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Palaeogeography, Palaeoclimatology, Palaeoecology 198 (2003) 373–380

PALAEO

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Magnetic susceptibility of early Paleozoic and Precambrian paleosols

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Received 15 March 2002; accepted 20 May 2003

Abstract

Paleosols formed by weathering and plant colonization during breaks in eolian deposition of Quaternary loesses are marked by enhanced magnetic susceptibility. These paleosols can be recognized in the field from their soil structure and soil horizons, but the most obvious and diagnostic feature of paleosols are root traces. For paleosols of early Paleozoic and Precambrian age, pre-dating the evolution of rooted land plants, root traces cannot be used as a diagnostic field criterion for recognizing paleosols. Surficial enhancement of magnetic susceptibility can be useful confirmation that some Precambrian and early Paleozoic rocks were paleosols. Unfortunately, magnetic susceptibility enhancement of some paleosol profiles is compromised by burial gleization, which reduces overall susceptibility values, but especially susceptibility at the surface of the profile, and produces a marked covariance of magnetic susceptibility with total iron content. Groundwater and surface water gleization during soil formation also depletes susceptibility over a wide range of iron content to give relatively flat depth functions of susceptibility. In contrast, well-drained soils and paleosols have pronounced surficial susceptibility enhancement over a narrow range of iron content. Magnetic susceptibility peaks are useful supporting evidence for paleosols entirely red and oxidized, but not for paleosols with common green-gray reduction spots, abundant organic matter, iron–manganese nodules or other evidence of gleization. All known Paleozoic and Precambrian paleosols have susceptibility an order of magnitude less than in comparable Quaternary paleosols and soils, so that Quaternary magnetic susceptibility climofunctions and chronofunctions cannot yet be applied to Paleozoic and Precambrian paleosols. Although their susceptibility values are comparable with those of modern gleyed soils, Paleozoic and Precambrian paleosols maintain a depth function of surficial enhancement of susceptibility, as well as red color, deeply penetrating cracks and other features of well-drained soils. Burial recrystallization of fine-grained magnetite and maghemite may have compromised the magnitude of their susceptibility peaks. Alternatively, they may not have been as biologically active in susceptibility-enhancing microbes as modern soils.

Keywords: paleosols; magnetic susceptibility; gleization; Precambrian; Paleozoic

1. Introduction

Paleosols are difficult to recognize in early Pa-

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doi:10.1016/S0031-0182(03)00479-6

leozoic and Precambrian alluvial sedimentary rocks because they lack the large root traces of vascular plants that characterize late Paleozoic and geologically younger paleosols (Retallack, 2001a). Only fine rhizome traces are known from Silurian paleosols (Mora and Driese, 1999) and the large root traces and profile form of forest soils are known only as far back as middle Devonian (Retallack, 1997a). Liverwort-like plants may have colonized soils as ancient as mid-Ordovician, but before that time life on land consisted of lichens or microbial scums (Retallack, 1992, Retallack, 2000).

Precambrian and early Paleozoic red paleosols contain iron-bearing minerals and pigments, which can be investigated by a variety of geochemical and rock magnetic techniques (Retallack, 1997b). For example, magnetic susceptibility is magnetization induced in a sample by an applied magnetic field, and is an easily measured rock property widely used as a proxy for paleoclimatic reconstruction of Quaternary loess (Verosub and Roberts, 1995; Maher and Thompson, 1999; Maher et al., 2002). Magnetic susceptibility can soar from background levels of 20×10^{-8} to 120×10^{-8} m^3/kg within Quaternary loessic paleosols, which represent times of wetter than usual paleoclimate and good grass cover of their dusty, dry plains. Early explanations of these susceptibility peaks invoked chemical weathering (Heller and Liu, 1986), eolian sorting (Kukla et al., 1988), or wildfires (Kletetschka and Banerjee, 1995), but none of these mechanisms can be shown to produce susceptibility enhancement of the magnitude observed in soils. A more likely explanation is that magnetic susceptibility is enhanced by accumulation of ferrimagnetic minerals magnetite and maghemite during soil formation through some kind of microbial activity. In an attempt to determine the microbes and processes involved, Dearing et al. (1996) showed that there was no significant enhancement of magnetic susceptibility in modern soils by anaerobic precipitation of greigite linked to microbial reduction, by anaerobic magnetite encouraged by GS-15 type dissimulatory bacteria, or by microaerophilic magnetotactic bacteria. They found instead that susceptibility is most enhanced by biotically encouraged hydrolytic and fermentative release of ferrous ions followed by uncontrolled extracellular oxidation to magnetite and maghemite grains less than 100 nm in size. Magnetite and maghemite are responsible for most of the signal because their susceptibility is three orders of magnitude greater than that of other iron-bearing minerals such as goethite, hematite, lepidocrocite and ferrihydrite (Maher, 1998). A positive linear correlation between magnetic susceptibility and organic matter content of soils indicates a relationship between susceptibility enhancement and soil productivity (Jia et al., 1997). There are also strong positive relationships between magnetic susceptibility and (1) time of soil development from 0.03 to 240 ka, (2) mean annual temperature from 0 to 15°C, and (3) mean annual precipitation from 100 to 1200 mm (Woodward et al., 1994; Singer et al., 1996; Han et al., 1996). Thus magnetic susceptibility peaks are potential guides to paleosol identification, and interpretation of duration, productivity and paleoclimate of former pedogenesis.

