Palaeomagnetic studies of the Early Permian Ingelside Formation of northern Colorado

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Summary. Palaeomagnetic results have been obtained from the Early Permian Ingelside Formation at a location just north of Owl Canyon in northern Colorado. A total of 243 stratigraphically distinct core samples were collected at a stratigraphic interval of 28 cm. Curie temperature analysis and IRM acquisition experiments indicate that hematite is the predominant carrier of remanence in these samples. All the samples were subjected to partial thermal demagnetization. A two-step selection procedure involving the method of Helsley was applied to the partial thermally demagnetized data restricting the stable sample population to 34 samples which yielded an Early Permian pole at 45.9°N, 122.1°E (δp = 1.1, δm = 2.1, kappa = 147.3). This result is similar to other cratonic North American Permian pole positions and, when combined with other data from the Late Palaeozoic, defines a polar wander path along which the palaeomagnetic pole appeared to move systematically north-west from a position near southern Japan during the Mississippian to near 55°N, 103°E during the Early Triassic. No normal polarity zones appear in the Ingelside section.

Introduction

The number of well-documented palaeomagnetic poles from Permian strata for cratonic North America is rather limited, and those that do exist are mainly restricted to the Early Permian (Gose & Helsley 1972; Diehl & Shive, in preparation). (The Dunkard series originally thought to be Early Permian has now been reassigned to the Late Pennsylvanian (Clendening 1974) and therefore the pole position determined by Helsley (1965) has to be considered a late Pennsylvanian pole.) As Farrell & May (1969), Helsley (1971) and Peterson & Nairn (1971) have pointed out, many studies of Permian strata were carried out before magnetic cleaning and should be considered unreliable (Graham 1955; Runcorn 1955, 1956; Doell 1955; Collinson & Runcorn 1960). The results from McMahon & Strangway (1968a, b) also should not be considered reliable, since only af demagnetization was performed (Helsley 1971). The work of Peterson & Nairn (1971) is based on too few samples

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per formation and should not be used, while much of the work of Farrell & May (1969) and Helsley (1971) has been superseded by Gose & Helsley (1972). Scott (1975c) has recently suggested that the Maritime Provinces of Canada and New England east of the Appalachians were not a part of the North American plate until the early or middle Permian; therefore, much of the data on which the North American polar wandering path for the Late Palaeozoic is based should perhaps not be used. Thus, it is essential to study rocks of Late Palaeozoic age in order to define precisely the North American polar wandering path.

For this reason, the Ingelside Formation of northern Colorado was studied. Since the age of the formation is Early Permian, it was thought that the study could also serve as a check to see if a short normal event did occur near the Pennsylvanian–Permian boundary during the Late Palaeozoic Reversed Interval, as several authors have tentatively reported (Graham 1955; Helsley 1965; Khramov 1967). Recent studies from the Colorado plateau have shown no evidence to support this short normal event (Farrell & May 1969; Helsley 1971; Gose & Helsley 1972; Scott 1975a); therefore, it appears that the Late Palaeozoic Reversed Interval is of constant reversed polarity from the Desmoinesian to at least the Late Permian when several other normal events have been reported (Guicherit 1964; Petrova 1965; Dachroth 1969). If this short normal event (known as either the 'J. W. Graham event' or the 'Oak Creek event') could be documented, then it may provide a unique magnetozone that could be used for worldwide stratigraphic correlation.

Geology

The Ingelside Formation is composed of an alternating sequence of light brown, moderate reddish orange, and orange pink sandstones and yellowish-grey, light grey, and greyish-pink limestones and dolomites of marine and marginal marine to fluvial origin (Maughan & Wilson 1960). The formation crops out along the eastern flank of the Front Range in northern Colorado and is time equivalent to strata of early Permian age from the Casper Formation on the eastern side of the Laramie Range in south-eastern Wyoming. Fusulinid data indicate an early Permian age for the Ingelside Formation (Maughan & Wilson 1960). Where exposed the Ingelside ranges upward to 78 m in thickness. At the type section (Ingelside, Colorado), carbonates make up 28 per cent of the formation with the proportion of carbonates increasing northward and decreasing southward and westward from the type section. The Ingelside Formation is conformably and unconformably underlain by the Fountain Formation of Pennsylvanian age (Maughan & Wilson 1960) and is unconformably overlain by the Owl Canyon Formation of Permian age (Pearson 1972).

