite imparts to the rock at some sites a distinctive pink colour. The feldspars are also sericitized and, less commonly, replaced by epidote and zeolites. These are believed to represent the effects of the secondary, lower temperature phase of oxidation resulting from regional hydrothermal activity (Ade-Hall, Palmer & Hubbard 1971) to which the masses of deuterically oxidized granite have been subsequently subjected. Primary biotite and hornblende have been extensively replaced by chlorite. According to Winkler & Nitsch (1963) stable epidote is generated at about 300 °C and this appears to have been the temperature of hydrothermal alteration. The alteration is the same for surface and subsurface granites and cannot, therefore, be ascribed to weathering (Ham et al. 1964, p. 78). The gabbros and anorthosites also reveal typical symptoms of deuteritic alteration with some regional hydrothermal alteration superimposed. Although some of the olivine has been typically altered to iddingsite, much of it is surprisingly fresh for such ancient rocks. Hydrothermal alteration is indicated by decomposition of plagioclase which has been changed to sericite and prehnite or replaced by zeolites. Epidote and chlorite replacements are also present. The alteration of gabbros and anorthosites is, however, less pronounced than that of granites or rhyolites and they typically contain a high percentage of iron (up to 12 per cent) residing in magnetite and ilmenite.

Clearly, investigation of the magnetic properties of Wichita intrusives cannot be conducted without considering varying degrees of oxidation of the magnetic minerals and the two-fold aspect of their alteration. Deuteric oxidation increases the stability of magnetization (Strangway, Larson & Goldstein 1968; Ade-Hall 1969), whereas hydrothermal alteration appears rarely to influence remanence stability (Ade-Hall et al. 1971). The temperatures and duration of oxidation during hydrothermal alteration are often related to the depth of burial. Our data will be considered in terms of such factors.

3. Sampling sites and laboratory methods

Oriented samples were obtained from thirteen sampling sites, the location of which is shown on the geological sketch map in Fig. 1. Nine sites were situated in exposures of granite, three in the gabbros, and one in the rhyolites.

Sampling was conducted in two stages, where the second stage involved re-sampling some of the sites sampled during the first stage. The reason for this was the very large scatter in the directions of magnetization of the samples obtained during the first sampling.

Measurement of intensity of magnetization was conducted on astatic and spinner magnetometers. For intensities greater than 10⁻⁴ emu cm⁻³ the observational error for the astatic magnetometers was always very much less than required to explain the observed scatter of directions. The stability of natural remanent magnetization (NRM) was investigated by alternating field (AF) demagnetization, using a three axis tumbler type of demagnetizer capable of producing peak fields up to 5000 Oe. Thermal demagnetization was conducted by heating the rock specimens to successively higher temperatures and cooling in a field-free space (maximum residual field 100 gammas but usually less than 50 gammas (Vincenz, Braught & Meyers 1965)) and the NRM was remeasured after each heating. The imperfections in the field-free space produced a random change in the direction of NRM in specimens heated to temperatures a few degrees below their highest blocking temperatures. To monitor some of the changes in the magnetic mineralogy produced by heating, weak-field susceptibility was measured after each cooling.

Identification of magnetic constituents was conducted by determination of Curie temperatures, X-ray diffraction analysis and microscopic study of polished sections. The Curie point measurements were made using a conventional Curie balance with
Fig. 2. NRM directions plotted on Schmidt equal area net. Solid circles, lower hemisphere; open circles, upper hemisphere. Symbol b indicates block samples. Nomenclature: a one or two digit figure identifies a core or a block sample; for the former the figure following the hyphen identifies specimens numbered from top to bottom; for the block samples the second digit identifies a core and the third digit following the hyphen successive specimens.
magnetizing fields ranging from 700 to 4000 Oe. X-ray diffraction studies were made with a Norelco X-ray diffractometer with a chromium target and vanadium filter. The WL-POL Zeiss and the Reichert Zeto Pan Pol microscopes were used in the polished section investigations.

4. Experimental results

4.1 Natural remanent magnetization

The results of measurements of the NRM are summarized in Figs 2–4. Fig. 2 gives the observed NRM directions. Large within site and between site scatter charac-
Table 1

Summary of sampling sites

<table>
<thead>
<tr>
<th>Site</th>
<th>Rock type</th>
<th>Texture</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>Granite</td>
<td>Medium to coarse</td>
</tr>
<tr>
<td>B</td>
<td>Granite</td>
<td>Medium to coarse</td>
</tr>
<tr>
<td>C</td>
<td>Granite</td>
<td>Medium to coarse</td>
</tr>
<tr>
<td>D</td>
<td>Granite</td>
<td>Coarse</td>
</tr>
<tr>
<td>E</td>
<td>Granite</td>
<td>Medium</td>
</tr>
<tr>
<td>F</td>
<td>Granite</td>
<td>Medium</td>
</tr>
<tr>
<td>H</td>
<td>Anorthosite</td>
<td>Medium to coarse</td>
</tr>
<tr>
<td>I</td>
<td>Anorthosite</td>
<td>Fine to medium</td>
</tr>
<tr>
<td>J</td>
<td>Granite</td>
<td>Coarse</td>
</tr>
<tr>
<td>K</td>
<td>Gabbro</td>
<td>Coarse</td>
</tr>
<tr>
<td>L</td>
<td>Rhyolite</td>
<td>Medium porphyritic</td>
</tr>
<tr>
<td>M</td>
<td>Granite</td>
<td>Coarse</td>
</tr>
<tr>
<td>N</td>
<td>Granite</td>
<td>Coarse</td>
</tr>
</tbody>
</table>

terizes the directional data. Since with the exception of site L, only large scale block-faulting disturbs the units studied, the directions could not be scattered through tectonic causes. The scatter must thus be attributed to the effect of significant secondary magnetizations. Since the scatter is large and relatively few directions fall close to the present day geomagnetic field direction, the effect of viscous remanent demagnetization (VRM) does not appear to have been dominant. The secondary demagnetization is, therefore, more likely a viscous partial thermoremanent (VPTRM), a chemical remanent (CRM), or thermochemical remanent magnetization (TCRM) acquired at various times in ambient fields of differing direction.

