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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

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ABSTRACT

A new magnetic anisotropy study was performed on samples of the Lower Carboniferous Mauch Chunk Formation of Pennsylvania. These red beds had been sampled for an inclination shallowing study by Tan and Kodama (2002), however, application of a high-field anisotropy of isothermal remanence magnetization (hf-AIR) technique specifically designed to measure the anisotropy of hematite provides considerably different results from those previously reported. The newly measured fabric has smaller anisotropy (~9–17% as opposed to ~25–40%) and shows a pronounced ENE–WSW magnetic lineation that is sub-parallel to the trend of the Appalachians and interpretable as a hematite intersection lineation that occurred during local NNW-directed shortening. The measured magnetic fabric yields a new inclination correction with a corrected paleopole that is in better agreement with recently corrected Carboniferous paleopoles than the previously corrected Mauch Chunk paleopole, defining a more consistent APW path. The corrected paleopoles allow calculation of new mean Early (~325 Ma) and Late (~312 Ma) Carboniferous inclination-corrected paleopoles for North America, which can be compared to coeval, but uncorrected, paleopoles from Gondwana. Results suggest a Pangea B assemblage unless inclination shallowing is considered for Gondwana. Estimating an inclination correction for Gondwana sedimentary rock-derived paleopoles permits a Pangea A-type assemblage at higher southern latitudes than previous reconstructions, which we term Pangea A3.

1. 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, 1990a), but their remanence acquisition mechanism remains controversial (Collinson, 1965; Butler, 1992; Dunlop and Özdemir, 1997).

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 (Roy and Park, 1972; Walker et al., 1981; Larson et al., 1982; Liebes and Shive, 1982).

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) (Collinson, 1974; Elston and Purucker, 1979; Steiner, 1983; Tauxe et al., 1990; Tan and Kodama, 2002; Tan et al., 2007; Bilardello and Kodama, 2009a, 2010a).

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 (Dunlop and Özdemir 1997; Kodama and Dekkers, 2004; Bilardello and Kodama, 2009a, 2010a,b).

Magnetic fabrics provide insights into the origin of a magnetization (e.g. Tauxe et al., 1990; Jackson, 1991; Tarling and Hrouda, 1993); however, an appropriate fabric measurement technique must be used among a wide variety of measurement techniques available (Jackson, 1991; Bilardello and Kodama, 2009a). 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; Bilardello and Kodama, 2009a). 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

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remanent magnetization (AIR) has been limited by the thermochemical 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; Tan et al., 2003) 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 (2009a) 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 (Bilardello and Kodama, 2009a) making it particularly effective in red beds with composite mineralogies.

In this paper we apply 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, c.f. Figure 10a of Tan and Kodama (2002), and that no significant changes in foliation values occurred upon heating up to 650 °C, c.f. Figure 10b of Tan and Kodama (2002). Tan and Kodama (2002) measured anisotropies ranging between ~25% and 40%, calculated as $(K_1\text{–}K_3)/K_{mean}$ (Owens, 1974).

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 and references therein). 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.

2. Geology and previous studies

Tan and Kodama (2002) sampled the Mauch Chunk Formation at the Schuylkill River Gap near Pottsville, Pennsylvania (Fig. 1). The sampling locality is situated within the northern limb of the Pennsylvania salient, on the southern limb of the Minersville Synclinorium. Here the formation is 340 m thick and comformably overlies the lower Mississippian Pocono Formation, while it underlies the lower Pennsylvanian Pottsville Formation. Sampled lithologies range from calcareous mudstone to sandstone, bedding planes trend ENE–WSW with vertical to slightly overturned dips.

DiVenere and Opdyke (1991) had previously sampled this same locality for a magnetostratigraphic study, tentatively correlating the upper part of the Mauch Chunk section to the lower part of the Maringouin Formation of New Brunswick, Canada.

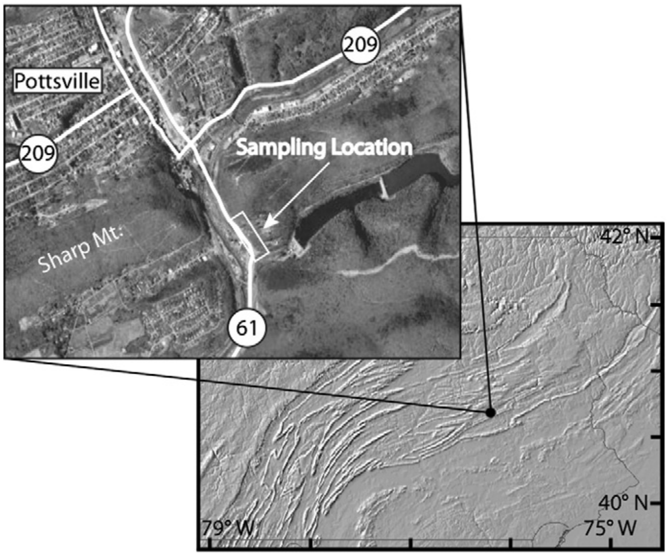

Fig. 1. Mauch Chunk Formation sampling locality. Greyscale digital elevation model of eastern Pennsylvania showing the study area on the northern limb of the Pennsylvania salient. Inset: aerial photograph showing the sampling location of Tan and Kodama (2002) along Route 61 in Pottsville, Pa.

Kent and Opdyke (1985) had also sampled the Mauch Chunk for a paleomagnetic and tectonic study in the Broad Top Basin of south-central Pennsylvania and in the Anthracite Coal Basin of eastern Pennsylvania, where the Minersville Synclinorium is located.

3. Methods

Small (9 mm diameter) cores were drilled perpendicular to bedding in hand samples collected from eight sites by Tan and Kodama (2002). From these cores 9 × 7 mm samples were cut for the hf-AIR anisotropy measurement technique of Bilardello and Kodama (2009a). 5 T IRMs were imparted in 9 orientations using a 13 mm diameter coil in an ASC scientific impulse magnetizer. Samples were successively thermally demagnetized at temperatures of 125 °C in an ASC TD-48 thermal demagnetizer, to demagnetize possible goethite remanence. Samples were then alternating field (af) demagnetized at 100 mT, to remove any magnetite remanence, and measured in a 2G Enterprises superconducting magnetometer at Lehigh University.

IRM acquisition experiments were performed in fields up to 5 T using the impulse magnetizer and magnetometer and modeled (Kruiver et al., 2001) to evaluate the magnetic mineralogy. Further rock-magnetic measurements designed to identify the magnetic mineralogy were performed at the Institute for Rock Magnetism, University of Minnesota: Low temperature measurements of selected specimens were made using a Quantum Designs MPMS cryogenic susceptometer. Samples were cooled from room temperature to 20 K in a null magnetic field (zero field cooling; ZFC), a 2.5 T field was applied isothermally and then the specimens were measured during thermal demagnetization up to 300 K. A 2.5 T field was re-applied at room temperature (300 K) and the samples were then measured on cooling back to 20 K in the absence of a magnetic field (room temperature remanence on cooling; RT cooling). Hysteresis loops of selected specimens were also measured on a variable temperature Princeton Measurements Corporation Vibrating Sample Magnetometer (VSM) to generate FORC diagrams and for a Thermal Fluctuation Tomography experiment (Bilardello, 2008). High-temperature susceptibility was also measured on a Geofyzika KLY-2 KappaBridge AC susceptibility bridge.