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Simplification of the anisotropy-based inclination correction technique for magnetite- and haematite-bearing rocks: a case study for the Carboniferous Glenshaw and Mauch Chunk Formations, North America

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SUMMARY

An anisotropy-based inclination correction was applied to the Carboniferous Glenshaw Formation from southwestern Pennsylvania. A combination of low-temperature thermal demagnetization followed by alternating field demagnetization isolated a palaeomagnetic remanence direction similar to that previously reported for these rocks. The inclination correction was conducted by fitting the samples' anisotropy of anhysteretic remanence (AAR) to the theoretical correction curves for a magnetite remanence that yielded a remanence individual magnetic particle anisotropy, the a_γ factor, equal to 1.86. Direct measurement of individual particle anisotropy in magnetic grain extracts, yielded an a_γ value of 2 in good agreement with the curve fitting technique. The inclination-corrected formation mean directions for these two a factors were statistically indistinguishable. This result shows that curve fitting is an easier, but accurate, method of applying an anisotropy-based inclination correction than direct measurement of the individual grain anisotropy in magnetic grain extracts. The corrected Glendale Formation magnetite-based palaeopole is very similar to haematite-based palaeopoles from the Carboniferous Canadian Maritimes. A new technique is described that extracts the detrital haematite grains from red sedimentary rocks. The measured haematite a_γ factors from the Carboniferous Mauch Chunk and Cretaceous Kapusaliang Formations yield values consistent with susceptibility individual particle anisotropies, a_χ, determined previously by curve fitting techniques, extending the use of curve fitting for individual particle anisotropy determination to haematite-bearing rocks. However, the corrected Mauch Chunk Formation palaeopole is significantly different from the corrected Glendale Formation palaeopole, calling the accuracy of the Mauch Chunk palaeopole into question. Tectonic strain during folding may have added to the compaction strain in the rocks, leading to an overcorrection of the inclination. A new, inclination-corrected palaeopole for the North American Carboniferous is reported for the Glenshaw Formation at 28.6˚N, 119.9˚E.

Key words: Magnetic fabrics and anisotropy; Palaeomagnetism applied to tectonics; Rock and mineral magnetism.

INTRODUCTION

The palaeomagnetism of sedimentary rocks is used extensively for tectonic and geomagnetic field studies. Accurate palaeomagnetic inclinations are essential for understanding intraplate tectonics, reconstructing continental palaeogeographies, and determining tectonostratigraphic terrane movements. Inaccurate palaeomagnetic inclinations not only cause faulty tectonic interpretations and palaeogeographies, but can lead workers to question the validity of the geocentric axial dipole hypothesis, the fundamental assumption of palaeomagnetism.

The anisotropy of anhysteretic remanence (AAR) has been used successfully in magnetite-bearing sedimentary rocks to detect and correct palaeomagnetic inclinations shallowed by depositional and post-depositional processes (Kodama & Davi 1995; Kodama 1997; Tan & Kodama 1998; Kim & Kodama 2004). In this technique, a sample's remanence anisotropy and individual magnetic particle anisotropy must both be measured. The magnetic particle anisotropy measurement is particularly time-consuming and requires specialized laboratory equipment. Magnetic particle extracts in addition to multiple redeposition experiments in relatively strong magnetic fields (50–60 mT) must be made to determine the magnetite's individual magnetic particle anisotropy. Simplifying the determination of individual particle anisotropy for magnetite would make the anisotropy-based inclination correction more accessible to standard palaeomagnetics laboratories.

The situation has been even more difficult for determining the individual particle anisotropy of haematite because of its lower spontaneous magnetization when compared to magnetite and the presence of both pigmentary and detrital haematite in a rock. Up to now, haematite individual particle anisotropy has only been determined by indirect means (Tan & Kodama 2002; Tan *et al.* 2003). Determining haematite's individual particle anisotropy directly would allow testing of the indirect techniques.

Tan & Kodama (2003) have developed equations to correct the inclinations of haematite-bearing sedimentary rocks using anisotropy. These equations take into account the differences in grain anisotropy (shape versus magnetocrystalline) between magnetite and haematite grains, but are essentially similar to those developed by Jackson *et al.* (1991) for magnetite-bearing rocks. Inclination shallowing corrections, using the haematite equations, have been applied to Cretaceous red sedimentary rocks from Central Asia (Kapusaliang Formation; Tan *et al.* (2003)) and Mississippian red sedimentary rocks from eastern Pennsylvania (Mauch Chunk Formation; Tan & Kodama 2002). The Central Asian correction resulted in a palaeolatitude for the northern Tarim basin that was consistent with the tectonics of the region. In contrast, the correction of the Mauch Chunk Formation implied a large magnitude of shallowing (38°) and was difficult to verify with coeval volcanic results (Tan & Kodama 2002).

In this study, we will apply an inclination correction to magnetite-bearing Carboniferous sedimentary rocks from southwestern Pennsylvania that have been previously studied palaeomagnetically (Payne *et al.* 1981). The corrected inclination of the magnetite-bearing rocks will be compared to the Tan & Kodama (2002) correction applied to the haematite-bearing, coeval Mauch Chunk Formation to test its accuracy. In addition, we will determine whether least-squares fitting of the sample anisotropy data to the theoretical correction curves for both magnetite and haematite can provide a simpler, but accurate, method for determining individual magnetic particle anisotropy. We will use direct measurement of individual particle anisotropy using standard magnetic extraction techniques to check determination of magnetite individual magnetic particle anisotropy by the fit to the theoretical curves. For haematite-bearing rocks, we have developed a technique for extracting the detrital haematite particles from a red sedimentary rock. This new procedure will allow the direct measurement of the individual particle anisotropy of the haematite particles to check the theoretical curve fitting approach for haematite.

This study will also show that the mean remanence anisotropy tensor for a sedimentary rock can be used to correct the rock's mean direction without a loss of accuracy compared to making corrections to individual samples and averaging the corrected sample directions. This result should further reduce the amount of laboratory work required for the anisotropy inclination correction since only a subset of samples will be necessary to determine the mean anisotropy tensor for correction of the mean direction obtained by standard palaeomagnetic measurements. This study will provide an inclination-corrected Carboniferous palaeomagnetic pole from cratonic North America.

PREVIOUS WORK AND GEOLOGY

Payne *et al.* (1981) reported palaeomagnetic results from the Brush Creek Limestone and the Buffalo Siltstone from southwestern Pennsylvania. These units are part of the Upper Pennsylvanian Glenshaw Formation that is in the lower half of the Conemaugh Group (Wagner *et al.* 1970; Fig. 1). The Glenshaw Formation is comprised of flat-lying, fine-grained sedimentary rocks deposited in a shallow marine sea that occupied the Appalachian Basin in southwestern Pennsylvania, eastern Ohio and northern West Virginia. Payne *et al.* (1981) collected oriented hand samples from the Brush Creek Limestone at five localities near Pittsburgh, Pennsylvania. They collected individually oriented cores from the Buffalo Siltstone at only one of the five localities. The Brush Creek Limestone is a thin unit (0.15–0.45 m in thickness). Lithologically, it is an argillaceous limestone with abundant silt and clay. Payne *et al.* (1981) sampled the Buffalo Siltstone over a greater stratigraphic thickness (6 m). This unit outcrops directly up section from the Brush Creek Limestone. Payne *et al.* (1981) reported individual palaeomagnetic poles for the Brush Creek Limestone and the Buffalo Siltstone. Their results are based solely on alternating field demagnetization and formation means were calculated by averaging sample directions, rather than site means.