Table 1 summarizes the rock types sampled. Fig. 3 shows intensity histograms of the granites and indicates that with a few exceptions the most frequent magnitudes of intensity are confined to the range of $10^{-3}$ to $10^{-2}$ emu cm$^{-3}$, with the modal value in the range $0.1$ to $0.2 \times 10^{-3}$ emu cm$^{-3}$ (Fig. 3(b)). The exceptions relate to the very high intensities observed in sites A, J and N, mainly in the range of $11 \times 10^{-3}$ to $47 \times 10^{-3}$ emu cm$^{-3}$. Some of these may be due to lightning strike, though the sites were not situated on topographic highs. The gabbros, including anorthosites, are rather magnetic, while the rhyolites are weakly magnetic. Fig. 4 summarizes the values here as for the granites.

4.2 Alternating field magnetization

The stability of the NRM of the granites was investigated using AF treatment which was also expected to remove some of the secondary magnetization. Fig. 5 shows AF demagnetization spectra for representative specimens and Fig. 6 gives the corresponding directional changes. Table 2 summarizes the magnitudes of NRM before and after AF treatment and compares them with the changes in direction. The spectra reveal a wide range of magnetic stabilities. Most of the specimens, however, have lost the bulk of their magnetization by 350 Oe. This suggests that the coercivity of the magnetic material is not high and magnetic grain size is generally large, as would be expected in a coarse grained rock. The directions also show a wide range of stabilities and little tendency to group after AF treatment.

Comparing Figs 5 and 6 and Table 2 it appears that there is an approximate inverse correlation between the magnetic stability with directional stability. The directional changes are complex and cannot be easily interpreted. The systematic changes in direction seem to reflect the removal of the components of remanence associated with the low coercivity coarse-grained magnetic material, but ‘clean’ directions differ substantially in several specimens. Some specimens show little
Fig. 5. Normalized AF demagnetization spectra. The initial NRM intensities (in $10^{-3}$ emu cm$^{-3}$) are given in parentheses.
Fig. 6. Directional changes on AF demagnetization. Symbols as in Fig. 2. Peak fields indicated in Oe.
Table 2

*Intensities of AF demagnetized specimens*

<table>
<thead>
<tr>
<th>Specimen</th>
<th>(J_n)</th>
<th>((J_n)_n)</th>
<th>Directional changes</th>
</tr>
</thead>
<tbody>
<tr>
<td>A1-4</td>
<td>8.75</td>
<td>0.22</td>
<td>75</td>
</tr>
<tr>
<td>A2-4</td>
<td>39.21</td>
<td>0.19</td>
<td>38</td>
</tr>
<tr>
<td>C2</td>
<td>0.08</td>
<td>0.02</td>
<td>50</td>
</tr>
<tr>
<td>D1</td>
<td>2.43</td>
<td>0.15</td>
<td>13</td>
</tr>
<tr>
<td>D4</td>
<td>0.23</td>
<td>0.01</td>
<td>12</td>
</tr>
<tr>
<td>J21</td>
<td>0.53</td>
<td>0.04</td>
<td>91</td>
</tr>
<tr>
<td>J23-1</td>
<td>37.42</td>
<td>2.10</td>
<td>308</td>
</tr>
<tr>
<td>J32-1</td>
<td>1.90</td>
<td>0.03</td>
<td>148</td>
</tr>
<tr>
<td>J4</td>
<td>0.69</td>
<td>0.05</td>
<td>115</td>
</tr>
<tr>
<td>J53-2</td>
<td>0.11</td>
<td>0.01</td>
<td>35</td>
</tr>
<tr>
<td>J73-1</td>
<td>11.06</td>
<td>0.05</td>
<td>216</td>
</tr>
</tbody>
</table>

*Notes*

Intensities are given in \(10^{-3}\) emu cm\(^{-3}\) and columns 3, 4 and 5 give the intensities corresponding to three values of peak alternating field \(H\) in Oersted. Directional changes are in degrees of arc.

change in direction while in others the change is large and reverses its sense after treatment with peak fields higher than 44 or 88 Oe.

Using the principle of minimum scatter (Irving, Stott & Ward 1961) the mean direction and associated statistical parameters were computed for the demagnetized specimens before and after AF treatment. It was found that AF treatment did not reduce the overall scatter, but on closer examination six specimens gave a mean direction in the lower hemisphere of the SE quadrant of the equal area net, while five gave a direction approximately reversed with respect to this direction. On reversing the directions of the five specimens and combining with the other six, an improved and more consistent result was obtained as summarized in Table 3. The palaeomagnetic pole of positive polarity computed from the data in column 2 is situated at 15.8° N and 148.5° E (semi-axes of confidence oval 18.3° and 35.5°) close to the pole obtained by Spall (1970) also from AF demagnetized samples.

It is concluded that although AF treatment does reduce the scatter after adjusting the reversed directions, the significance of the resulting mean direction with an \(\alpha_{95}\) of 34.5° for eleven directions is not high. The secondary magnetization has evidently more than one component with a component or components sharing the same coercivity spectra as any remaining original TRM.

