Latinmag Letters, Volume 1, Special Issue (2011), B02, 1-6. Proceedings Tandil, Argentina

HEMATITE ANISOTROPY AND INCLINATION CORRECTIONS: CASE STUDY OF THE MAUCH CHUNK FORMATION OF PENNSYLVANIA. IMPLICATIONS FOR THE CARBONIFEROUS NORTH AMERICAN APW PATH AND PANGEA RECONSTRUCTIONS.

Invited

Dario Bilardello[1*], Kennet P. Kodama[2]

[1] Ludwig Maximilians University, Department of Earth and Environmental Sciences, Munich, Germany (dario.bilardello@googlemail.com)

[2] Lehigh University, Department of Earth and Environmental Sciences, Bethlehem, PA

Abstract

A rock-magnetic study was performed on samples of the Lower Carboniferous Mauch Chunk Formation of Pennsylvania. These red beds had been previously sampled for an inclination shallowing study. High anisotropy values lead to suspect that the Formation had been strained. However, more detailed rock-magnetic measurements show that both magnetite and hematite contribute to the remanence, leading to the application of a high field anisotropy of isothermal remanence magnetization technique (hf-AIR) specifically designed to isolate the anisotropy of hematite, the characteristic remanence carrier. The newly measured fabric has smaller anisotropy and shows a pronounced magnetic lineation, interpretable as a hematite intersection lineation.

The measured magnetic fabric yields a new inclination correction with a corrected paleopole that is in better agreement with recently corrected Carboniferous paleopoles from North America, defining a more consistent APW path. The corrected paleopoles allow calculation of new mean Early and Late Carboniferous paleopoles for North America, which can be compared to coeval, but uncorrected, paleopoles from Gondwana. Results suggest a Pangea B assemblage in the Carboniferous unless Gondwana sedimentary rocks have been affected by inclination shallowing. Estimating an inclination correction for Gondwana sedimentary rock-derived paleopoles permits a Pangea A-type assemblage at higher southern latitudes than previous reconstructions.

Introduction

Red beds have provided a wealth of paleomagnetic information due to their abundance in the stratigraphic record and their stable paleomagnetic remanence (e.g. Van der Voo, 1990), but their remanence acquisition mechanism remains controversial (Butler, 1992).

A common view is that secondary hematite of chemical origin is responsible for the remanence, in which case the remanence will be a chemical remanent magnetization (CRM). The timing of the acquisition of a CRM is thus fundamental to the interpretation and application of a paleomagnetic study. In other cases the remanence is demonstrated to be carried by detrital hematite, in which case the remanence will be a detrital remanent magnetization (DRM). Moreover, different magnetic mineralogies often coexist in red beds: primary detrital hematite (specularite) and/or pigmentary hematite of chemical origin have often been observed together with magnetite or goethite, for example. Magnetic fabrics provide insights into the origin of a magnetization (e.g. Tauxe et al., 1990); however, an appropriate fabric measurement technique must be used among a wide variety of measurement techniques available (Jackson, 1991). For example, because of hematite's high coercivity remanence, hematite anisotropy has been difficult to measure, especially if it coexists with other magnetic mineralogies (Kodama and Dekkers, 2004). Anisotropy of magnetic susceptibility (AMS) measurement is not affected by hematite's coercivity, but AMS measures the composite fabric of all magnetic mineralogies present, and is inevitably dominated by the one with the highest susceptibility. Measuring hematite anisotropy by anisotropy of anhysteretic remanence (AAR) is virtually impossible for most paleomagnetic laboratories because most commercially available alternating field demagnetizers cannot reach the high fields needed to activate the high coercvities of hematite grains. Similarly, anisotropy of isothermal remanent magnetization (AIR) has been limited by the thermo-chemical alteration of the magnetic mineralogy of the samples by the high-temperature (680° C) thermal demagnetization required to remove the remanence between each AIR orientation (Tan and Kodama, 2002) or by the inability of most paleomagnetic laboratories to af demagnetize a high-field isothermal remanent magnetization (IRM).