METHODS

I collected thirty-six oriented hand samples from four of Payne *et al.*'s (1981) five sampling localities (Fig. 1). Because of urbanization, it was not possible to collect samples from the fifth Payne *et al.* (1981) locality near Sewickley Bridge. I did collect hand samples from Stoop's Ferry nearby to the Sewickley Bridge locality. The sample collection is comprised of samples from both the Brush Creek Limestone and the Buffalo Siltstone. The results from these samples were averaged together, so rather than reporting separate results from the Brush Creek Limestone and Buffalo Siltstone, I will report a result from the Glenshaw Formation.

Three to four 25 mm diameter cores were drilled from each oriented hand sample, resulting in a total of 81 cores for measurement and demagnetization. About 1/3 of the cores were thermally demagnetized in at least 10 steps up to 580°C. One-third of the samples were alternating field demagnetized in fields up to 80 mT. The remaining third were subjected to a combination of thermal and alternating field demagnetizations. These samples were first thermally demagnetized in three steps up to 200°C and then alternating field demagnetized in at least five to seven steps up to 50 mT. The combination of thermal and alternating field demagnetizations gave the best results.

The anisotropy of AAR was measured for samples that had been alternating field demagnetized to avoid any chemical alteration that may have been caused by heating during thermal demagnetization. Partial anhysteretic remanent magnetizations (pARMs) were applied in nine different orientations to determine the anisotropy tensor (McCabe *et al.* 1985). The 97 μT biasing field was applied in the presence of alternating fields that isolated the characteristic remanence (ChRM), typically between 10 and 40 mT. Anisotropy of magnetic susceptibility (AMS) was also measured as a check of the primary nature of the magnetic fabrics in the samples.

To measure the individual particle anisotropy of the Glenshaw Formation, magnetic grain extracts were made from three samples collected from three of the four sampling localities previously sampled by Payne *et al.* (1981). The samples were crushed by hand and further disaggregated by being placed in an ultrasonic bath for several weeks. The disaggregated sediments were circulated past a magnetized needle (Hounslow & Maher 1999) for approximately 1 week. Magnetic grain separates were collected once a day from the needle. The magnetic separates were mixed with epoxy and allowed to dry overnight in the presence of a dc magnetic field applied by an electromagnet. Fields of 50, 55, 60 and 65 mT were used for the separate from each sample. The AAR of each epoxy sample was

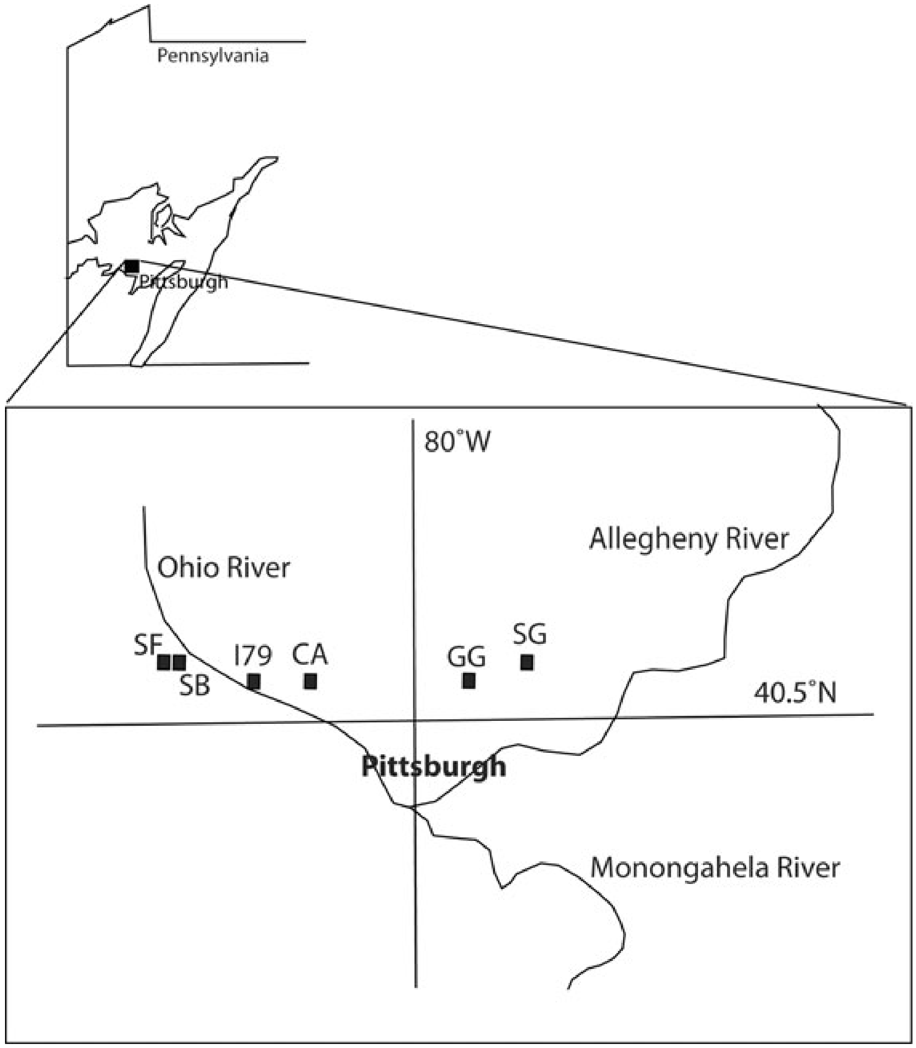

Figure 1. Location map of sampling sites for the Glenshaw Formation. Inset figure shows location of the Glenshaw Formation in western Pennsylvania. Outline of the outcrop of the Conemaugh Group is shown (based on Wagner *et al.* 1970). The sampling localities are the same as those used by Payne *et al.* (1981). SF, Stoop's Ferry; SB, Sewickley Bridge; I79, Interstate 79 exit ramp; CA, Camp Avonworth; GG, Glenshaw Glass; SG, State Gamelands.

measured to determine the individual magnetic grain anisotropy, assuming that the grains' easy magnetic axes were perfectly aligned during drying in the strong magnetic fields. The application of a range of magnetic fields was used to assure that the anisotropy degree saturated, indicating nearly perfect alignment and an accurate individual particle anisotropy measurement.