Table 3

*Directions and statistics before and after AF treatment*

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Virgin NRM</th>
<th>NRM after AF treatment (5 specimens reversed)</th>
</tr>
</thead>
<tbody>
<tr>
<td>(D)</td>
<td>280.3</td>
<td>116.2</td>
</tr>
<tr>
<td>(I)</td>
<td>-6.8</td>
<td>17.0</td>
</tr>
<tr>
<td>(k)</td>
<td>1.4</td>
<td>2.7</td>
</tr>
<tr>
<td>(\alpha_{95})</td>
<td>71.6</td>
<td>34.5</td>
</tr>
<tr>
<td>(\delta)</td>
<td>70.3</td>
<td>48.3</td>
</tr>
<tr>
<td>(\epsilon)</td>
<td>21.2</td>
<td>14.6</td>
</tr>
</tbody>
</table>

*Notes*

\(D\) is the declination, \(I\) the inclination, both measured in degrees; \(k\), the estimate of precision parameter; \(\alpha_{95}\), radius of 95 per cent circle of confidence (Fisher 1953); \(\delta\), angular standard deviation and \(\epsilon\), angular standard deviation of the mean (Wilson 1959) all three given in degrees.
Fig. 7. Thermal demagnetization curves. Hexagonal symbols denote the temperatures at which the directions become random. The initial NRM intensities (in $10^{-3}$ emu cm$^{-3}$) are given in parentheses.
Fig. 8. Directional changes produced on thermal demagnetization. Symbols as in Fig. 2. The temperatures in °C are given next to the symbols.
4.3 Thermal demagnetization

The results of thermal demagnetization of representative specimens are summarized in Figs 7 and 8. Fig. 7 shows curves representing the variation of normalized NRM with temperature. Although some of the granites have distributed blocking temperatures, the highest blocking temperatures are clearly confined to the range 520°–680 °C. The gabbros at site K all have distributed blocking temperatures, the magnetization showing a monotonic decrease and disappearing at 580 °C. The anorthosites (sites H and I) reveal a much higher NRM thermal stability and their high blocking temperatures are confined to the range of about 500 °C to 650 °C. The NRM of the rhyolites (site L) appears rather unstable, decreasing substantially between room temperature and 250 °C, an effect possibly associated with the removal of VRM (compare with Fig. 8). They have low blocking temperatures near 430 °C.

The directional changes are shown in Fig. 8. Some granites reveal a high directional stability (e.g. A2–2, D2), but others show fairly systematic changes not always towards the same final direction (e.g. F11 or J11). The systematic change in site J specimens is towards the directions observed by Al-Khafaji & Vincenz (1971) in the Cambrian sandstone of Missouri. The anorthosites also show a high directional stability in some specimens and systematic changes in direction in others, but the final directions are unrelated to those of the granites and do not appear to have any significance. The pattern of change in both the gabbros and rhyolites suggests a removal of VRM.

At first sight it would appear that thermal treatment did not materially reduce the directional scatter of the fourteen granite specimens. This can be seen from the first two columns of Table 4 in which the mean directions have been obtained using the principle of minimum scatter. Although R has increased after heating to a value greater than that for a random distribution of directions (Watson 1956; Vincenz & Bruckshaw 1960) the other statistical parameters have not changed materially after heat treatment. On reversing the directions of four specimens with high directional stability (A2–1, A2–2, D2 and D8), the adjusted mean directions yield improved statistical parameters. It is clear, however, that even after heating the scatter is large and the computed palaeomagnetic pole has confidence limits containing poles derived from both early and late North American Palaeozoic rocks (Hicken et al. 1972).

Table 4

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Virgin NRM</th>
<th>NRM after heating</th>
<th>Virgin NRM adjusted</th>
<th>Heated adjusted</th>
</tr>
</thead>
<tbody>
<tr>
<td>D</td>
<td>216·5</td>
<td>167·6</td>
<td>110·4</td>
<td>133·5</td>
</tr>
<tr>
<td>I</td>
<td>52·4</td>
<td>-12·6</td>
<td>42·6</td>
<td>10·9</td>
</tr>
<tr>
<td>k</td>
<td>1·1</td>
<td>1·9</td>
<td>1·9</td>
<td>3·3</td>
</tr>
<tr>
<td>g0·5</td>
<td>110·9</td>
<td>42·2</td>
<td>40·9</td>
<td>25·8</td>
</tr>
<tr>
<td>δ</td>
<td>60·8</td>
<td>60·0</td>
<td>59·9</td>
<td>43·8</td>
</tr>
<tr>
<td>R</td>
<td>2·245</td>
<td>7·001</td>
<td>7·208</td>
<td>10·103</td>
</tr>
<tr>
<td>λ'</td>
<td>14·0°N</td>
<td>59·4°N</td>
<td>1·2°N</td>
<td>30·5°N</td>
</tr>
<tr>
<td>φ'</td>
<td>51·3°E</td>
<td>108·1°E</td>
<td>136·7°E</td>
<td>138·2°E</td>
</tr>
<tr>
<td>δp</td>
<td>—</td>
<td>21·9°</td>
<td>33·1°</td>
<td>13·2°</td>
</tr>
<tr>
<td>δm</td>
<td>—</td>
<td>43·0°</td>
<td>51·1°</td>
<td>26·1°</td>
</tr>
</tbody>
</table>

Notes

R is the magnitude of the sum of fourteen unit vectors; λ', is the latitude and φ', the longitude of the northern polarity palaeomagnetic pole, and δp and δm are the semi-axes of its oval of confidence. Other symbols as in Table 3.
FIG. 9. Weak-field susceptibility measured at room temperature after each heating and cooling cycle.
FIG. 10. Determinations of Curie temperatures. Solid circles, heating; open circles, cooling. A, D, and J heated in 2530 Oe; E in 3,600 Oe; C and F in 4,200 Oe; K in 510 Oe; L in 2,200 Oe. A, C, E, and F heated in nominal vacuum (about 10⁻³ Torr); D, K, and L heated in air.
Fig. 11. Determinations of Curie temperatures for site B. Samples heated in 2530 Oe. Solid circles, heating; open circles, and triangles, cooling. (a) Heated in air; (b) curves 1 and 2 for identical sample as in (a) heated in vacuum ($10^{-3}$ Torr); curve 3 the same sample after baking in vacuum for 13 h at 610 °C and giving 36.3 arbitrary units of magnetization at 430 °C; and (c) the same sample as in (b) but reduced in size to less than one-sixth in mass and heated in air.
4.4 Weak-field susceptibility

The results of measurements of weak-field susceptibility after each cooling are summarized in Fig. 9. In almost all cases the susceptibility increases sharply after heating above 250–300 °C. There is no change on heating only in specimens from sites J, F and L.