Following the idea of Kodama and Dekkers (2004) that saturation of the remanence at each AIR orientation would avoid the need to demagnetize between successive orientations, Bilardello and Kodama (2009) have successfully developed a hematite AIR measurement technique that is applicable by most paleomagnetic laboratories. Moreover, the technique allows isolation of the magnetic fabric of hematite from that of other magnetic minerals present, making it particularly effective in red beds with composite mineralogies. In Bilardello and Kodama (2010c) we have applied the high-field AIR technique to cores drilled out of hand samples of the Mauch Chunk formation of eastern Pennsylvania that had been previously collected by Tan and Kodama (2002) for an inclination shallowing study.

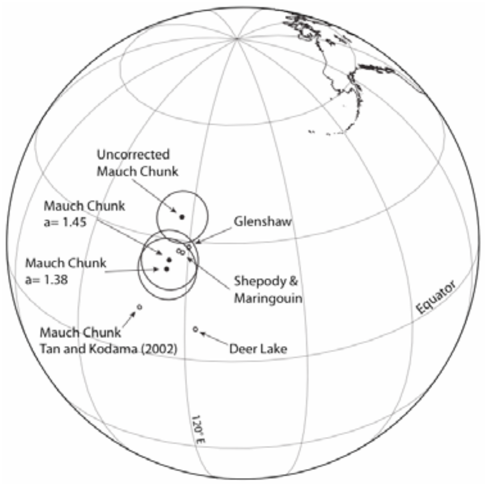
Tan and Kodama (2002) had determined, by IRM acquisition and thermal demagnetization of the IRM, that hematite was the sole carrier of the remanence and measured the magnetic fabric using AMS in conjunction with chemical leaching to isolate the fabric of the ChRM-carrying grains. They also used AIR acquired in fields of 1.2 T and thermally demagnetized the IRMs at 670 °C between each orientation to measure the remanence anisotropy, claiming that 1.2 T fields were sufficient to activate the ChRM-carrying grains and that no significant changes in foliation values occurred upon heating up to 650 °C. Tan and Kodama (2002) measured anisotropies ranging between ~25%-40%, calculated as $(K_1\text{-}K_3)/K_{mean}$. Such high anisotropy values yielded a large magnitude of inclination shallowing (38°), which corresponds to a corrected paleopole position that is inconsistent with other recently corrected Carboniferous paleopoles (Kodama, 2009). This observation, together with the high anisotropy measured by Tan and Kodama (2002) led Kodama (2009) to suspect the Mauch Chunk anisotropy to be modified by late stage tectonic strain, while it's characteristic remanence (ChRM) had remained unaffected.

We re-assessed the magnetic mineralogy by IRM acquisition, low temperature heating/cooling cycles and FORC data and realized that the Mauch Chunk magnetic fabric should be re-measured using hf-AIR. The newly measured hematite anisotropy of the Mauch Chunk is smaller than previously observed and in turn yields a smaller inclination correction, bringing the corrected Mauch Chunk paleopole in full agreement to all other corrected Carboniferous paleopoles from North America (Bilardello and Kodama, 2010c).

Inclination Correction and Paleopoles

Using the measured fabric and the mean red bed *a* factor of 1.38 (Bilardello et al., 2011) or the measured *a* factor for the Mauch Chunk of 1.45 yields similar inclination corrections of 18.1° and 15.4°, respectively. Of the two we prefer the first one because we feel that a mean value of hematite particle anisotropy measured from magnetic extracts of different red bed formations will be closer to the true 'unique' hematite *a* factor. This direction corresponds to a paleopole located at 22.6° N, 114.4° E.

The corrected late Mississippian Mauch Chunk paleopole falls at latitudes in between the older, Visean, Deer Lake corrected paleopole (8.4° N, 122.7° E) (Bilardello and Kodama, 2010b) and the younger Mississippian/Pennsylvanian Maringouin Formation paleopole (27.4° N, 117.2° E) (Bilardello and Kodama, 2010a). The other corrected Carboniferous North American paleopoles, the early Pennsylvanian Shepody (27.2° N, 118.3° E) (Bilardello and Kodama, 2010a) and late Pennsylvanian Glenshaw (28.6° N, 119.9° E) (Kodama, 2009) are positioned at more northerly latitudes. Overall, the corrected apparent polar wander (APW) path trends northwest from the Deer Lake paleopole to the newly corrected Mauch Chunk pole, after which the paleopoles define a straight path to the northeast.