Unfortunately, not all soils or paleosols show simple peaks of magnetic susceptibility at the surface. Low susceptibility values throughout the profile are found in gray, carbonaceous, and waterlogged soils, in which the soil-forming process gleization is active (Maher, 1998; de Jong et al., 2000). Magnetic susceptibility of less than 20×10^{-8} m^3kg^{-1} can be used as a field indication of hydric soils (Grimley and Vepraskas, 2000). This contrast between gleyed and ungleyed soils can be demonstrated by plots of magnetic susceptibility versus iron content (Fig. 1A) and versus depth (Fig. 1B). Covariance between dithionite extractable iron and magnetic susceptibility of Chinese Quaternary paleosols (Vidic et al., 2000) and soils (Lu, 2000) is matched by our data for particular soil orders, but not for soils as a whole (Fig. 1A). Modern ungleyed soils show susceptibility enhancement over a narrow range of iron content, whereas gleyed profiles show low magnetic susceptibility over a wide range of iron content created by redox-related mobilization and precipitation of iron within the profile. In addition, some paleosols show burial gleization in which a well-drained soil subsided below water table after burial with subsequent selective gleiza-

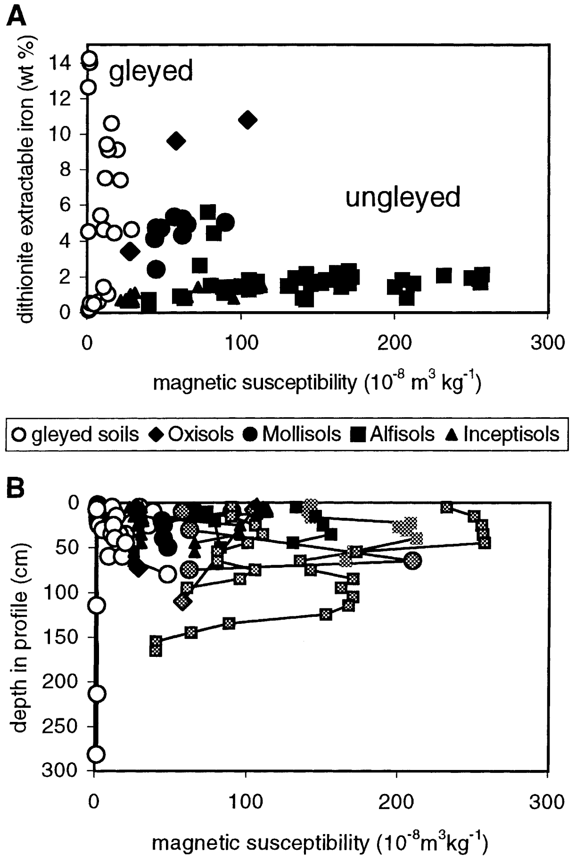

Fig. 1. Relationship between iron extracted by dithionite and magnetic susceptibility (A) and between depth in profile and magnetic susceptibility (B) in a variety of modern soils (data from Maher, 1998; Hanesch and Petersen, 1999; Alekseeva and Alekseev, 1999; de Jong et al., 2000).

tion around roots and other remnant organic matter (Retallack, 1997b, 2001a). Magnetic susceptibility promises to aid in discriminating between original and burial gleization of paleosols, as we demonstrate in this study of paleosols ranging in age from Precambrian to Devonian.