It is possible that the sharp increase in susceptibility produced by heat treatment is associated to some extent with hitherto unknown phase changes in the existing magnetic minerals, but in addition it may be related to the generation of fresh magnetic material by decomposition of ferromagnesian minerals or to magnetite produced by reduction of haematite present in the rock.

4.5 Identification of magnetic minerals

4.5.1. Curie points. The dependence of saturation magnetization on temperature was investigated using the Curie balance. The observations were made in nominal vacuum of about 10⁻³ Torr using rock chips and not pure magnetic material extracted from the rock. This was expected to provide information on temperature dependent chemical changes in the rock suggested by the susceptibility measurements. The results of observations are shown in Figs 10 and 11 in which the saturation magnetization expressed in arbitrary units is plotted versus temperature. With allowance for experimental errors the observed Curie temperatures are listed in Table 5. The results reveal Curie points typical for magnetite, titanomagnetite, haematite and titanohema-

tite.

The behaviour of the rhyolites is unusual, because the NRM disappears near 430 °C yet the observed Curie temperatures are essentially those of magnetite and of an 8–10 per cent ilmenite–haematite solid solution. In an investigation of viscous secondary remanence Wilson & Smith (1968) have observed the opposite effect, in most cases the NRM blocking temperature occurring above the Curie temperature. The discrepancy between the two results suggests that the secondary remanence of the rhyolites is not of viscous origin. It seems probable, therefore, that the magnetic material with the Curie points near 600 °C carries little or no NRM.

The changes in magnetic minerology caused by heating are reflected in the difference or lack of difference between the heating and cooling curves. As a rule heating in vacuum results in an increase of saturation magnetization as reflected by the cooling curves for sites A, C, E and B (Figs 10 and 11(b)). There are, however, some exceptions to this rule as seen in the behaviour of the specimens from sites J and F. The

<table>
<thead>
<tr>
<th>Site</th>
<th>High temperature</th>
<th>Low temperature</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>572</td>
<td>200</td>
</tr>
<tr>
<td>B</td>
<td>578, 600</td>
<td>150, (480)</td>
</tr>
<tr>
<td>C</td>
<td>570, 670</td>
<td>150,350</td>
</tr>
<tr>
<td>D</td>
<td>580, 610</td>
<td>(150), 360, (450)</td>
</tr>
<tr>
<td>E</td>
<td>580, 670</td>
<td>(150), 360, (450)</td>
</tr>
<tr>
<td>F</td>
<td>570</td>
<td>150, 350</td>
</tr>
<tr>
<td>J</td>
<td>522, 580, 605</td>
<td>(100)</td>
</tr>
<tr>
<td>K</td>
<td>585</td>
<td>—</td>
</tr>
<tr>
<td>L</td>
<td>580, 620</td>
<td>(150)</td>
</tr>
</tbody>
</table>

Notes
The figures in parentheses refer to uncertain or indistinct Curie temperatures.
specimens heated in air either show a decrease in saturation magnetization on cooling (D and L, Fig. 10) or a more or less exact reproduction of the heating curve (site K, Fig. 10 and site B, Fig. 11(a)). This effect was studied in greater detail and the results are shown in Fig. 11. On heating in a vacuum of about $10^{-3}$ Torr a specimen identical to that heated in air (Fig. 11(a)), the curves 1 and 2 in Fig. 11(b) were obtained and the magnetization has clearly increased after heating. On reheating the same specimen and baking it in vacuum for 13 h at 610 °C, an enormous increase in magnetization was observed, exceeding the capability of the Curie balance at temperatures below 430 °C (curve 3, Fig. 11(b)). On reducing the mass of the sample to less than one-sixth of the one used in Fig. 11(b) and heating it in air, the curves of Fig. 11(c) were obtained, typical for the other granite samples heated in air. Similar results were obtained with rock chips from sites A, C and D.

An analogous effect has recently been observed by Dasgupta & Vincenz (1974) who have noted that no increase in room temperature saturation moment occurs if the magnetic material is heated alone, without any rock matrix.

The above experiments should be viewed in the light of the results of weak-field susceptibility measurements. It would appear that prolonged heating in vacuum has resulted in change of the original magnetic material into a new one. Such a phase change cannot, however, account fully for more than a ten-fold increase in room temperature moment (compare curve 1 in Fig. 11(b) with the cooling curve in (c)). It seems probable that the heating has also produced a great deal of magnetite and, as a result, the saturation magnetization of the sample increased to many times that of the virgin rock. Heating in air, on the other hand, has resulted in oxidation of not only the primary magnetic material but also of magnetite created by heating and this caused either a decrease in saturation magnetization (as in D, Fig. 10 or in B, Fig. 11(c)) or allowed the newly-generated magnetite to make up for the loss of magnetite caused by oxidation (as in K, Fig. 10 or in B, Fig. 11(a)).

An alternative interpretation for the effect of increase of saturation magnetization is that the abundant haematite has been reduced to magnetite. Heating in air would in such a case cause simultaneous oxidation of all the magnetite, yielding the observed changes in magnetization. The evidence is at present insufficient to show which interpretation is correct.

If the former interpretation is accepted it would be reasonable to conclude that secondary oxidation of the Wichita Mountains basement complex occurred mostly at temperatures near, but not much above, 300 °C since the source of secondary magnetite, i.e. the decomposition products of ferromagnesian minerals were not substantially depleted in view of their supposed ability to produce additional magnetite. Where hydrothermal alteration was weak, there was apparently little or no decomposition of ferromagnesian minerals and hence no subsequent generation of magnetite in the laboratory (as in specimens J and F, Fig. 9; but compare with D, Fig. 10).

