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Magnetic minerals as recorders of weathering, diagenesis, and paleoclimate: A core–outcrop comparison of Paleocene–Eocene paleosols in the Bighorn Basin, WY, USA

Daniel P. Maxbauer[a,b,*], Joshua M. Feinberg[a,b], David L. Fox[b], William C. Clyde[c]

[a] Institute for Rock Magnetism, University of Minnesota, Minneapolis, MN, USA
[b] Department of Earth Sciences, University of Minnesota, Minneapolis, MN, USA
[c] Department of Earth Sciences, University of New Hampshire, Durham, NH, USA

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ABSTRACT

Magnetic minerals in paleosols hold important clues to the environmental conditions in which the original soil formed. However, efforts to quantify parameters such as mean annual precipitation (MAP) using magnetic properties are still in their infancy. Here, we test the idea that diagenetic processes and surficial weathering affect the magnetic minerals preserved in paleosols, particularly in pre-Quaternary systems that have received far less attention compared to more recent soils and paleosols. We evaluate the magnetic properties of non-loessic paleosols across the Paleocene–Eocene Thermal Maximum (a short-term global warming episode that occurred at 55.5 Ma) in the Bighorn Basin, WY. We compare data from nine paleosol layers sampled from outcrop, each of which has been exposed to surficial weathering, to the equivalent paleosols sampled from drill core, all of which are preserved below a pervasive surficial weathering front and are presumed to be unweathered. Comparisons reveal an increase in magnetization in outcrops compared with core equivalents, which is principally driven by secondary hematite production. Authigenic hematite production in outcrops presents a complication for goethite–hematite based paleoprecipitation proxies where estimates will be biased toward drier climate regimes. The occurrence of low coercivity minerals is more consistent between core and outcrop. However, we propose an alteration process for pedogenic magnetite that is observed in both core and outcrop, where pedogenic magnetite becomes progressively oxidized leading to higher mean coercivities and broader coercivity distributions compared to modern pedogenic magnetite. This combination of diagenetic processes and surface weathering influences the magnetic properties of paleosols. Despite these changes, magnetic enhancement ratios from B-horizons correlate with independent MAP estimates from geochemical proxies, which suggests that paleoprecipitation information is preserved. Future work should continue to address these complications by developing useful protocols that isolate the magnetic properties that are most resistant to alteration and remain strong indicators of MAP and climate.

1. Introduction

The magnetic properties of soils and paleosols are often used to make environmental and climatic interpretations throughout the geologic record (see reviews by Maher, 1998; Maxbauer et al., 2016). This is possible largely because magnetic minerals such as goethite (FeOOH), hematite (α-Fe_2O_3), magnetite (Fe_3O_4), and maghemite (γ-Fe_2O_3) form through a combination of processes that are often critically dependent on soil moisture (Maxbauer et al., 2016, and references therein). Many studies have established empirical, quantitative relationships between pedogenic iron oxide minerals and the mean annual precipitation (MAP) under which the soil formed (e.g., Maher and Thompson, 1995; Geiss et al., 2008; Long et al., 2011; Hyland et al., 2015). These quantitative methods, along with earlier more qualitative interpretations, hold enormous potential for understanding environmental variability in the deep past. Two recent studies have highlighted the potential for methods based on the ratio of goethite-to-hematite (G/H; Hyland et al., 2015) and direct estimates of pedogenically produced magnetite (Geiss et al., 2008). The G/H method presented by Hyland et al. (2015) was calibrated using modern soils that formed over a wide range of MAP values (200–3000 mm yr^{-1}). In contrast,

* Corresponding author at: 310 Pillsbury Dr. SE, Department of Earth Sciences, University of Minnesota, Minneapolis, MN 55408, USA.
E-mail address: maxba001@umn.edu (D.P. Maxbauer).

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the calibrations of Geiss et al. (2008) are similar to other pedogenic magnetic susceptibility based proxies (e.g., Maher and Thompson, 1995) in that they only range up to ~1000 mm yr^{-1}. However, Geiss et al. (2008) offered calibrations between MAP and magnetic enhancement ratios (M_B/M_C, where M is the mean value of a generic magnetic property for the B and C soil horizons) or direct measures of pedogenic magnetite (e.g., ratio of anhysteretic to isothermal remanence) that may prove useful in expanding methods developed on loessic soils into other soil types and climatic regimes.

Most paleosol studies are based on observations from Quaternary or younger loess–paleosol sequences (e.g., Geiss et al., 2008; Maher and Thompson, 1995; Maher et al., 2003) so little is known about the magnetic properties of more ancient paleosols as paleoclimatic indicators. The few studies that examine this topic report low magnetic susceptibility (χ) in ancient paleosols compared to modern soils (Rankey and Farr, 1997; Cogoini et al., 2001; Retallack et al., 2003; Tramp et al., 2004). However, in some ancient systems there is evidence for preservation of pedogenic magnetic mineral assemblages that may be useful for reconstructing past environmental conditions (Rankey and Farr, 1997; Cogoini et al., 2001; Tramp et al., 2004; Morón et al., 2013; Hyland et al., 2015). Despite these exciting suggestions, there remains a general lack of information regarding the role of diagenesis and weathering in altering the original magnetic mineral assemblages in ancient paleosols, which limits our ability to interpret environmental conditions from ancient paleosol sequences with confidence. We must learn more about the diagenetic changes that affect soil magnetic mineral assemblages throughout their transformation into paleosols, throughout the subsequent burial history and exposure to chemically variable groundwater, and throughout their weathering history (for a recent review on magnetic mineral diagenesis, see Roberts, 2015).