Sampling

Sampling of the Ingelside Formation was undertaken just north of Owl Canyon, Colorado in roadcut along Highway 287 (40.8° N, 105.2° W). At this location, the formation consists of four sandstone units and three interbedded carbonate units that strike N 8° E and dip 16° east. The formation is approximately 70 m thick with the carbonate units making up 34 per cent of the section. Core samples were collected using a portable gasoline powered diamond drill and oriented in situ with a Brunton compass. A total of 243 stratigraphically distinct samples were drilled at an average stratigraphic interval of 28 cm. Assuming an upper limit of 10 Myr for the deposition of the Ingelside Formation, a 28 cm sampling interval should detect any normal polarity event greater than 50 000 yr in duration. Therefore, the sampling interval is small enough to ensure sufficient data to detect any thin normal polarity zones.
Laboratory procedure

In the laboratory, samples were cut into as many 2.5-cm long cylinders as possible (usually two) avoiding the uppermost (weathered) part of the sample. Natural remanent magnetization (NRM) measurements were made both on a Schonstedt SSM-1 spinner magnetometer and on a ScT cryogenic magnetometer. Subsequent measurements after demagnetization were made on the cryogenic magnetometer. Samples were thermally demagnetized in a horizontal, non-inductively wound furnace of 24 sample capacity housed in six nested mu-metal cans, and cooled in three nested mu-metal cylinders which reduced the ambient field inside the cooling region to less than 15 gammas (nanotesla). Alternating field demagnetization was accomplished using an apparatus fitted with a four-axis tumbler. All samples were stored in a two-layer mu-metal can where the ambient field was less than 50 gammas (nanotesla) until measurement.

NRM and thermal demagnetization results

The NRM directions of all samples from the Ingelside Formation are shown in Fig. 1, corrected for geological dip. Directions from specimens from the core sample were vectorially averaged to give one direction per sample. As seen in Fig. 1, many of the samples have a heavy secondary magnetic overprint as indicated by the streaking or smearing of the NRM directions from an anticipated Permian direction (shallow upward inclination toward the south-east) toward the present day (secondary) direction \(D = 59.0^\circ, I = +69.0^\circ\) after structural correction with some samples displaying random directions. The average intensity of 166 sandstone samples is \(1.6 \times 10^{-6}\) emu cm\(^3\) \((10^{-9}\) A/m\)), while 13 samples from the

Figure 1. NRM directions \((N = 243)\) of the Ingelside Formation before thermal demagnetization, corrected for geological dip. Equal area projection. Open symbols are in the upper hemisphere, + in the lower hemisphere. Solid square, ●, represents the present geomagnetic field direction in the sampling area corrected for geological dip. Same symbols apply to all figures.
lowest carbonate unit in the section had an average intensity of $1.5 \times 10^{-6}$ emu cm$^{-3}$ ($10^{-2}$ A/m) with 64 samples from the other two carbonate units averaging $1.4 \times 10^{-7}$ emu cm$^{-3}$ ($10^{-10}$ A/m) in intensity.

Many of the samples acquired a very low stability component of magnetization between the time they were removed from the mu-metal storage cans and inserted into the magnetometer, causing these samples to drift noticeably during measurement. Generally, the relaxation time of this low stability component is short and measurement drift usually disappears within five minutes after the sample has been placed in the low field environment of the measuring region of the cryogenic magnetometer. The direction of this low stability vector is always that of the ambient magnetic field in the laboratory regardless of the orientation of the core in the sample holder, and therefore is probably of viscous origin. The degree of viscous decay also appears to increase with increasing thermal demagnetization; i.e. a sample showing little drift during NRM measurement would show an increase in drift when re-measured after thermal demagnetization. This viscous magnetization is mainly restricted to sandstone samples and did not have a stable magnetic direction upon thermal demagnetization. Viscous magnetization was not a problem in the carbonate samples. At least some of the secondary magnetization seen in Fig. 1 is probably viscous in origin, resulting from recent weathering at the outcrop affecting the sandstones much more so than the carbonates. Similar behaviour was exhibited by many of the sandstone samples from the Casper Formation collected near Horse Creek Station, Wyoming (Diehl & Shive, in preparation).