To measure the individual particle anisotropy of the haematite that carries the ChRM of the Mauch Chunk red beds, we developed a new extraction technique for haematite-bearing rocks. A magnetic grain extract was made from a sample collected from site MCP6 previously sampled by Tan & Kodama (2002). The sample was crushed by hand and further disaggregated by being ball milled for about 30 min in a ceramic sample holder with ceramic balls. During ball milling, the resulting sediment powder was dry sieved with a 63 μm sieve to ensure a consistently small grain size. A slurry was made with the ball milled, sieved sediment and distilled water. A beaker containing the slurry was put in an ultrasonic bath for 24 hr. The slurry was then centrifuged at 1000 rpm for 30 min (Dekkers & Linssen 1991) resulting in a dark layer of dense grains at the bottom of the centrifuge tube indicating separation of iron oxides from the pigmentary haematite. The dark layer was sampled, added to distilled water, and the resulting slurry was circulated past a magnetized needle (Hounslow & Maher 1999) for approximately 1 week. Magnetic grain separates were collected once a day from the needle. The magnetic separates were mixed with epoxy and allowed to dry overnight in the presence of a dc magnetic field applied by an electromagnet. Fields of 100, 140, 160 and 185 mT were used, higher than those used for magnetite, because of haematite's lower spontaneous magnetization. A field of 185 mT was the highest field possible with our laboratory's electromagnet. Isothermal remanent magnetization (IRM) acquisition experiments were conducted with each epoxy sample to ensure that haematite had been separated from the sample. The IRM acquisition experiment showed that both magnetite and haematite were extracted from the Mauch Chunk Formation (Fig. 2). Therefore, to determine the individual particle anisotropy of the haematite, an anisotropy of isothermal remanence (AIR) for each epoxy sample was determined with 1.2 T fields followed by alternating field demagnetization at 100 mT for each of the nine measurement orientations. The range of magnetic fields during the drying of the epoxy samples was used to assure that the anisotropy degree saturated, indicating alignment of the haematite particle's easy axes of magnetization. The resulting remanence anisotropy individual particle anisotropy, a_γ, can be compared to the susceptibility anisotropy individual particle anisotropy, a_χ,

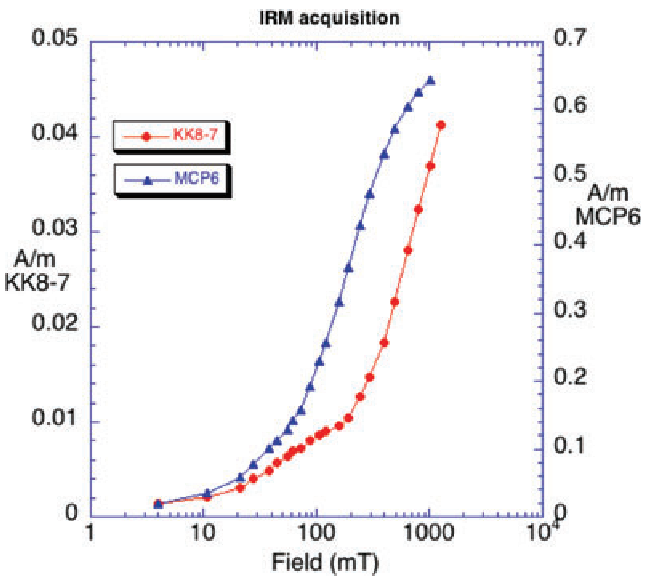

Figure 2. IRM acquisition results for magnetic extracts from the Mauch Chunk Formation (MCP6) and the Kapusaliang Formation (KK8–7). Note a break in slope in both curves at about 100 mT indicating both low coercivity magnetite and high coercivity haematite in these magnetic extracts.

determined by curve fitting (Tan & Kodama 2002), from the slope of the AIR eigenvalue versus AMS eigenvalue curve determined by Tan & Kodama (2002) for the Mauch Chunk Formation from the equation:

$$\text{Slope} = [(2\alpha_\chi+1)(\alpha_\gamma - 1)/(2\alpha_\gamma+1)(\alpha_\chi - 1). \quad (1)$$

This procedure was also applied to a sample from site KK8 of the Kapusaliang Formation in western China, to compare the measured individual particle anisotropy to that determined by curve fitting (Tan *et al.* 2003).

The curve fitting determination of the individual particle anisotropy, or *a* factor, is used both for magnetite- and haematite-bearing rocks using Jackson *et al.*'s (1991) and Tan & Kodama's (2003) theoretical correction curves, respectively. Either remanence anisotropy data or susceptibility anisotropy data may be used, as long as the appropriate *a* factor, a_γ (for remanence), or a_χ (for susceptibility) is also used. Remanence data are preferable for the anisotropy correction because susceptibility measurements cannot easily isolate the anisotropy of the remanence carrying magnetic grains from the anisotropy carried by the paramagnetic or diamagnetic minerals in the samples. In the curve fitting technique, the theoretical correction for a given sample is calculated from a sample's anisotropy and compared to the tangent of the sample's uncorrected (ChRM) inclination, tan I_o, where I_o is the uncorrected, measured inclination. In effect, the comparison determines how well the uncorrected inclinations in the data set fit their measured anisotropies assuming the theoretical correction relationship. For magnetite, the theoretical relationship is:

$$\tan I_o/\tan I_c = [K_{min}(a+2) - 1]/[K_{max}(a+2) - 1], \quad (2)$$

where I_c is the corrected inclination, K_{max} and K_{min} are the maximum and minimum normalized eigenvalues, respectively, and *a* can be either a_γ or a_χ, depending on whether remanence or susceptibility data are used for K_{min} and K_{max}. For haematite, the equation is slightly different:

$$\tan I_o/\tan I_c = [K_{min}(2a+1) - 1]/[K_{max}(2a+1) - 1] \quad (3)$$

because haematite's easy axis of magnetization is assumed to lie in a particle's basal plane rather than along its long axis, as in magnetite. In eqs (2) and (3), the theoretical correction (right-hand side of the equation) is equated to the ratio of the tangents of the corrected, I_c, and uncorrected, I_o, inclinations; therefore, tan I_o is divided by the mean inclination of the corrected inclination for all the samples for the curve fitting.

In the curve fitting technique, the difference between the right-hand side of either eq. (2) or (3) and tan I_o/tan I_m, where I_m is the mean of the corrected inclinations, is calculated for each sample, squared, and the sum of the squares is divided by the total number of samples. These rms errors are calculated for a range of *a* values. The *a* value that corresponds to the lowest rms error should be the value that gives the best fit of the data set's measured inclinations to their measured anisotropies, assuming the theoretical relationship in (2) or (3).

The error in the corrected inclination can be estimated from the rms error of the *a* factor determined by curve fitting or the error from repeated laboratory measurements of the *a* factor. From eqs (2) and (3) the error in tan I_c is directly related to the error of the *a* factor.

To quantitatively compare my results for the Glenshaw Formation with the previous palaeomagnetic results from Payne *et al.* (1981), I digitized Payne *et al.*'s figures showing the virtual geomagnetic pole distributions for the Brush Creek Limestone and the Buffalo Siltstone samples.

Typically, when the anisotropy inclination correction is applied to the palaeomagnetism of a sedimentary rock unit, the remanence anisotropy for each sample is measured and used to correct the ChRM of each sample. The corrected directions are then averaged, as in a standard palaeomagnetic study, to derive the corrected formation mean direction. This approach was used when comparing the directly measured individual particle anisotropy to that determined by the fit of the data to the theoretical correction curves. However, because we were only able to isolate a small number of acceptable ChRMs from the Glenshaw Formation, we need to extend our anisotropy correction to the much larger combined data set of the samples measured in this study plus those in Payne *et al.*'s (1981) study. If the corrected direction resulting from applying the mean anisotropy tensor to the mean direction for our Glenshaw Formation data set is the same as the corrected direction resulting from the application of the anisotropy correction to each individual sample, then we could use the mean anisotropy tensor to correct the mean direction of the combined data set.