Carboniferous Paleopoles of North America. Solid symbols are the uncorrected and corrected Mauch Chunk paleopoles (please refer to legends). Open symbols are corrected paleopoles from other studies: Deer Lake Group (Bilardello and Kodama, 2010b), Shepody and Maringouin Formations (Bilardello and Kodama, 2010a), Glenshaw Formation (Kodama, 2009). The corrected Mauch Chunk paleopole of Tan and Kodama (2002) is also plotted for comparison.

Inclination Correction and Pangea Reconstructions

Our corrected paleopoles allow calculation of new mean Carboniferous paleopoles for North America. An Early Carboniferous pole ~ 325 Ma (mean age and position of the Deer Lake, Mauch Chunk and Maringouin poles) falls at 19.5° N, 118.2° E, A_{95}=16.4°, while a Late Carboniferous pole ~312 Ma (from the Maringouin, Shepody and Glenshaw poles) is located at 27.7° N, 118.5° E, A_{95}=2.2°.

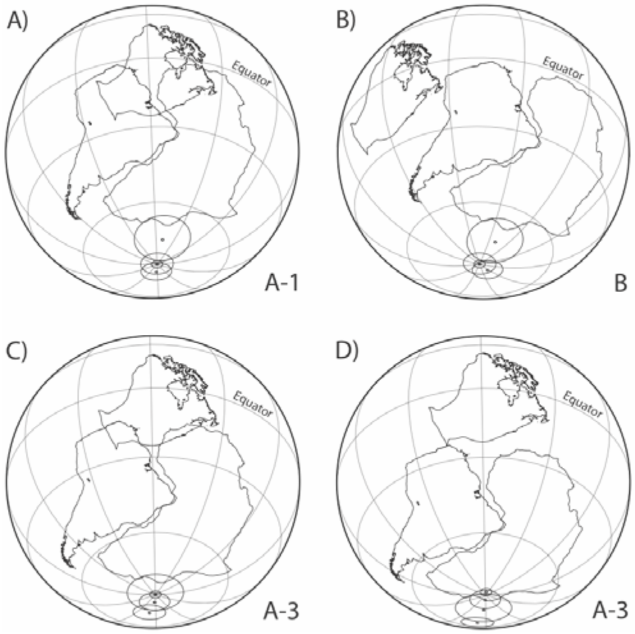
All the major continents assembled between the Late Carboniferous and the Middle Jurassic to form the Pangea supercontinent (Wegener, 1915; Van der Voo, 1993; Irving, 2004). In Pangea reconstructions for earlier parts of the Carboniferous-Jurassic time period, paleomagnetic data require an overlap between the northern (Laurentia) and the southern continental blocks (Gondwana). This has led to the proposal of different models:

The classical Pangea model, A-1, places Laurentia directly north of Gondwana and is consistent with paleomagnetic data for the latter times of the existence of Pangea. To overcome the overlap required by older paleomagnetic data Van der Voo and French (1974) envisioned a Pangea A-2 reconstruction, whereby Gondwana is rotated a few degrees clockwise, however this reconstruction was not supported by all available paleomagnetic data at the time it was proposed (Irving, 2004). Because paleolongitude is unconstrained by paleomagnetic data, Irving (1977) legitimately argued for a Pangea B model in which Gondwana is placed at a more easterly position with respect to Laurasia. The main criticism of this model is that the transition necessitated from a Pangea B to a Pangea A configuration must be achieved by the Late Permian (Muttoni et al., 2003), by means of a large-scale (~3500 km) continental shear zone know as the Tethys Twist (Morel and Irving, 1981). There is little geological evidence of a large shear zone in this time period.