A group of samples showing varying degrees of secondary magnetic overprint was selected from the various sandstone and carbonate units for thermal and alternating field (af) demagnetization experiments. The samples chosen for thermal demagnetization out of this group were sequentially thermally demagnetized at temperatures of 100, 200, 300, 400, 500, 550 or 570, 600 and 630 or 675°C while those chosen for af demagnetization were magnetically cleaned at 50 (5.0), 75 (7.5), 100 (10.0), 125 (12.5), 150 (15.0), 175 (17.5), 200 (20.0), 300 (30.0), 400 (40.0), 600 (60.0) and 800 (80.0) oersteds (mtesla). The samples proved to have high af coercivities; therefore, af demagnetization had little effect. Thermal demagnetization proved to be much more successful in eliminating secondary magnetization and was used on all samples. The response to thermal demagnetization for

![Figure 2](https://academic.oup.com/gji/article-abstract/56/2/271/648590/56217/1645580)
some representative samples is shown in Fig. 2. In many instances, demagnetization, even at temperatures as high as 675°C, did not entirely eliminate the secondary overprint.

Curie temperature analysis and isothermal remanent magnetization (IRM) acquisition experiments were performed in conjunction with thermal and af demagnetization experiments to determine the magnetic mineralogy of the Ingelside Formation. Large block samples crushed to a powder were used for the Curie temperature determinations while standard core samples were used for IRM experiments.

A recording thermomagnetic balance similar to those of Schwarz (1968) and Doell & Cox (1967) was used to determine the Curie temperatures of the magnetic phases present in the samples collected. Powdered specimens of the samples were heated and cooled in air (see Shive & Diehl 1977a, b for discussion). Curie temperature analysis indicates that hematite was the primary carrier of remanence in the sandstones and in samples from the lowest carbonate unit. Not enough magnetic material was present in samples from the upper two carbonate units to give reliable Curie temperature data. Typical magnetization ($J_\tau$) curves exhibiting characteristic hematite Curie points are shown in Fig. 3 for a sandstone sample and a sample from the lower carbonate unit. The initial concave upward appearance of these curves upon heating is the probable result of a large component of paramagnetic minerals in these samples (Collinson 1968). The small inflections seen in both the sandstone and carbonate curves near the magnetite Curie point indicates that a small amount of magnetite is present in these samples. Binocular microscope examination of magnetic separates from various disaggregated sandstone samples revealed that hematite occurs as a red pigment staining and cementing grains together and as the black oxide mineral, specularite, in these samples. Specularite was not observed in any of the magnetic separates from the carbonate samples. Hematite appears only as a finely disseminated pigment in these samples.

![Figure 3. Representative thermomagnetic curves from (a) a sandstone sample, and (b) a sample from the lowermost carbonate unit.](https://academic.oup.com/gji/article-abstract/56/2/271/648590)
Successive isothermal remanent magnetizations (IRM) were given in progressively increasing fields (up to 10 kOe [1 tesla]) to at least one representative sample from each of the sandstone and carbonate units using a 4-inch electromagnet. Most of the IRM acquisition curves (Fig. 4) from these samples show no tendency to level off in fields up to 10 kOe (1 tesla). This behaviour can be attributed to hematite, present as pigment in these samples. The curves from samples belonging to the lower and middle carbonate units (Fig. 4(b)) are concave upward near the origin, indicating the lack of any significant amount of magnetite in these samples (Dunlop 1972). The coercivity spectra (Fig. 4(e)) of these samples also indicates a lack of IRM contribution from magnetite (Dunlop 1972). The IRM acquisition curves from the sandstone samples (Fig. 4(a)) and samples from the upper carbonate unit (Fig. 4(c)) are not as distinctly concave upward near the origin as those from the lower and middle carbonate units. However, if the magnetite content were only 0.5–1.0 per cent of the hematite in the sample, the IRM curves from these samples would be definitely convex upward. The coercivity spectra (Fig. 4(d) and (f)) of some of these samples indicate a possible small IRM contribution from magnetite, but this may also be due to specular hematite whose coercivity spectrum may range from 0 up to 5 kOe (0.5 tesla) (Dunlop 1972). Therefore, the character of the IRM curves also suggests that the magnetic mineralogy of the Ingelside samples consists predominantly of hematite (pigment and specularite) with the possible presence of very small amounts of magnetite.