For this test, we have chosen to correct directions following the method of Kim & Kodama (2004) in which the inverse of DRM tensor is applied to the uncorrected direction.

$$(H_x, H_y, H_z) = \text{DRM}^{-1}(\text{ChRM}_x, \text{ChRM}_y, \text{ChRM}_z), \quad (4)$$

where H_i are the components of the corrected direction, DRM^{-1} in the inverse of the DRM tensor and ChRM_i are the components of the characteristic (uncorrected) remanence. The DRM tensor is best determined from the measured remanence anisotropy tensor and the individual particle anisotropy, a_γ, because the anisotropy tensor is a quantification of the orientation distribution of magnetic particles in a rock. The remanence anisotropy eigenvectors are the eigenvectors of the DRM tensor, and the DRM eigenvalues, $X_{i\text{DRM}}$, are given by

$$X_{i\text{DRM}} = (X_{i\text{ARM}}(a_\gamma+2) - 1)/(a_\gamma - 1), \quad (5)$$

where $X_{i\text{ARM}}$ are the remanence anisotropy eigenvalues. This modification of the Jackson *et al.* (1991) correction equation for

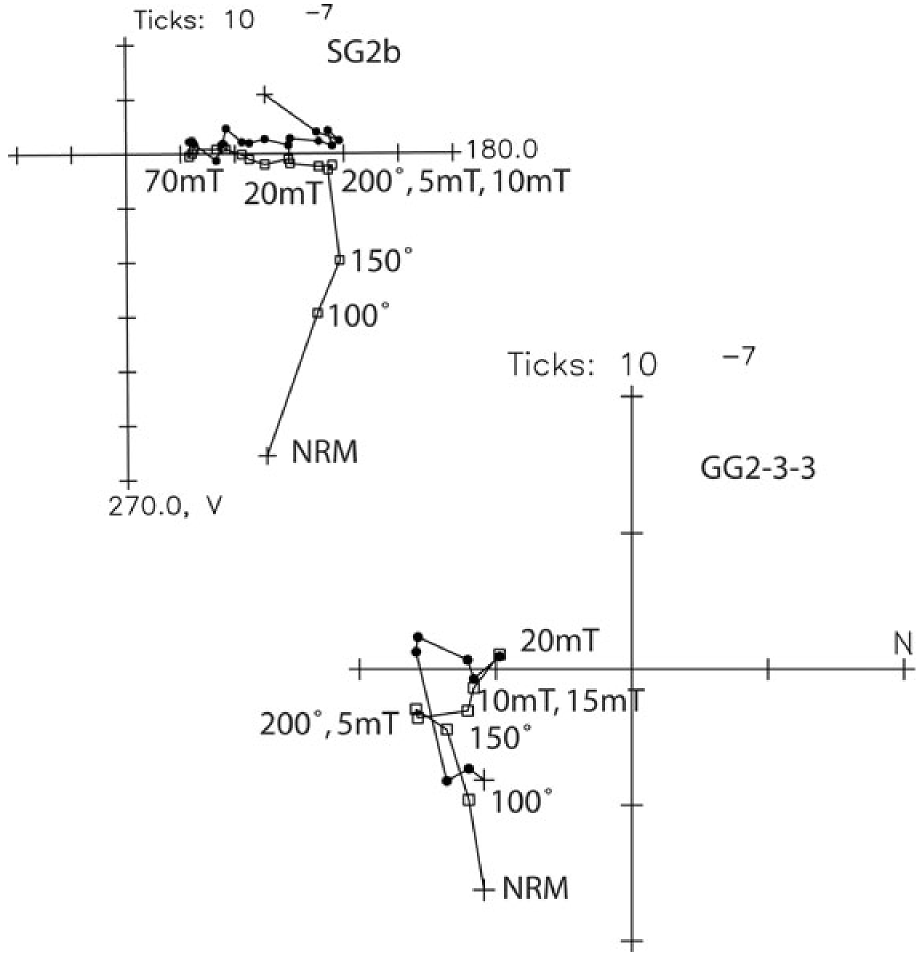

Figure 3. Representative vector endpoint diagrams showing demagnetization behaviour during low-temperature thermal demagnetization followed by alternating field demagnetization. The State Gamelands locality (sample SG2b) gave the best results. The Glenshaw Glass locality (sample GG2–3-3) gave some of the poorer quality demagnetograms.

magnetite was used because Jackson *et al.*'s method assumes that the DRM tensor eigenvectors lie exactly parallel and perpendicular to the bedding plane that even for the best anisotropy data is not observed to be the case.

All remanence measurements were made on a three axis 2G superconducting magnetometer housed in a magnetically shielded room at Lehigh University. pARMs were applied using a modified Schonstedt GSD-5 alternating field demagnetizer. AMS was measured with an Agico KLY-3s Kappabridge. An ASC TD-48 oven was used for thermal demagnetization. IRMs were applied using an ASC Impulse magnetizer. Alternating field demagnetization was conducted with the 2G's built in demagnetization coils.

RESULTS

Interpretable demagnetization diagrams were obtained for only about 25 per cent of the Glenshaw Formation cores (Fig. 3). A high coercivity overprint, possibly carried by goethite, makes isolation of a ChRM by principal component analysis (Kirschvink 1980) difficult. The combination of low-temperature thermal demagnetization, to remove a goethite magnetization, followed by alternating field demagnetization gave the best results. Table 1 shows the site and formation means. The directions are all reversed polarity (Fig. 4). The mean of the sample directions ($D = 162.6^\circ$, $I = 25.8^\circ$, $\alpha_{95} = 6.7^\circ$) is used for comparison to Payne *et al.*'s (1981) results since they averaged directions at the sample level. My sample level formation mean direction is statistically indistinguishable at the 95 per cent confidence level with Payne *et al.*'s (1981) combined Brush Creek Limestone and Buffalo Siltstone results ($D = 157.9^\circ$, $I = 23.0^\circ$, $N = 126$, $\alpha_{95} = 3.5^\circ$, Fig. 4) using the discrimination of means technique of McFadden & Lowes (1981). A fold test is not possible because of the very gentle dip of these beds (Table 1).

Both AMS and AAR fabrics show minimum axes perpendicular to bedding, consistent with primary magnetic minerals affected by depositional processes and by compaction (Fig. 5). The remanence individual particle anisotropy, a_γ, was determined from the measurement of eight different epoxy/magnetic mineral separate samples dried in fields greater than 50 mT where the anisotropy had saturated. The average a_γ factor is determined to be 1.96 ± 0.13 ($\pm 1\sigma$; Table 2).

The inclination correction applied to each individual sample and based on the measured individual particle anisotropy ($a_\gamma = 2$) is indistinguishable from that determined by a least-squares fit of the sample AARs to Jackson *et al.*'s (1991) theoretical anisotropy correction curves (Fig. 6). In the least-squares fit, an individual particle anisotropy of $a_\gamma = 1.86$ is the result (Fig. 7). The rms error is observed to decrease monotonically until an a_γ value of 1.86 is reached. At lower a_γ values the theoretical values calculated from

Table 1. Palaeomagnetic results—Glenshaw Formation.