Oxidation of decomposition products of ferromagnesian minerals has not so far been observed in the laboratory, but Pucher (1969) reported generation of magnetite by oxidation at 600 °C from the ilmenite in the 79 per cent ilmenite-haematite solid solution. There is evidence, however, (Turner 1968) that processes of this kind occur in nature. The minerals involved are biotite and chlorite. Chlorite breaks down into muscovite and on reacting with pyrophylite eventually turns into biotite, which on dehydration yields orthoclase and magnetite. The reactions are related to already present 'opaques' which determine the temperature at which biotite and chlorite will react.

It is suggested that this natural process also takes place in the laboratory, but there is no evidence that the reaction could occur during the short time of an experiment. On the other hand, the alternative interpretation does not explain the increase
Fig. 12. X-ray spectrograms. M, magnetite or titanomagnetite; H, haematite or titanohaematite; I, ilmenite; γH, maghaemite; P, pyrrhotite.
in susceptibility observed in gabbro specimens from site K (Fig. 9), which were found to contain no haematite (see below). As an overall conclusion it is evident that although magnetite and titanomagnetite are magnetically dominant, the presence of haematite and titanohaematite is also clearly indicated by Curie points in excess of 580 °C. In view of the low saturation magnetization of the latter two it is likely that in granites, except at site J, at most 40 per cent, but usually a much smaller fraction of the existing magnetic constituents consists of magnetite or titanomagnetite, while the more abundant haematite and titanohaematite are almost wholly secondary oxidation products of primary titanomagnetite.

4.5.2. X-ray diffraction analysis. The powdered magnetic material extracted from representative samples from sites B, J, and K was investigated by X-ray diffraction. The resulting X-ray spectrograms are shown in Fig. 12.

The spectrogram for site B reveals predominance of peaks associated with haematite, but magnetite or titanomagnetite are also present. This agrees broadly with the picture obtained from thermal demagnetization of NRM (Fig. 7) which in one case disappears to a large extent at the blocking temperature of about 570 °C, but persists in the other case up to 670 °C. The main Curie temperatures are near 578 °C and 600 °C, suggesting that magnetite predominates in the acquisition of saturation magnetization, though presence of abundant titanohaematite and haematite is suggested.

Table 6
Opaque mineralogy

<table>
<thead>
<tr>
<th>Column 1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
<th>7</th>
<th>8</th>
<th>9</th>
<th>10</th>
<th>11</th>
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<tr>
<td>A</td>
<td>p</td>
<td>t</td>
<td>a</td>
<td>—</td>
<td>—</td>
<td>2-3</td>
<td>h</td>
<td>70-200</td>
<td>m-l</td>
<td>ss</td>
</tr>
<tr>
<td>B</td>
<td>a</td>
<td>p</td>
<td>a</td>
<td>—</td>
<td>—</td>
<td>3</td>
<td>h</td>
<td>50-200</td>
<td>—</td>
<td>su</td>
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<tr>
<td>C</td>
<td>a</td>
<td>p</td>
<td>a</td>
<td>—</td>
<td>—</td>
<td>3</td>
<td>h</td>
<td>100-200</td>
<td>ms</td>
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<tr>
<td>D</td>
<td>a</td>
<td>t</td>
<td>a</td>
<td>—</td>
<td>—</td>
<td>3</td>
<td>h</td>
<td>200-300</td>
<td>su</td>
<td>ls</td>
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<td>E</td>
<td>t-p</td>
<td>p</td>
<td>a</td>
<td>—</td>
<td>—</td>
<td>2</td>
<td>m-h</td>
<td>20-50</td>
<td>—</td>
<td>ls</td>
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<tr>
<td>F</td>
<td>t-p</td>
<td>p</td>
<td>p</td>
<td>—</td>
<td>—</td>
<td>2</td>
<td>m-h</td>
<td>10-100</td>
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<td></td>
</tr>
<tr>
<td>J</td>
<td>a</td>
<td>a</td>
<td>p</td>
<td>t</td>
<td>p</td>
<td>2</td>
<td>w-m</td>
<td>200-400</td>
<td>ms, lu</td>
<td>ms-ls</td>
</tr>
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<td>K</td>
<td>a</td>
<td>a</td>
<td>t</td>
<td>p</td>
<td>p</td>
<td>2</td>
<td>w</td>
<td>500+</td>
<td>—</td>
<td>su-ms</td>
</tr>
<tr>
<td>H</td>
<td>a</td>
<td>a</td>
<td>t</td>
<td>p</td>
<td>p</td>
<td>1</td>
<td>w</td>
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<td>—</td>
<td>ms-lu</td>
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<td>t</td>
<td>p</td>
<td>t</td>
<td>—</td>
<td>—</td>
<td>1</td>
<td>w</td>
<td>20-50</td>
<td>—</td>
<td>ss-ms</td>
</tr>
<tr>
<td>L</td>
<td>a</td>
<td>t</td>
<td>a</td>
<td>—</td>
<td>—</td>
<td>3</td>
<td>h</td>
<td>5-10</td>
<td>—</td>
<td>ss-mu</td>
</tr>
</tbody>
</table>

Notes
- Column 1, site.
- 2, abundance of magnetic minerals.
- 3, magnetite or titanomagnetite.
- 4, haematite or titanohaematite, usually pseudomorphing after magnetite, peripheral, in the form of veinlets and rarely in discrete rhombohedral grains.
- 5, maghaematization of magnetite.
- 6, pyrrhotite.
- 7, deuteric oxidation class.
- 8, secondary oxidation: h, high; m, medium; w, weak or none.
- 9, predominant grain diameters in μm.
- 10, directional changes on AF treatment.
- 11, directional changes on heating.

Description of changes: s, none or small (0°-20°)
- m, medium (20°-60°)
- l, large (greater than 60°)

Second letters: s, systematic; u, unsystematic.

Throughout the table a indicates abundant; p, present; t, trace; blank, not present.
The spectrogram for site J indicates clearly a predominance of magnetite or titanomagnetite, with little haematite, but apparently some maghaemite and the distinct presence of ilmenite.