Based on thermal demagnetization experiments, all samples were thermally demagnetized at 500, 550 and 600°C. Samples showing divergent directions at 600°C were thermally demagnetized at 640°C with no appreciable results, so further demagnetization was abandoned. Most of the samples whose IRM showed a strong secondary magnetic overprint never completely responded to thermal demagnetization. These samples usually had directions that lay between their NRM directions and the characteristic Permian direction. This secondary magnetization is probably carried by hematite or iron hydroxides (goethite) or a combination of both formed during near surface weathering in the roadcuts. However, none of the samples subjected to Curie temperature analysis indicated the presence of goethite, and IRM data cannot distinguish between hematite and goethite. Nevertheless,
many of these samples showing a strong secondary component were yellowish in colour or had yellow specks throughout, strongly suggesting goethite.

Only two samples from the upper carbonate unit gave stable directions upon thermal demagnetization. Most of the samples from this unit were very weakly magnetized and many possibly contained goethite. Since the presence of magnetite was possible in these samples, the upper carbonate unit was resampled and all samples subjected to af demagnetization. Unfortunately, the sample response was no better than to thermal demagnetization, and therefore very little palaeomagnetic information could be derived from this unit.

No consistent clustering of samples about a normal Permian direction occurred at any level of demagnetization. Samples that did display north-westerly directions (270—360°) also showed erratic behaviour from one level of demagnetization to another. Secondary magnetization acquired during the Tertiary may have camouflaged the presence of a normal polarity zone within the Ingelside Formation, but this seems unlikely, since no samples show any indication of containing a stable normal component of magnetization. Therefore, the samples of the Ingelside Formation are considered to have acquired their primary remanence while the field was reversed.

Analysis of remanent directions

A two-step approach was employed in order to isolate the stable primary remanence of the 243 stratigraphically distinct samples of the Ingelside Formation. If a sample direction changed by more than 5 arc degrees over the two successive demagnetization intervals the sample was discarded from the population and not used in determining a pole position for the formation. This rejection criteria eliminates any sample in which a stable magnetization could not be isolated. For samples that did demonstrate a stable magnetization over a finite temperature interval, the directions within that interval were vectorially averaged to give one direction per sample. A similar technique has been used by Scott (1975a, b).

Since many of the samples surviving the above rejection criterion still contained a secondary magnetization, a stability test similar to that devised by Helsley (1973) was used. The closer the NRM direction lies toward a secondary field direction, the greater the probability that the thermally demagnetized direction will contain a mixture of both primary and secondary components of magnetization. Therefore, samples that appear to retain a stable direction over some finite temperature interval may contain a large secondary component of magnetization if the blocking temperature spectra of the two components are nearly identical. Selection of data using Helsley’s test is based on the initial NRM data and the principle that the dispersal coefficients of a Gaussian type population will increase as more directionally biased (streaked) data are added to the population. The NRM population of the samples surviving the first rejection criterion were partitioned into groups contained within a sequentially expanding cone centred about an estimate of the true mean direction of the formation. The statistical parameters of the demagnetized directions of those samples in each NRM group were calculated. When a minimum in population dispersal (maximum kappa, minimum \( \alpha_{95} \)) was obtained for the NRM group, that group was used in the pole calculation. Samples whose NRM directions were within 25° of the estimated mean direction of the Ingelside Formation give a minimum in population dispersal. The results are summarized in Table 1 and shown in Fig. 5.

Table 1. Summary of palaeomagnetic data for the Ingelside Formation.

<table>
<thead>
<tr>
<th>D</th>
<th>I</th>
<th>N</th>
<th>R</th>
<th>( \alpha_{95} )</th>
<th>( \delta )</th>
<th>Pole position</th>
<th>( \delta p )</th>
<th>( \delta m )</th>
</tr>
</thead>
<tbody>
<tr>
<td>149.0</td>
<td>-12.7</td>
<td>34</td>
<td>33.76</td>
<td>147.3</td>
<td>2.0</td>
<td>6.6</td>
<td>45.9° N, 122.1° E</td>
<td>1.1</td>
</tr>
</tbody>
</table>
Figure 5. NRM directions \((N = 34)\) after thermal demagnetization from the samples of the Ingelside Formation that survived reliability criteria. Equal area projection.