Locality[c]	Bed dip (°)	Bed dip dir (°)	N	Declination (°)[b]	Inclination (°)[b]	K
Camp Avonworth	10	224	6	166.6	21.5	14.8
I79 ramp	4	72	7	162.6	30.5	58.4
Glenshaw Glass	8[a]	41	5	144.3	33.8	59.8
	14[a]	277				
State Gamelands	10	158	5	173.6	14.5	70.2
Stoop's Ferry	6	289	_[d]	_[d]	_[d]	
Mean of site means			4	162.4	25.5	32.9
Mean of samples			23	162.6	25.8	21.4

[a]There were two different bedding attitudes for the Glenshaw Glass locality.
[b]Declination and inclination are reported in stratigraphic coordinates.
[c]Locality names are taken from Payne *et al.* (1981).
[d]No interpretable results were obtained from the Stoop's Ferry locality.

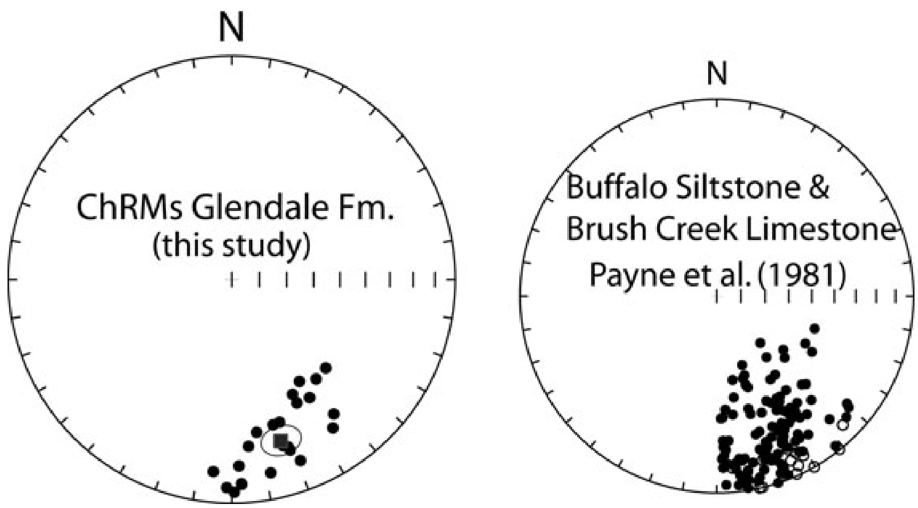

Figure 4. (Left) Equal area stereonet showing characteristics remanence (ChRM) isolated for the Glenshaw Formation. (Right) Equal area stereonet showing the characteristic magnetizations reported by Payne *et al.* (1981) in their study of the Buffalo Siltstone and Brush Creek Limestone (both parts of the Glendale Formation). Solid circles lower hemisphere, open circles upper hemisphere. All directions plotted in stratigraphic coordinates. The square and ellipse show the mean direction and its 95 per cent confidence limits (α_{95}).

the right-hand side of eq. (1) become negative for at least one sample in the data set. This is because this sample has a minimum normalized eigenvalue, $K_{\rm min}$, low enough to make $K_{\rm min}(a_\gamma + 2) < 1$. The physical interpretation of this result is that individual particle anisotropies lower than 1.86 are incompatible with the range of measured anisotropies for these samples, assuming that the data follow the theoretical correction curves. Therefore, $a_\gamma = 1.86$ is the best fit to the curves. Fig. 7 also shows the fit of the inclination data to the theoretical correction curves. The tan $I_{\rm o}$/tan $I_{\rm m}$ fit the theoretical curves for $a_\gamma = 1.86$ better than for $a_\gamma = 5$; however, the scatter is still obvious and most likely due to noise caused by the sedimentary recording process and incompletely removed magnetic overprints. Because it is very difficult to extract the complete magnetic grain size distribution in magnetic grain separation experiments, determination of the a factor by curve fitting may actually be more accurate than direct measurement of the individual particle anisotropy using magnetic grain extraction experiments. It is heartening that the two different determinations of the a_γ factor ($a_\gamma = 2$ and $a_\gamma = 1.86$) are in very good agreement and is a testament to the robustness of the approach despite the scatter in the fit to the theoretical correction curves.

When the Kim & Kodama (2004) inverse DRM tensor approach of anisotropy inclination correction is applied sample by sample to the 23 ChRMs determined for the Glenshaw Formation, a mean corrected direction of $D = 167.7^\circ$, $I = 36.5^\circ$, $\alpha_{95} = 9.5^\circ$ results. This is virtually identical to a corrected mean direction of $D = 166.4^\circ$, $I = 36.5^\circ$ that was determined by applying the mean DRM tensor to the mean uncorrected ChRM direction. Therefore, the mean DRM tensor for the $N = 23$ samples, whose anisotropy was measured for this study, was applied to the combined mean direction ($D = 158.6^\circ$, $I = 23.4^\circ$, $\alpha_{95} = 3.1^\circ$, $N = 149$) from our 23 samples and Payne *et al.*'s (1981) $N = 126$ samples resulting in a corrected mean direction for the Glenshaw Formation of $D = 161.7^\circ$, $I = 33.7^\circ$, $\alpha_{95} = 3.1^\circ$. The corresponding corrected palaeomagnetic pole is located at 28.6°N, 119.9°E (dp = 3.7°, dm = 3.5°). The directly measured a_γ factor used for this correction has 6.6 per cent error bars, therefore the error in the corrected inclination, due to the error in a_γ, is $\pm 1.7^\circ$, from tan(33.7°) $\pm$ 6.6 per cent. The error in the corrected inclination, due to the a_γ factor, is less than the scatter in the corrected ChRMs.

One of the purposes of this paper is to compare the corrected Mauch Chunk Formation palaeopole, which is carried by haematite and uses different theoretical correction curves, to the corrected Glenshaw Formation palaeopole, which is derived from the magnetite theoretical correction curves. The corrected Mauch Chunk Formation direction reported by Tan & Kodama (2002) ($D = 170.2^\circ$, $I = 56.4^\circ$) implies 38° of inclination shallowing. This correction was made with a susceptibility individual particle anisotropy of 1.06 that