In the gabbro K haematite is absent and magnetite or titanomagnetite predominate, but some ilmenite and possibly maghaemite also seem to be present, as well as some pyrrhotite.

4.5.3. Opaque mineralogy. The results of microscopic study of polished sections are summarized in Table 6 where a correlation is made with the directional changes listed in columns 10 and 11. The magnetic mineralogy of the granites can be summarized as follows:

<table>
<thead>
<tr>
<th>High proportion of magnetite</th>
<th>J → F &amp; E → B → C → A → D</th>
</tr>
</thead>
<tbody>
<tr>
<td>Little secondary alteration</td>
<td>Highly altered</td>
</tr>
</tbody>
</table>

The data clearly indicate the predominance of minerals of the ilmenite-haematite series, which are rarely of primary origin, most of the grains being pseudomorphs after magnetite. The presence of primary magnetite or titanomagnetite is noted in some of the granites, especially at site J, and also in the gabbros.

The most prominent characteristic of the opaque mineralogy of the granites and rhyolite is the clear evidence of hydrothermal alteration up to epidote zone conditions, i.e. a 300 °C or more reheating by hot groundwater (Ade-Hall et al. 1971). The diagnostic mineralogical features are the partial or complete replacement of magnetite in the typical Class 2 or Class 3 grains (Wilson & Watkins 1967; Ade Hall et al. 1968) by an aggregate of haematite (Fig. 13). Other features of interest are the occasional replacement of magnetite by a bright yellow ochreous phase (sample E11-a, Fig. 14(a)) and, in sample A1–2 (Fig. 14(b) and (c)) the complete removal of magnetite, leaving only a latticework of altered ilmenite lamellae. The degree of alteration of the magnetites is consistent with the presence of epidote in the granites. In contrast, the opaque minerals of the gabbro and anorthosite samples are relatively little altered, partial maghaemitization affecting some of the large Class 2 magnetites of the former and rare granulation of the Class 1 magnetites of the latter.

The main question arising from the opaque mineralogical investigation is whether magnetites that have seen such extreme hydrothermal alteration conditions can possibly retain any memory of original cooling thermoremanence (TRM) directions. The evidence from other investigations does not provide clear guidance on this question, examples of both retention and significant remanence overprinting being reported. The conclusion from this investigation appears to be that partial remagnetization has, in fact, taken place during hydrothermal alteration and that both remaining original cooling TRM and later magnetizations must have considerably overlapping blocking temperature and coercivity ranges. This follows from the fact that magnetic tests have not been able to separate clearly two remanences. A thermochronical type of later magnetization (Nagata & Kobayashi 1963; Kellog, Larson & Watson 1970) might be consistent with the requirements of the data.

4. Discussion of the results

5.1 Secondary remanence

The results of magnetic measurements must be viewed in the light of the information derived from opaque mineralogy. Most granites and the rhyolite clearly
show (Table 6 and Figs 13 and 14) a high degree of secondary oxidation of the opaques produced by the hydrothermal alteration up to epidote zone conditions as revealed by either complete or partial replacement of magnetite by haematite. The magnetization of the oxidized material may be expected to carry a memory of the ambient field contemporaneous with the hydrothermal alteration process, while the memory of the original cooling TRM directions has been retained by the residual primary magnetite (and perhaps also the rarely occurring primary haematite). Judging from the data it seems probable that the ambient field was at the time of remagnetization a resultant of two components, one representing the direction of the contemporaneous geomagnetic field and the other related to the magnetostatic effect of the original magnetization of the magnetite. In single grains the latter effect would be particularly significant. The secondary magnetization has in most cases blocking temperatures and coercivities comparable with those of the original titanomagnetite. This is clearly indicated by the results of AF and thermal demagnetization. The primary remanence, if existent, is usually dominated by secondary components and, with a few exceptions, cannot be recovered by the demagnetizing process. The secondary remanence appears to have more than one component, suggesting that the secondary material, as it was progressively generated, retained the memory of ambient fields of different directions. AF treatment of AI-4, A2-4 and C2 (Fig. 6 and Table 2) suggests such composite effect, the ‘clean’ direction in removal of the less stable components. The ‘clean’ directions of these samples apparently represent the stable secondary remanance probably of thermochemical origin and generally reflect the direction of the late Palaeozoic field in North America (Hicken et al. 1972). Similar effects are reflected in the behaviour of D2 and B8–1 (Fig. 8). In some cases the secondary remanence is of high stability, but apparently not always reflecting the direction of the late Palaeozoic field (e.g. D1 and D4 in Fig. 6).

The ‘clean’ and some NRM directions of the granites fall into two groups, one reversed with respect to the other (e.g. C1–1, C2, J4, J73–1 versus A1–4, A2–4, D1, D2 and J23–1). The ‘clean’ directions associated with the rhyolites, when corrected for the 45° NE tectonic tilt, and those of the gabbros match the first of these groups. The division into two oppositely magnetized groups suggests the effect of field reversal or of self-reversal at the time of remagnetization. In some cases the directions reflect the presence of several components of remanence with overlapping blocking temperature ranges. Thus at site E the NRM has a direction in the lower north-western quadrant of the equal area net, while the component with the high blocking temperature has a direction within the lower south-eastern quadrant (Fig. 8). The behaviour of J4 (Fig. 6) suggests a removal of the less stable NRM partly of primary origin. On the other hand, in J21 and J32–1 (Fig. 6) and J11 and J31 (Fig. 8) some components have been removed in part or wholly before the removal of what appears to be the primary remanence with a direction similar to that observed by Al-Khafaji & Vincenz (1971) in the Cambrian sandstone of Missouri. This agrees with the information obtained from opaque mineralogy of the rock at site J, showing predominance of class 2 titanomagnetite with only peripheral secondary oxidation (Table 6 and Fig. 13(d)). All the other granites are characterized by generally high hydrothermal alteration. Whenever the directional changes on demagnetization are small they are associated with material in which most of the magnetite has been replaced by haematite. Medium or large changes usually imply the presence of titanomagnetite unaffected by the hydrothermal process and sometimes carrying a VRM.