In a Pangea reconstruction, our uncorrected North American Late Carboniferous pole places North America in a prominent (and well known) overlap with Gondwana. Correcting for inclination shallowing moves North America to the south, away from the equator in the southern hemisphere, further increasing the overlap with Gondwana (Bilardello and Kodama, 2010a, 2010b). To overcome this discrepancy in paleomagnetic data it would be necessary to move North America westward in a Pangea B-type assemblage.

Torsvik et al. (2008) present an updated compilation of global paleopoles and rotation parameters used to compile a global APW path. We have selected the Gondwana paleopoles that are the closest in age to our Late Carboniferous paleopoles. The five paleopoles for Gondwana have been calculated from one South America Craton pole, two Parana-Salado poles, four North West Africa poles, one North East Africa pole and from one South Africa. Only one of these poles is derived from volcanic rocks (rhyolites), the remaining eight poles are from sedimentary rock formations, which could be affected by inclination shallowing.

The effect of possible inclination shallowing on the Gondwana paleopoles is tested by applying an inclination correction to the sedimentary rock-derived paleopoles. Bilardello and Kodama (2010b) presented a compilation of the shallowing factors (*f*) observed for magnetite and hematite-bearing sedimentary rocks. Here, the smallest magnetite and hematite shallowing factors observed are used in order to give the maximum possible inclination correction to the sedimentary rock formations. The rationale for maximizing the correction is to test whether inclination shallowing could bring the poles into better agreement with each other and eliminate the overlap in a Pangea A-type assemblage. However, it is not always easy to determine from the global paleomagnetic database (GPDB) entries what magnetic mineralogy carries the ChRM. The *f* factors applied for the corrections were chosen based on the demagnetization temperatures used to isolate the ChRMs and the description of the lithology: for four formations *f*=0.4 was used (hematite), and for the remaining four *f*=0.54 was used (magnetite). As a test, a more conservative correction was applied using only two hematite *f* factors (*f*=0.4) and six magnetite *f* factors (*f*=0.54). The resulting difference was less than a degree in both corrected pole latitude and longitude and by a degree in A_{95}, therefore negligible for these estimated corrections.



Paleogeographic reconstructions at ~310 Ma. Longitude in all plots is arbitrary: A) Pangea A reconstruction using the inclination corrected North American paleopole and the uncorrected Gondwana paleopole, showing the considerable overlap between North America and Gondwana; B) Pangea B reconstruction using the inclination corrected North America paleopole and the uncorrected Gondwana paleopole, as a solution to the overlap; C) Pangea A-type assemblage (Pangea A-3) obtained using the corrected North America and Gondwana paleopoles; D) Pangea A-3 obtained by using the full extent of the paleopole 95% circles of confidences to completely eliminate the overlap (Bilardello and Kodama 2010c).

When an estimated inclination correction is applied to “restore” the position of Gondwana, the corrected Gondwana paleopole moves the South America-Africa block further south, creating sufficient space for a Pangea A-type assemblage. We call the new reconstruction that places the whole supercontinent closer to the South Pole Pangea A-3 (Bilardello and Kodama, 2010c).

Further work will determine which Pangea configuration is the best fit to all the data, however, the inclination corrections applied in this study to North American data suggest that Gondwana paleopoles should be checked for inclination shallowing. Furthermore, after an estimated correction of Gondwana paleopoles, both Pangea A- and B- type reconstructions are compatible with the paleomagnetic data. In our opinion, Pangea A-3 represents the most elegant solution because it eliminates the need for the 3500 km shear zone needed to shift from a Pangea B to a Pangea A configuration.

References

Bilardello, D., Kodama, K.P., 2009. Measuring remanence anisotropy of hematite in red beds: anisotropy of high-field isothermal remanence magnetization (hf-AIR), Geophys. J. Int., 178, 3, 1260-1272, doi: 10.111/j.1365-246X.2009.04231.x.