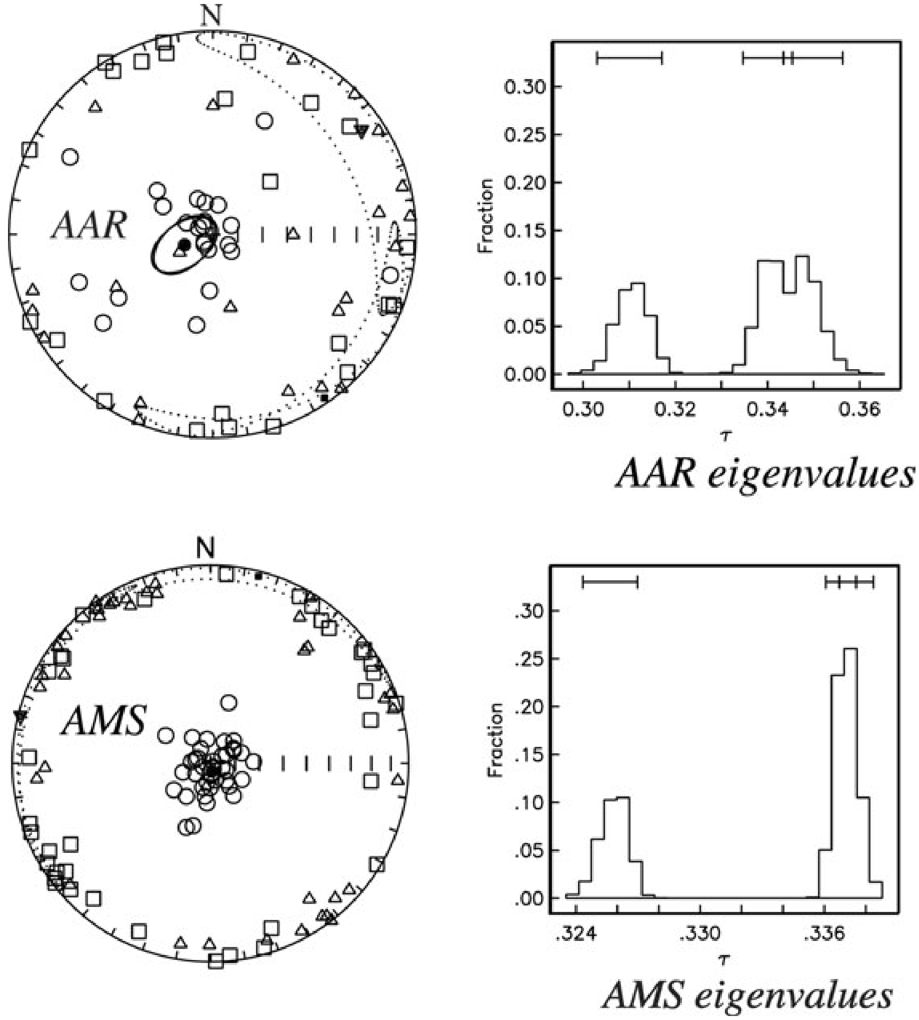

Figure 5. Equal area stereonets showing the anisotropy of anhysteretic remanence (AAR) principal axis directions for the 23 samples plotted in Fig. 2 including the mean principal axes directions with Jelinek 95 per cent confidence limits (dotted lines; Jelinek 1978) (top left-hand side), the anisotropy of magnetic susceptibility (AMS) principal axes directions for 36 specimens from all four sites (bottom left-hand side). Jelinek 95 per cent confidence limits are shown with dotted lines. All points lower hemisphere and plots are in stratigraphic coordinates. Minimum axes: circles; intermediate axes, triangles; maximum axes, squares. Histograms of eigenvalues are plotted in the upper and lower right-hand side showing that the maximum and intermediate axes lengths are indistinguishable statistically from each other and distinct from the minimum axes for both AMS and AAR indicating oblate fabrics. The oblate fabric and minimum axes perpendicular to bedding are consistent with primary magnetic minerals affected by depositional processes and compaction.

Table 2. Measured haematite individual particle anisotropies.

Unit/sample	Drying field strength (mT)	a_γ factor ($K_{\max}/K_{\min}$)
Mauch Chunk Formation		
MCP6	100	1.488
MCP6	140	1.355
MCP6	160	1.459
MCP6	185	1.496
Kapusaliang Formation		
KK8–7	160	1.438
KK8–7	180	1.492
KK8–7	185	1.389
KK8–7	185	1.475

was derived by a least-squares fit of the sites' mean susceptibility anisotropy to the haematite theoretical correction curves. Our direct measurement of the Mauch Chunk's individual particle anisotropy gave a remanence a_γ factor of 1.45 ± 0.07 ($\pm 1\sigma$) based on four epoxy sample measurements (Table 2). This remanence a_γ factor is equivalent to a susceptibility a_χ factor of 1.05 ± 0.01 based on the slope of the line fit to a plot of AIR eigenvalues versus AMS eigenvalues (Tan & Kodama 2002). Since Tan & Kodama (2002) corrected the Mauch Chunk direction using AMS measurements, derived from chemical demagnetization, and an AMS a_χ factor of 1.06 determined from fitting the AMS data to the theoretical haematite correction curves, our direct measurements confirm both the corrected Mauch Chunk direction and the curve fitting approach for determining the individual particle anisotropy. However, the corrected palaeomagnetic pole for the Mauch Chunk is located at 12°N, 108°E and is 20° distant from the Glenshaw Formation's corrected palaeopole.

The mean remanence a_γ factor derived from the four haematite-bearing Kapusaliang Formation epoxy samples, $a_\gamma = 1.45 \pm 0.05$, is identical to that derived for the Mauch Chunk (Table 2). However, a different slope for the AIR versus AMS eigenvalue plot indicates that the measured remanence a_γ factor is equivalent to an AMS a_χ factor of 1.10 ± 0.01. In their anisotropy correction for the Kapusaliang Formation red beds Tan *et al.* (2003) used AMS a_χ

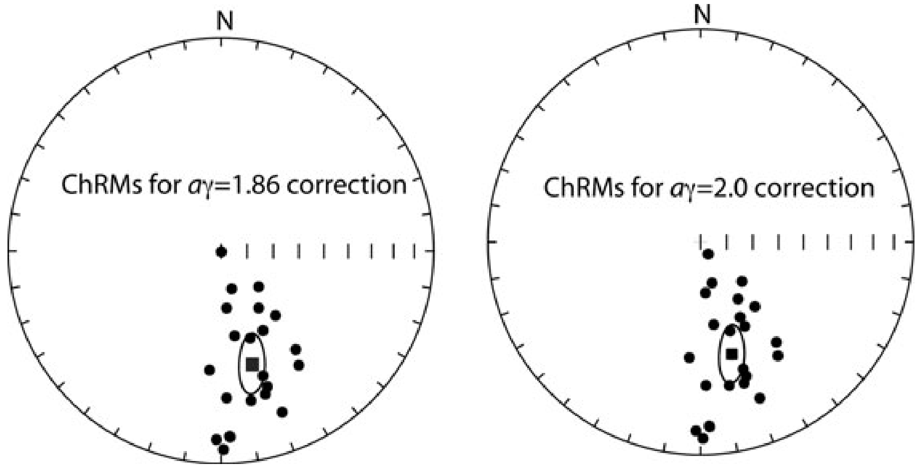

Figure 6. Equal area stereonet showing ChRMs corrected for the best fit individual particle anisotropy of 1.86. Shown for comparison are the ChRMs corrected for the measured particle anisotropy of 2.0. All points lower hemisphere and plotted in stratigraphic coordinates.

factors ranging from 1.09 to 1.06 that gave the best fits of the AMS data to the theoretical correction curves. Our measurements confirm the $a_\chi = 1.09$ correction that indicates inclination shallowing for the Kapusaliang of 20.4°. The corresponding corrected palaeopole for the Kapusaliang is located at 75.5°, 206.2°E (dm = 9.1°, dp = 6.3°) and is within 4° of the Besse & Courtillot (2002) 125 Ma Eurasian palaeopole (75.7°N, 192.4°E, $A_{95} = 3.5°$) supporting the conclusion made earlier that the Kapusaliang Formation has not moved with respect to stable Eurasia.