Here, we examine these processes in paleosols preserved at the Polecat Bench locality in the Bighorn Basin, Wyoming (Fig. 1). The Bighorn Basin Coring Project (BBCP; Clyde et al., 2013) recovered nearly 900 m of sediment core from three localities in the Bighorn Basin, including Polecat Bench. Core scan images (Fig. 2A) clearly indicate that oxidative weathering has altered sediment color to depths of up to 25 m below the ground surface (Clyde et al., 2013). This observation calls into question whether magnetic mineral assemblages in paleosol outcrops reflect the original pedogenic assemblage and the environmental conditions in which they formed. This question has important implications for applying most magnetic-based paleoprecipitation proxies to ancient systems since they assume that the magnetic minerals preserved in paleosols are pedogenic and are not significantly altered by subsequent diagenesis and late-stage weathering.

The presence of the same paleosols in both BBCP cores and nearby outcrops presents an opportunity to test whether surficial weathering of outcrops significantly affects magnetic mineral preservation. We present magnetic data from nine marker bed paleosols, which were sampled from both core and outcrop (Fig. 3). All paleosols occur well below the oxidative weathering front in the sediment core and we assume that these sediments are largely unweathered compared to equivalent outcrop exposures (see Fig. 2). Both core and outcrop paleosols have likely been subjected to various long-term diagenetic processes (for example, interaction with fluids and elevated temperatures post-burial and before exposure of the basin). We compare magnetic properties of the Bighorn Basin paleosols to those of some modern soils to evaluate the effects that diagenesis can have on magnetic mineral preservation, independent from weathering.

Our record spans the Paleocene–Eocene Thermal Maximum (PETM, 55.5 Ma), which was a rapid global warming event driven

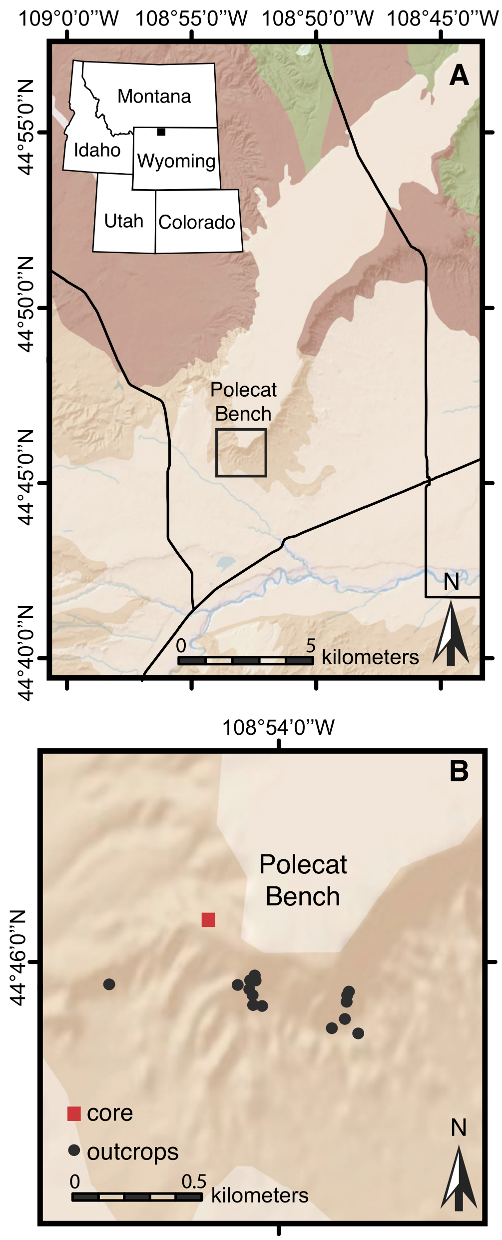

Fig. 1. Maps of the study site at Polecat Bench in the Bighorn Basin, WY. (A) Map of the northern Bighorn Basin. The highlighted and labeled box indicates the study area at Polecat Bench. The location of the study site in Wyoming is indicated in the inset of panel A. (B) Polecat Bench locality with sampling locations indicated for outcrop paleosols (black circles) and coring location (red square). Color guide: darkest brown = Paleocene Fort Union Formation, dark tan = Paleocene–Eocene Willwood Formation, light tan = Quaternary gravels, and green = Cretaceous units. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

by a massive release of isotopically light carbon into the mixed atmosphere/ocean system (see review by McInerney and Wing, 2011). In the Bighorn Basin, the PETM was associated with a transient precipitation decrease that has been well documented in qualitative and quantitative paleoflora records (Wing et al., 2005) and from paleosol geochemistry and morphology (Kraus and Riggins, 2007; Adams et al., 2011; Kraus et al., 2015). We compare our rock magnetic record to a recent study of MAP estimates derived from geochemical weathering indices (Kraus et al., 2015) to evaluate whether magnetic mineral assemblages in these paleosols record paleoprecipitation changes during the PETM.