Bilardello, D., Kodama, K.P., 2010a. Paleomagnetism and magnetic anisotropy of Carbonifeous red beds from the Maritime Provinces of Canada: Evidence for shallow paleomagnetic inclinations and implications for North American apparent polar wander, Geophys. J. Int., 180, 3, 1013-1029, doi: 10.1111/j.1365-246X.2009.04457.x.

Bilardello, D., Kodama, K.P., 2010b. Rock magnetic evidence for inclination shallowing in the early Carboniferous Deer Lake Group red beds of western Newfoundland. Geophys. J. Int., 181, 275-289, doi: 10.1111/j.1365-246X.2010.04537.x.

Bilardello, D., Kodama, K.P., 2010c. A new inclination shallowing correction of the Mauch Chunk Formation of Pennsylvania, based on high field-AIR results: Implications for the Carboniferous North American APW path and Pangea reconstructions. *Earth Planet. Sci. Lett.*, 299, 218-227, doi: 10.1016/j.epsl.2010.09.002.

Bilardello, D., Jezek, J., Kodama, K.P., 2011. Propagating and incorporating the error in anisotropy-based inclination corrections. Earth Planet. Sci. Lett. Accepted.

Butler, R.F., 1992. Paleomagnetism: Magnetic Domains to Geologic Terranes. Blackwell, Boston.

Irving, E., 1977. Drift of the major continental blocks since the Devonian. Nature, 270, 304-309.

Irving, E., 2004. The case for Pangea B, and the intra- Pangean megashear. Channel J. in: J. E. T. Channell, et al., Editors, Timescales of the Paleomagnetic Field, Geophys. Monogr. Ser., 145, 13-27.

Jackson, M., 1991. Anisotropy of Magnetic Remanence: A brief review of mineralogical sources, physical origins, and geological applications, and comparison with susceptibility anisotropy. Pure. App. Geophys., 136, 1, 1-28.

Kodama, K.P., 2009. Simplification of the anisotropy-based inclination correction technique for magnetite- and hematite bearing rocks: A case study for the Carboniferous Gleshaw and Mauch Chunk Formations, North America. Geophys. J. Int., 176, 467-477, doi: 10.1111/j.1365-246X.2008.04013.x

Kodama, K.P., Dekkers, M.J., 2004. Magnetic anisotropy as an aid to identifying CRM and DRM in red sedimentary rocks. Stud. Geophys. Geod., 48, 747-766.

Morel, P., Irving, E., 1981. Paleomagnetism and the evolution of Pangea. J. Geophys. Res., 86 1858-1872.

Muttoni, G., Kent, D.V., Garzanti, E., Brack, P., Abrahamsem, N., Gaetani, M., 2003. Early Pangea ‘B’ to Late Permian Pangea ‘A’. Earth Planet. Sci. Lett., 215, 379-394.

Tan, X., Kodama, K.P., 2002. Magnetic anisotropy and paleomagnetic inclination shallowing in red beds: Evidence from the Mississippian Mauch Chunk Formation, Pennsylvania. J. Geophys. Res., 107 (B11), EPM 9, 17 pp.

Tauxe, L., Constable, C., Stokking, L., Badgley C., 1990. Use of anisotropy to determine the origin of characteristic remanence in the Siwalik red beds of northern Pakistan. J. Geophys. Res. 95, B4, 4391-4404.

Torsvik, T.H., Müller, R. D., Van der Voo, R., Steinberger, B., Gaina, C., 2008. Global plate motion frames: toward a unified model. Rev. Geophys. 46, RG3004, 1-44.

Van der Voo, R., French, R.B., 1974. Apparent Polar Wandering for the Atlantic-bordering continents: Late Carboniferous to Eocene. Earth-Sci. Rev. 10, 99-119.

Van der Voo, R., 1990. Phanerozoic paleomagnetic poles from Europe and North America and comparisons with continental reconstructions. Rev. Geophys., 28, 167-206.

Van der Voo, R., 1993. Paleomagnetism of the Atlantic, Tethys and Iapetus oceans. Cambridge University Press, New York, 411 pp.

Wegener, A., 1915. Die Entstehung der Kontinente und Ozeane. Braunschweig: Friedr. Vieweg u. Sohn.