The complex behaviour of specimens J23–1 and J73–1 (Fig. 6) suggests that the coercivity spectrum is divided between at least two secondary components and a weak primary component (J73–1 at 44 Oe). Since the NRM of these two specimens was very high (Fig. 5), it may have also contained a horizontally directed isothermal component due possibly to a lightning strike.
FIG. 13. (a) Sample B11: Peripheral replacement of magnetite by haematite in a Class 3 grain. (b) Sample B11: Islands of magnetite in a haematite pseudomorph after a Class 3 grain. (c) Sample J3a: Partial replacement of magnetite in a Class 2 grain. (d) Sample J1a: Islands of magnetite in a haematite pseudomorph after a Class 2 grain. Note the unaltered ilmenite lamellae.
Fig. 14. (a) Sample E11–a: Bright yellow ochreous replacement of magnetite in a Class 2 grain. (b) and (c) Sample A1–2: Lattice of altered ilmenite lamellae remaining after complete leaching of magnetite from Class 3 grains.
The mineralogy of the gabbro (site K) would demand a behaviour similar to that of the granite at site J, but large grain size and lower oxidation index suggest a lower stability of primary remanence. This is borne out by the unstable primary remanence and a VRM which predominates over the less significant TCRM associated with the small amount of haematite. The behaviour of the anorthosites is more complex and also suggests absence of primary components.

A separate comment is required about the two groups of directions of opposite sense. It is not clear whether they imply a field reversal or a self-reversal. The palaeomagnetic poles, if computed from these directions, would be suited either in the Northeast Pacific–Eastern Asian region or in the South Atlantic. Choosing the Pacific–Asian area as a convenient location, the poles computed from the directions grouped in the north-western upper hemisphere of the equal area net will have a positive (northern) polarity while those from the south-eastern group of directions a negative (southern) polarity. Spall (1970) suggested the possibility of self-reversal of remanence of Wichita granites, but it could be argued that the observed two groups of directions represent a record of field reversal. At this stage no unequivocal solution of the dilemma can be offered.

5.2 Origin of observed remanence directions

As discussed above, the magnetization of Wichita granites is predominantly of secondary origin and only some of the rock reveals traces of what appears to be the original remanence. While the latter, though rarely recognized, reflects the direction of the Cambrian geomagnetic field, the former was imposed at later dates. It is proposed that the NRM directions reflect magnetization by a composite ambient field which was a resultant of the geomagnetic field contemporaneous with the hydrothermal alteration and the field produced by the original remanence carried by titanomagnetite. The hydrothermal process was probably associated with the late Palaeozoic orogeny which produced the uplift of the Wichita Mountains during the Pennsylvanian. The direction of the geomagnetic field contemporaneous with the hydrothermal alteration process would thus be expected to have been late Palaeozoic. The contribution to the ambient field by the magnetostatic field of the titanomagnetite within each magnetic grain would be expected to have decreased with time. Hence the direction of the resultant field should in general have also been time-dependent, stabilizing after most of the magnetite had been converted to haematite. A result, the secondary remanence imposed by this ambient field would vary in direction depending on the degree of the alteration process and the time of its cessation. The observed dispersion in directions both before and after AF or thermal ‘cleaning’ is in agreement with the proposed mechanism.

It could be argued that assuming the much quoted average geothermal gradient of $30^\circ$/km for the Wichita Mountains area, an overburden of 10 km would be required to obtain a temperature of 300°C. This is not an unreasonable estimate in terms of what is known about the geology of the area (Ham et al. 1964). It is, however, clear that an elevated temperature of this magnitude would not alone have produced the observed thermochemical changes in the Wichita rocks. In such a case the secondary remanence would be predominantly a viscous PTRM or a partial TRM and not a TCRM produced by a widespread hydrothermal alteration process. Even allowing for the time factor (Chamalaun 1964; Briden 1965), ‘cleaning’ by normal laboratory techniques would then be expected to reveal the original thermoremanence. The results show that, with a few exceptions, such ‘cleaning’ was not successful, because of overlapping coercivity and blocking temperature ranges of the original and secondary remanences. It would appear, therefore, that burial alone cannot account for the observations and a regional hydrothermal process, i.e. the effect of hot fluids
during the late Palaeozoic orogeny must have been dominant in the generation of secondary remanence. There is little doubt that the basement complex was subjected to reheating by burial during the time span between the Cambrian diastrophism and Pennsylvanian orogeny. The results do not exclude the possibility of such an additional effect, but the presence of a TCRM with a high blocking temperature precludes in most cases its dominant influence. Moreover, the observed mineralogy is typical for a widespread hydrothermal alteration and not for changes produced solely by extended burial.

The secondary remanence is thus expected to be mostly of thermochemical origin. Although the magnetostatic component of ambient field was produced by multidomain titanomagnetite, the magnetization of secondary haematite is associated with single domains. In connection with this a possible mechanism of self-reversal can be hypothesized along the lines originally suggested by Stacey (1963). Creer, Petersen & Petherbridge (1970) have considered the possibility of a self-reversal in basalts in terms of the magneto-static interaction process produced by oxidation of titanomagnetics at 400°C. Although the medium and conditions of the process were different

Fig. 15. Relative contributions to remanence direction by the geomagnetic fields and the magnetostatic field of primary titanomagnetite. Mean field directions are shown by broken lines for vectors in lower hemisphere and full lines for those in upper hemisphere. Mean directions: E, early Palaeozoic; L, late Palaeozoic; R, recent axial; + and − give the polarity. 95 per cent confidence circles and the great circle containing E and L are also shown. The individual remanence directions are those of Figs 6 and 8 and mean remanence directions from Tables 3 and 4.
from those considered here, the possibility of an analogous mechanism cannot be