DISCUSSION

One of the important results of this study is that a least-squares fit of the samples' anisotropy to the theoretical correction curves achieves an accurate estimate of the individual particle anisotropy for both magnetite and for haematite. It affords a much easier way to use the anisotropy-based inclination shallowing correction and could remove stumbling blocks to more widespread application of the approach. The proposed rubric would be to conduct a typical palaeomagnetic study and also measure the anisotropy, either remanence or susceptibility isolated by chemical demagnetization, of enough samples in a site (3 or 4) to measure the site's average anisotropy. The site direction and site anisotropy means would then be fit, using least squares, to the theoretical correction curves (Jackson *et al.* 1991 for magnetite; Tan & Kodama 2003 for haematite) to derive the best average individual particle anisotropy for the formation. The resulting inclination correction should be similar in accuracy to the direct measurement of the individual particle anisotropy by magnetic mineral extraction, redeposition and drying in epoxy, and measurement of the epoxy samples' anisotropy after drying in different field strengths to check for saturation of anisotropy degree. In addition, our results show that the sample by sample anisotropy inclination correction may be replaced by correcting the formation mean direction with the mean anisotropy tensor for the formation, as long as Kim & Kodama's (2004) inverse DRM tensor approach is used. This result has important implications for correcting the mean formation directions of previously reported palaeomagnetic results. The anisotropy of a subset of representative samples from a formation could be measured and the mean anisotropy could be used to correct the mean formation direction.

In addition, this study shows that detrital haematite particles can be extracted from a sedimentary red bed, if centrifuging, as suggested by Dekkers & Linssen (1991), is added to the laboratory procedure for magnetic mineral extraction. While this leads to a more laboratory-intensive technique, that is unlikely to be used widely for correcting the inclination of haematite-bearing sedimentary rocks, it allowed us to confirm the validity of curve fitting for determining haematite individual particle anisotropies. The strong agreement between the measured a_γ factors for two diverse red beds, the Carboniferous Mauch Chunk Formation from North America and the Cretaceous Kapusaliang Formation from Central Asia, suggests that haematite *a* factors in red sedimentary rocks do not vary significantly. The remanence a_γ factor of 1.45, then, could be used, with some caution, for other haematite-based anisotropy corrections. It will be interesting to see if it is borne out as more studies of haematite inclination shallowing are completed. Tan *et al.* (2007) have used a haematite a_γ factor of 1.37 for their correction of the Passaic Formation; however, this value was taken from the Kapusaliang Formation, which had been indirectly determined by curve fitting.

A second important result of this study is the poor agreement of the corrected Glenshaw Formation magnetite-based palaeopole and the corrected Mauch Chunk Formation haematite-based palaeopole of Tan & Kodama (2002). One possible explanation for the divergence between these two corrected palaeopoles is that apparent polar wander has occurred between the deposition of these two units, if their age difference is great enough. Based on the magnetostratigraphy of the Mauch Chunk Formation (Hounslow *et al.* 2004) and the Gradstein *et al.* (2004) timescale, the sites sampled by Tan & Kodama (2003) are early Visean (334 Ma) in age. The Glenshaw Formation, in the lower part of the Conemaugh Group, is Upper Pennsylvania (Missourian) in age (Englund *et al.* 1986). According to the Gradstein *et al.* (2004) timescale, this makes the Glenshaw Formation 305 Ma or about 30 Myr younger than the Mauch Chunk Formation, enough time for 20° of apparent polar wander to occur (approximately 7.5 cm yr^{-1}). However, recent anisotropy-based inclination corrections for the Carboniferous Shepody and Maringouin Formations from the Canadian Maritimes result in corrected palaeopoles of 27.2°N, 118.3°E, $A_{95} = 6.2°$ and 27.4°N, 117.2°E, $A_{95} = 13.1°$, respectively, in very good agreement with the corrected Glenshaw Formation palaeopole (Bilardello & Kodama 2005, 2007). Based on their magnetostratigraphy the Shepody and Maringouin Formations are nearly as old as the Mauch Chunk Formation (315–326 Ma; Gradstein *et al.* 2004; Hounslow

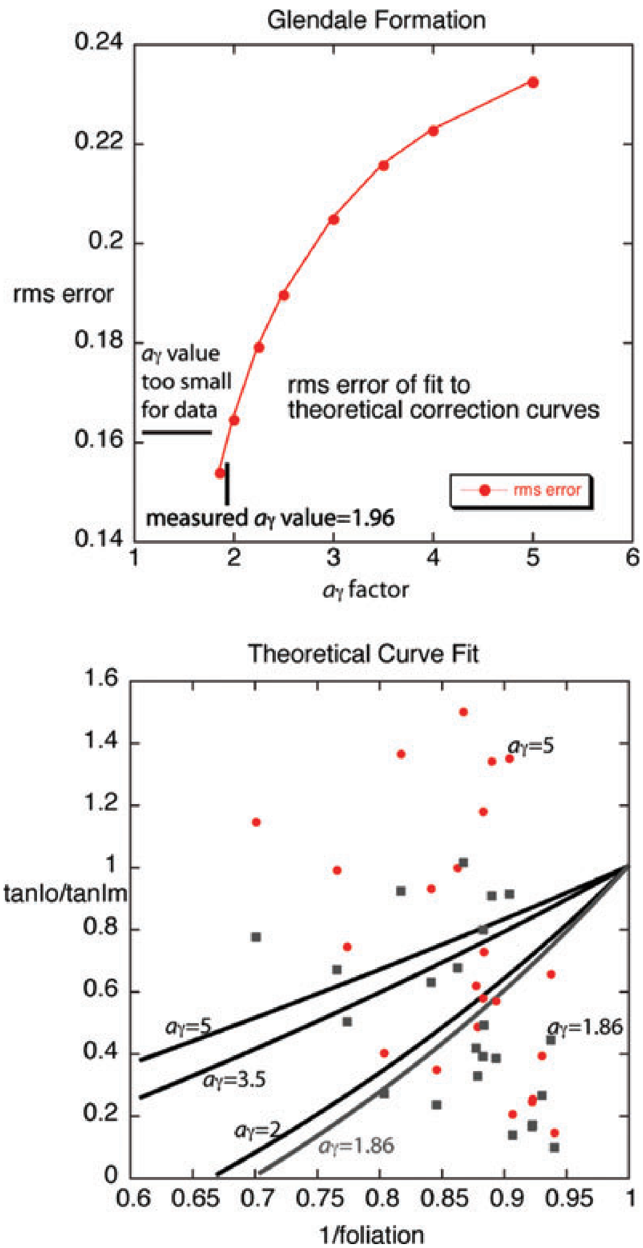

Figure 7. (Top) Results from the Glendale Formation of the least-squares curve fitting of sample remanence anisotropy data to the theoretical inclination correction curves for magnetite (Jackson *et al.* 1991) for the 23 characteristic remanences and their measured AAR anisotropies. The rms error decreases until $a_\gamma = 1.86$. Smaller values of a_γ are inconsistent with the AAR data (see text). The lowest rms error therefore occurs at $a_\gamma = 1.86$. This a_γ value compares favourably with the measured a_γ factor of 1.96 ± 0.13. (Bottom) The fit of inclination data corrected with a_γ values of 5 (red dots) and 1.86 (blue dots) to the Jackson *et al.* (1991) theoretical correction curves, see eq. (1) in the text. The scatter in the data is probably due to the noise in DRM acquisition and incomplete removal of secondary overprints.

et al. 2004). This result strongly suggests little apparent polar wander during the Carboniferous and shows good agreement between haematite-corrected inclinations (Shepody and Maringouin Formations) and magnetite corrected inclinations (Glenshaw Formation), thus supporting the haematite-based inclination correction.