Figure 6. Northern hemisphere plot of the Late Palaeozoic pole positions for cratonic North America (Table 2), including the Early Triassic pole of Helsley & Steiner (1974). Solid triangle indicates the position of the Ingelside pole. Solid lines outline path of polar wandering.
Table 2. Cratonic North American palaeomagnetic pole positions.

<table>
<thead>
<tr>
<th>#</th>
<th>Age</th>
<th>Formation</th>
<th>Pole position</th>
<th>$\alpha_p$</th>
<th>$\delta_p$</th>
<th>$\delta_m$</th>
<th>References</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>E. Triassic</td>
<td>Moenkopi Fm.</td>
<td>54.8 N 103.3 E</td>
<td>-</td>
<td>1.6</td>
<td>3.2</td>
<td>Helsley &amp; Steiner (1974)</td>
</tr>
<tr>
<td>2</td>
<td>E. Permian</td>
<td>Cutler Fm.</td>
<td>44.4 N 116.2 E</td>
<td>1.8</td>
<td>-</td>
<td>-</td>
<td>Gose &amp; Helsley (1972)</td>
</tr>
<tr>
<td>3</td>
<td>E. Permian</td>
<td>Ingelside Fm.</td>
<td>45.9 N 122.1 E</td>
<td>-</td>
<td>1.1</td>
<td>2.1</td>
<td>This report</td>
</tr>
<tr>
<td>4</td>
<td>E. Permian</td>
<td>Casper Fm.</td>
<td>50.0 N 128.4 E</td>
<td>-</td>
<td>1.1</td>
<td>2.1</td>
<td>Diehl &amp; Shive (in preparation)</td>
</tr>
<tr>
<td>5</td>
<td>L. Pennsylvanian</td>
<td>Honaker Trail Fm.</td>
<td>55.0 N 106.4 E</td>
<td>-</td>
<td>0.8</td>
<td>1.5</td>
<td>Scott (1975a)</td>
</tr>
<tr>
<td>6</td>
<td>Pennsylvanian</td>
<td>Casper Fm.</td>
<td>44.7 N 132.4 E</td>
<td>-</td>
<td>1.0</td>
<td>1.8</td>
<td>Diehl &amp; Shive (in preparation)</td>
</tr>
<tr>
<td>7</td>
<td>L. Pennsylvanian</td>
<td>Dunkard Fm.</td>
<td>44.1 N 122.3 E</td>
<td>-</td>
<td>2.0</td>
<td>3.9</td>
<td>Helsley (1965)</td>
</tr>
<tr>
<td>8</td>
<td>Pennsylvanian</td>
<td>Maroon Fm.</td>
<td>40.8 N 123.5 E</td>
<td>2.1</td>
<td>-</td>
<td>-</td>
<td>Christiansen (1974)</td>
</tr>
<tr>
<td>9</td>
<td>Pennsylvanian</td>
<td>Kittanning Coal</td>
<td>37.0 N 131.6 E</td>
<td>3.0</td>
<td>-</td>
<td>-</td>
<td>Kopacz &amp; Nolﬁer (1976)</td>
</tr>
<tr>
<td>10</td>
<td>L. Mississippian</td>
<td>Mauch Chunk Fm.</td>
<td>43.0 N 127.0 E</td>
<td>-</td>
<td>3.1</td>
<td>6.3</td>
<td>Knowles &amp; Opdyke (1968)</td>
</tr>
<tr>
<td>11</td>
<td>E. Mississippian</td>
<td>St Joe Limestone</td>
<td>41.3 N 131.6 E</td>
<td>-</td>
<td>0.8</td>
<td>1.5</td>
<td>Scott (1975b)</td>
</tr>
<tr>
<td>12</td>
<td>E. Mississippian</td>
<td>St Joe Limestone</td>
<td>35.6 N 134.8 E</td>
<td>-</td>
<td>0.7</td>
<td>1.5</td>
<td>Scott (1975b)</td>
</tr>
</tbody>
</table>
Discussion