2. Materials, methods and results

Samples were selected from paleosol profiles previously studied in detail by petrography and geochemistry, including major-element chemical analysis by XRF (Retallack, 1985, 1992, 1997a; Retallack and Storaasli, 1999). Field data shown here include grain size, Munsell color, sedimentary and pedogenic structures (Fig. 2). Also shown are interpretations of soil horizons and of the degree of development of the paleosols using scales and nomenclature outlined by Retallack (1997b). Cores were taken from fresh rock specimens from various levels within each of the paleosols and bulk magnetic susceptibility of each measured using an SI-2 meter.

The Precambrian paleosols sampled near Fishtrap Lake overlie the Libby Formation (middle Proterozoic, 1170–930 Ma), northwest Montana (Link et al., 1993), and may be an outlier of the Windermere Supergroup (730–550 Ma; Retallack and Storaasli, 1999). They are overlain by the Early Cambrian, Flathead Sandstone. These red Entisols are thermally mature and deeply buried, but not metamorphosed. Filamentous organic microfabrics are found within paleosol surface horizons in clasts of claystone breccia horizons, indicating that these fabrics are Precambrian in age. There are weak peaks in magnetic susceptibility marking each of the paleosols (Fig. 2D), and susceptibility is independent of total iron content (Fig. 3).

Paleosols in the Late Ordovician (Ashgillian), Juniata Formation, near Potters Mills, Pennsylvania, include a well-drained Inceptisol above an Entisol (Retallack, 1985; Feakes and Retallack, 1988), both metamorphosed to low within the greenschist facies. These paleosols also contain burrows of invertebrates, probably millipedes (Retallack, 2001b). Drab mottles in the surface of the paleosols indicate that liverworts, lichens or microbes were arrayed in scattered clumps (Retallack, 1992). Magnetic susceptibility in both a weakly and moderately developed profile was low and relatively constant (Fig. 2C), with no enhancement of susceptibility in the Entisol and little enhancement in former surface of the Inceptisol.

Entisol (below) and Inceptisol (above) paleosols in alluvial sedimentary rocks of the Late Silurian (Ludlovian) Bloomsburg Formation were sampled near Palmerton, Pennsylvania, and are also metamorphosed within the lower greenschist facies (Retallack, 1985). These paleosols contain a variety of burrows and rhizome-like impressions like