Accepting the composite character of the ambient field during the hydrothermal
process it follows that the relative contributions of the components of the resultant
field determine the direction of the NRM in the rock. As a working hypothesis it is
assumed that the early Palaeozoic field direction is near that obtained for the Cambrian
Lamotte formation by Al-Khafaji & Vincenz (1971). The direction of the late Palaeo-
zoic field is computed for the Wichita Mountains locality from the mean of 20 Carbon-
iferous directions listed by Hicken et al. (1972). The resultant ambient field direction
depends on the relative contributions of the late Palaeozoic field and the magnetosota-
tic field having early Palaeozoic direction generated by the primary titanomagnetite.
The original remanence associated with unaltered titanomagnetite should reflect the
early Palaeozoic direction alone. Assuming, as suggested by the data, that both
normal and reversed directions occur, the resultant unit vectors will lie on the great
circle containing both early (E) and late (L) Palaeozoic vectors. This should occur
within the significance limits of the error circles of the two vectors, i.e. the great
circle is really a circular band the width of which is prescribed by the radii of confi-
dence of E and L. Fig. 15 illustrates the directional relationships for a few represen-
tative specimens and some remanence directions do in fact lie on the great circle.
Many of them, however, deviate from the great circle and to account for these devia-
tions it is necessary to introduce an additional component of remanence parallel or
antiparallel to a third vector not in the plane containing E and L. Any third vector
will account for these deviations, and it is reasonable to assume that it has the direc-
tion of the recent geomagnetic field of either normal or reversed sense. This third
vector is represented in the figure by the axial dipole field direction R at the Wichita
Mountains latitude. A contribution by such a VRM component accounts for the
NRM directions which do not lie on the great circle. Its effect should be apparent in
specimens which have revealed presence of maghaemite or of haematite derived
from maghaemite, both resulting from a low temperature oxidation process such as
weathering. As pointed out before, Wichita Mountains intrusives are remarkably
fresh and hence occurrence of maghaemite or of maghaemite oxidized to haematite
is infrequent. If, however, the latter is present, AF or thermal demagnetization
would be incapable of removing the secondary remanence and hence the observed
‘ clean ’ direction also would not lie on the great circle. As the Figure shows there are
indeed specimens which reveal this effect. The VRM carried by primary titanomag-
netite and maghaemite is, on the other hand, removable as illustrated by the behaviour
of K8–1 or J32–1. The Figure shows that most demagnetized specimens with a high
degree of hydrothermal alteration have directions clustering near the late Palaeozoic
direction and those containing an appreciable amount of primary titanomagnetite
tend to occur near the early Palaeozoic direction, though the correspondence is seldom
exact. There are, in fact, several notable exceptions and the interpretation is clearly
limited by the inherent directional scatter, because any perturbation of each of the
two unit vectors increases the overall error limits. The error is further increased if
the third vector i.e. the VRM, is associated with haematite derived from maghaemite.
The proposed interpretation is, nevertheless, supported by the fact that the mean
directions obtained after both AF and thermal treatment actually fall on the great
circle. The fact that they are close to the late Palaeozoic direction shows that it is
not possible to remove effectively secondary components.

There are several uncertainties in the proposed mechanism. It is not certain that
the mineralogical changes due to hydrothermal alteration have been produced
exclusively during the late Palaeozoic orogeny. Moreover, a continuous oxidation
process over a long period of time cannot be entirely excluded. The assumed early
Palaeozoic field direction is also subject to uncertainty, but the results of this investi-
gation support the view that there is a significant difference between the early and late Palaeozoic field directions.

6. Conclusive remarks

Much of the previous work on the effect of regional hydrothermal alteration has related to Tertiary basaltic lavas and has suggested that suitable cleaning techniques can recover the original cooling TRM directions unless the alteration has been extreme. The implications of this effect have not so far been clearly recognized for igneous bodies other than lavas. In the present case the investigation of the Wichita Mountains basement complex is of direct relevance and shows that extreme hydrothermal alteration up to epidote zone conditions affects adversely the original remanence directions. The central issues resolved by this investigation are:

1. Hydrothermal alteration of the Wichita Mountains basement complex appears to have been associated with the late Palaeozoic orogeny. It has resulted in a partial or complete destruction of the original TRM and generation of a secondary remanence of thermochemical origin.

2. The secondary remanence associated with the minerals of the ilmenite-haematite series carries a memory of an ambient field direction which may be modelled as a resultant of the geomagnetic field direction contemporaneous with the hydrothermal process and of the direction of the magnetostatic field of the primary titanomagnetite.

3. Though there exists no clear evidence for the difference between the early and late Palaeozoic field directions, in the Wichita Mountains intrusives the late Palaeozoic direction is associated with effects of hydrothermal alteration, while the rarely occurring unaltered material has a direction observed by several investigators in other Cambrian rocks of North America.

4. In a few cases, when the alteration has been less extreme, the original TRM directions can be recovered, but in the majority of cases, apart from considerable scatter, the directions are mostly those of the late Palaeozoic geomagnetic field.

From the point of view of palaeomagnetism these conclusions are disappointing since they leave little hope of the ability of recovery of original cooling TRM directions in an igneous body subjected to extreme conditions of hydrothermal alteration. A further complication in the data was introduced by the possibility of a self-reversal of secondary remanence as well as geomagnetic field reversal. The resulting structure of the NRM involves at least two components with overlapping coercivity and blocking temperature ranges. A laboratory simulation of the natural process of thermochemical magnetization in a composite ambient field appears difficult because of the time factor involved.

A problem unresolved by this investigation relates to the changes in magnetic properties produced by heating in the laboratory. Weak field and strong field data show a phenomenal increase of room temperature saturation moment after heating to 300 °C. This increase appears, in part at least, to be due to generation of secondary magnetite from the decomposition products of ferromagnesian minerals produced by the hydrothermal alteration of the rock, but could also result from reduction of abundant haematite. Such an effect has not so far been observed to be common in polished section studies and urgently needs to be investigated.

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