The pole position from the Ingelside Formation (45.9°N, 122.1°E) is very near the pole position from equivalent strata of the upper part of the Casper Formation (50.0°N, 128.4°E, from Diehl & Shive, in preparation), and agrees closely with other published pole positions of similar age. Other well-documented Late Palaeozoic pole positions for cratonic North America are listed in Table 2 (modified from Scott 1975a, b) and shown in Fig. 6, including the Early Triassic pole of Helsley & Steiner (1974). As seen in Fig. 6, these pole positions define a distinct path of apparent polar wandering for cratonic North America during Late Palaeozoic – Early Triassic times.

The pole positions from Table 2 were divided into groups based on age; i.e. Mississippian, Pennsylvanian, Permian and Early Triassic, and the resulting pole positions calculated. The Honaker Trail Formation (Scott 1975b) was excluded from this calculation since the age of magnetization appears to be very much younger than the age of the strata (Diehl & Shive, in preparation). The results are listed in Table 3 and shown in Fig. 7. The calculated Mississippian, Pennsylvanian, Early Permian and Early Triassic poles all lie on a great circle. These results indicate that during the Late Palaeozoic, the North American polar wandering

<table>
<thead>
<tr>
<th>Age</th>
<th>N</th>
<th>Pole location</th>
<th>α₉₅</th>
<th>δp</th>
<th>δm</th>
</tr>
</thead>
<tbody>
<tr>
<td>E. Triassic</td>
<td>1</td>
<td>54.8° N, 103.3° E</td>
<td>–</td>
<td>1.6</td>
<td>3.2</td>
</tr>
<tr>
<td>E. Permian</td>
<td>3</td>
<td>46.9° N, 122.0° E</td>
<td>7.7</td>
<td>–</td>
<td>–</td>
</tr>
<tr>
<td>Pennsylvanian</td>
<td>4</td>
<td>41.7° N, 127.5° E</td>
<td>6.0</td>
<td>–</td>
<td>–</td>
</tr>
<tr>
<td>Mississippian</td>
<td>3</td>
<td>40.3° N, 131.2° E</td>
<td>6.8</td>
<td>–</td>
<td>–</td>
</tr>
</tbody>
</table>

Figure 7. Northern hemisphere plot of the Mississippian, Pennsylvanian, Early Permian and Early Triassic poles for cratonic North America, including their respective circles (ovals) of 95 per cent confidence: triangle, Mississippian pole; circle, Pennsylvanian pole; diamond, Early Permian pole; square, Early Triassic pole of Helsley & Steiner (1974).
curve was characterized by a systematic north-westerly movement of the apparent palaeomagnetic pole from a position near southern Japan to the Early Triassic position (55° N, 103° E) of Helsley & Steiner (1974). At least 24° of apparent polar movement took place during this interval of time with approximately 14° of this apparent movement being confined to the Permian.

Conclusions

(1) Both Curie temperature analysis and IRM acquisition experiments indicate that hematite is the predominant carrier of the primary remanence in the Ingelside Formation, although some secondary remanence may be associated with goethite.

(2) The Ingelside Formation is considered to be reversely magnetized and thus does not record any normal events within the Late Palaeozoic Reversed Interval.

(3) Data from the Ingelside Formation along with other data from the Late Palaeozoic (Table 2) define a distinct path of apparent polar wander. When data from the different periods of the Late Palaeozoic are combined, the cratonic North American polar wandering curve defines at least 24° of systematic north-westerly movement of the apparent palaeomagnetic pole during this interval of time. This is in contrast to other published polar wandering curves that indicate that during the Permian apparent polar movement changes from a north-easterly direction to a north-westerly direction (deBoer & Brookins 1972; Irving & Park 1972). This has been termed 'hairpin 6' by Irving & Park (1972). However, much of the data on which these curves are based should perhaps no longer be used to describe the North American polar wandering path since many of the studies come from a portion of North America that may not have been attached to the North American plate until early or middle Permian (Scott 1975c). Therefore, it appears that the North American polar wandering path for the Late Palaeozoic is characterized by a systematic north-westerly movement of the apparent palaeomagnetic pole.

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