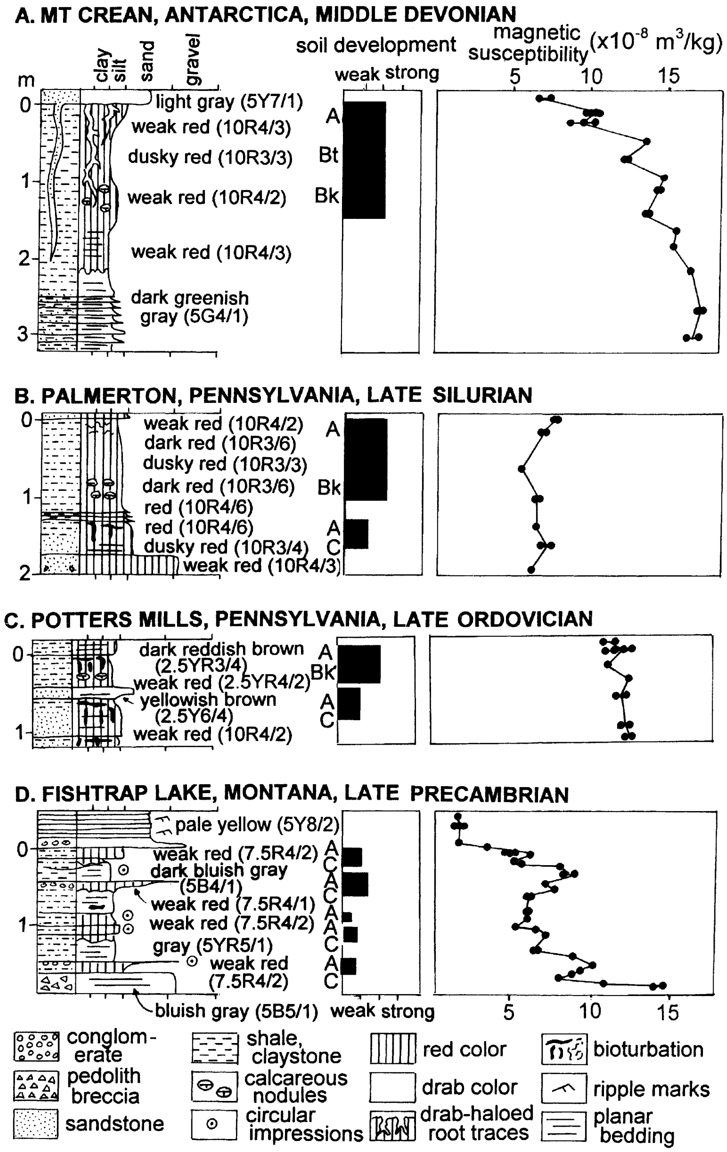

Fig. 2. Field observations, including Munsell color and grain-size variation, interpretations of paleosol horizons and degree of development (after Retallack, 1997b), and magnetic susceptibility of selected Precambrian and early Paleozoic paleosols. (A) From the Middle Devonian (Givetian) Aztec Siltstone, on Mt. Crean, Victoria Land, Antarctica. (B) Late Silurian (Ludlovian) Bloomsburg Formation, at Palmerton, Pennsylvania. (C) Late Ordovician (Ashgillian) Juniata Formation, near Potters Mills, Pennsylvania. (D) Late Precambrian, 'upper Libby Formation' at Fishtrap Lake, Montana.

those of early land plants (Retallack, 1992). These paleosols also show very modest covariance of iron content and magnetic susceptibility and a subdued depth function (Fig. 2B), with no enhancement for the Entisol and modest surficial enhancement in the Inceptisol.

The middle Devonian (Givetian) paleosol from the Aztec Siltstone, Mt. Crean, Antarctica, is thermally mature, and underlies coal measures of bituminous grade. It was probably an Alfisol supporting monsoon forests of the progymnosperm *Archaeopteris* (Retallack, 1997a). This pro-

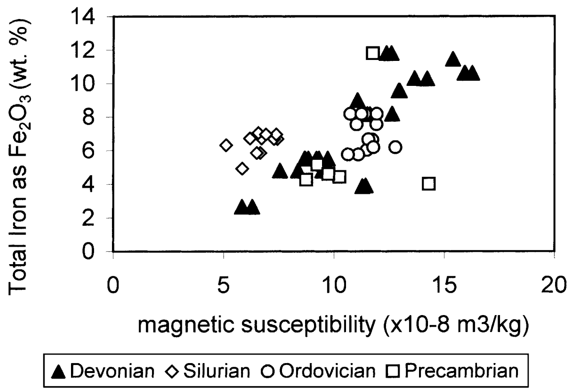

Fig. 3. Relationship between total iron as oxide and magnetic susceptibility in the paleosols shown in Fig. 2. The Precambrian (squares), Ordovician (circles) and Silurian (diamonds) profiles do not show a clear relationship, but a relationship is clear in the Devonian paleosol (large triangles), which is the only paleosol showing strong burial gleization.

file has a strongly depleted depth function of magnetic susceptibility, with minimum values near the surface and the highest values in the parent material (Fig. 2A). Its magnetic susceptibility is low and highly correlated with total iron content (Fig. 3), unlike either gleyed or ungleyed modern soils (Fig. 1).

3. Other comparable results for paleosols

Pennsylvanian–Permian loessite facies of the Maroon Formation near Aspen, Colorado, include red Entisols and Inceptisols, with stout woody root traces and rare reduction spotting, probably from desert shrubland vegetation (Johnson, 1989; Retallack, 1995). These paleosols show low but clear peaks of enhanced magnetic susceptibility (Soreghan et al., 1997). More complex depth functions of magnetic susceptibility were found in paleosols in the late Pennsylvanian Roca Shale near Manhattan, Kansas (Rankey and Farr, 1997). There was enhanced susceptibility in the surface of a red ungleyed Entisol, but depleted susceptibility in burial gleyed Alfisols and Vertisols. Other Vertisols from the Mississippian (Chesterian) Pennington Formation near Monterey, Tennessee, and the Pennsylvanian (Virgilian) Lawrence Shale near Lawrence, Kansas (Rankey and Farr, 1997) show erratic depth functions for magnetic susceptibility with slight surficial depletion. These Carboniferous–Permian paleosols are thermally mature, and associated with bituminous coals.