However, the accuracy of the Mauch Chunk Formation corrected palaeopole, reported by Tan & Kodama (2002) is brought into question. The Mauch Chunk Formation has been unique, so far, in our studies of inclination shallowing, having an inclination almost 40° too shallow. Most magnetite-based remanences have inclinations between 10° and 15° too shallow (Kodama & Davi 1995; Kodama 1997; Tan & Kodama 1998; Vaughn *et al.* 2005), while haematite-based remanences from formations other than the Mauch Chunk range from 10° (Shepody and Maringouin) to 20° (Kapusaliang Formation). One possible explanation is that tectonic, grain-scale strain, in addition to compaction strain, is present in the Mauch Chunk rocks collected by Tan & Kodama (2002). The Pottsville, PA locality sampled for the Mauch Chunk inclination shallowing study is on the limb of an NE–SW trending fold with a nearly 90° dip. Late stage layer-parallel shortening, that is, regionally horizontal shortening, could modify a steeply dipping fold limb and add strain with a shortening axis nearly parallel to the bedding-normal minimum axis of compaction strain. Gray & Mitra (1993), in their rock deformation study of the Appalachians in eastern Pennsylvania, in fact, do see evidence of late stage, regionally horizontal, layer-parallel shortening that occurred after folding, resulting in fold modification. If tectonic strain is present in the rocks, and it affected the rock's anisotropy, this may have led to an overcorrection by the anisotropy technique. This possibility is supported by the comparison of the mean anisotropy of remanence for the four red bed units for which we have remanence anisotropy data. The Mauch Chunk's mean remanence foliation ($K_{\mathrm{int}}/K_{\mathrm{min}}$) is 1.38 ± 0.09, $n = 7$ (Tan & Kodama 2002) a value significantly higher than that for the Kapusaliang (1.095 ± 0.09, $n = 21$; Tan *et al.* 2003), and for the combined Shepody and Maringouin Formations (1.05 ± 0.03, $n = 28$; Bilardello & Kodama 2006). This interpretation implies that even though the anisotropy of the Mauch Chunk was modified by late stage strain, its ChRM was apparently not affected.

This study has also provided an updated and corrected palaeomagnetic pole for the North American Carboniferous. Even though the Glendale Formation direction reported here is based on a few samples, the uncorrected direction accurately reproduces the direction previously reported by Payne *et al.* (1981) that was determined from an order of magnitude greater number of samples. We were then able to correct the mean direction calculated from data of Payne *et al.* (1981) combined with the results of this study for a robust corrected palaeopole for the Upper Pennsylvanian (305 Ma; Fig. 8). The inclination correction for this palaeopole is based on a reasonable number of remanence anisotropy measurements collected from a range of lithologies (limestone and siltstone). Because the North American apparent polar wander path in the Palaeozoic is dependent predominately on uncorrected palaeopoles from red sedimentary rocks, the corrected palaeopoles reported here suggest that the North American apparent polar wander path may be subject to an inclination shallowing bias.

CONCLUSIONS

A least-squares fit of remanence anisotropy and directional data to theoretical inclination shallowing curves yields an inclination shallowing correction consistent with that determined by direct measurement of the individual particle anisotropy for both magnetite-bearing rocks and haematite-bearing rocks. This results in an easy, but accurate, application of the anisotropy-based inclination shallowing correction using curve fitting to determine the individual particle anisotropy. Inclination corrections for the magnetite-bearing Carboniferous Glenshaw Formation and the haematite-bearing Carboniferous Mauch Chunk Formation yield palaeopoles that are significantly different, whereas comparison

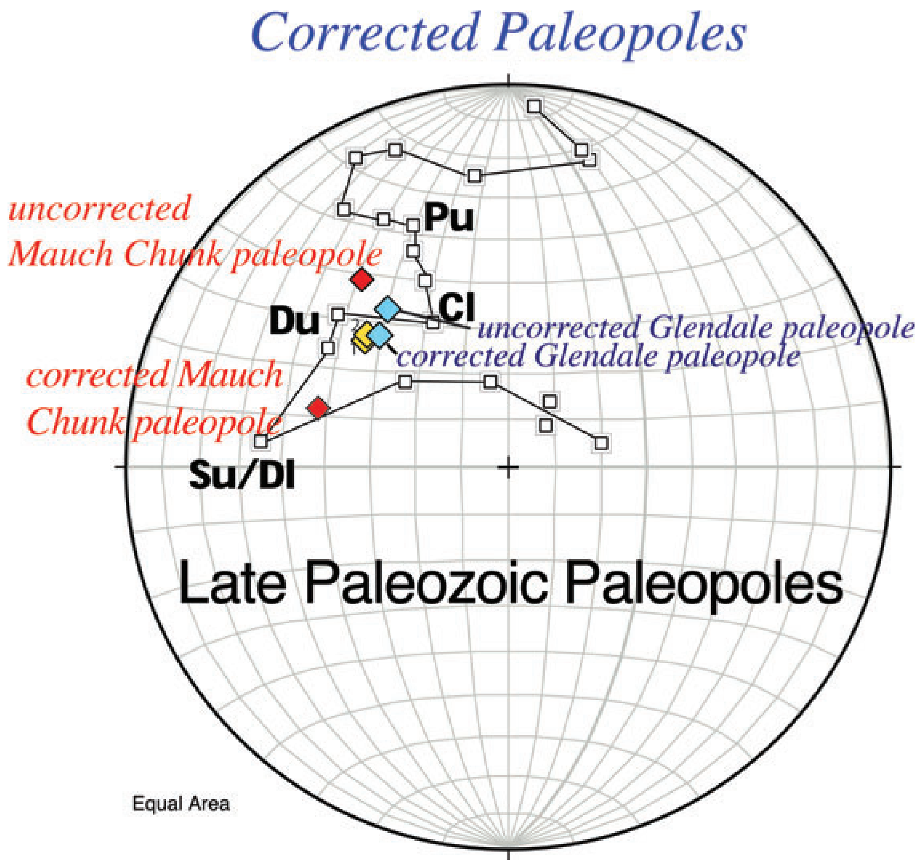

Figure 8. Equal area stereonet showing the Late Palaeozoic North American apparent polar wander path (Van der Voo 1993). Blue diamonds show the uncorrected and corrected palaeopoles for the Glendale Formation. Red diamonds show the uncorrected and corrected Mauch Chunk Formation palaeopoles from Tan & Kodama (2002). 1, corrected Maringouin Formation palaeopole; 2, corrected Shepody Formation palaeopole (Bilardello & Kodama 2008); Pu, upper Permian, Cl, lower Carboniferous, Du, upper Devonian, Su, upper Silurian, Dl, lower Devonian.

of the Glendale palaeopole to coeval, corrected, haematite-based palaeopoles from the Canadian Maritimes shows good agreement. The agreement adds support for the accuracy of the theoretical correction curves derived for haematite-bearing sedimentary rocks, but calls into question the accuracy of the corrected Mauch Chunk palaeopole. The addition of grain-scale tectonic strain to the compaction strain of the Mauch Chunk may have caused an overcorrection of the inclination. The results of our study also show that the mean formation direction of a sedimentary unit may be corrected, accurately, by the mean anisotropy tensor derived from the unit. This opens the way for correction of previously reported sedimentary palaeopoles by determining the mean anisotropy of the unit from a representative group of samples. Finally, a new, inclination-corrected palaeopole for the Carboniferous Glenshaw Formation (28.6°N, 119.9°E) has resulted from this study.

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