4. Burial gleization of paleosol magnetic susceptibility

Burial gleization is a process inferred for shallowly buried paleosols. In the field, burial gleization looks like surface-water gleization from perched water because gray-green reduction spotting is most intense near the surface of the soil and within root traces and soil cracks, but leaving subsoil and clod interiors oxidized. Burial gleization can be distinguished from surface-water gleization in paleosols with deeply reaching root traces and no other indication of subsoils impermeable enough to have ponded water. Groundwater gleization, in contrast, maintains chemically reduced iron minerals and drab colors deep within the profile, but root traces and soil cracks may have oxidized rims where oxygen-rich air diffused into the soil.

Surface-water gleyed, groundwater gleyed and burial gleyed paleosols may be distinguished using field criteria outlined above, but also useful is a combination of chemical and magnetic data. Soils that are well-drained show strong magnetic susceptibility enhancement with limited variation in total iron content. Soils affected by groundwater gleization in contrast show uniformly low magnetic susceptibility, even in iron-rich horizons formed by translocation of reduced iron within the profile into low-susceptibility birnessite (amorphous iron–manganese), ferrihydrite and goethite (Fig. 1). Gleization of a formerly well-drained soil buried within a sedimentary sequence should produce yet another pattern, which can be predicted from studies of marine sediments. Early diagenetic destruction of magnetic susceptibility in marine sediments is linked to abundant buried organic matter that fuels ‘bacterial respiration to cause reductive dissolution of magnetite' (Hesse and Stolz, 1999). The nature of the microbial community involved in this chemical reduction and how they achieve this dissolution remains unclear. For well-drained soils subsiding below water table, originally enhanced magnetic susceptibility would be strongly depleted in iron-poor and organic-rich upper parts of the profile (A and E horizons) but less depleted in iron-rich and organic-poor lower parts of the profile (B and C horizons).

This prediction is confirmed by our observations of magnetic susceptibility in the Devonian paleosol affected by burial gleization (Fig. 2A) and by data on comparable paleosols (Rankey and Farr, 1997). The Devonian paleosol shows a relationship between susceptibility and total iron (Fig. 3) and a susceptibility depth function (Fig. 2) unlike that of modern soils (Fig. 1). The surface horizon, clastic dikes of sandstone, and deeply reaching root traces of this paleosol are green-gray in color and chemically reduced. Yet, the original soil was originally well-drained, considering its deep sand-filled cracks, calcareous rhizoconcretions and geochemical differentiation (Retallack, 1997a). In contrast, the Silurian, Ordovician and Precambrian paleosols (Fig. 2B–D) do not show a clear relationship between susceptibility and total iron (Fig. 3), despite very minor reduction spotting. The Silurian, Ordovician and Precambrian paleosols have preserved modest surficial magnetic susceptibility peaks (Fig. 2). Surficial susceptibility depletion together with covariance of magnetic susceptibility and iron content of paleosols may provide physicochemical criteria for distinguishing between original and burial gleization of paleosols.

5. Environmental significance of paleosol magnetic susceptibility

Our attempts to apply to Paleozoic and Precambrian paleosols transfer functions for temperature (Han et al., 1996), precipitation (Han et al., 1996; Maher and Thompson, 1999) and time of development of Quaternary soils (Singer et al., 1996; Woodward et al., 1994), were unsuccessful because magnetic susceptibility values in Precambrian and Paleozoic paleosols are an order of magnitude lower than those for Quaternary soils and paleosols (Maher and Thompson, 1999). Loessites of the Pennsylvanian–Permian Maroon Formation of Colorado show peaks of only 17×10^{-8} m^3 kg^{-1} above background of about 4×10^{-8} m^3 kg^{-1} (Soreghan et al., 1997), whereas background for the sedimentologically and lithologically comparable Chinese loess is 20×10^{-8} m^3 kg^{-1} and peaks are commonly 120×10^{-8} m^3 kg^{-1} (Maher and Thompson, 1999).

Paleozoic and Precambrian paleosols have magnetic susceptibility values within the range for gleyed soils (Grimley and Vepraskas, 2000), but their depth functions differ in showing very small subsurface values as well as a low peak of susceptibility at the surface. Furthermore, the depth of clay skins, carbonate nodules and other pedogenic features of the paleosols indicate that they were well drained soils. Paleozoic and Precambrian paleosols with susceptibility peaks do not match the depth function nor iron-susceptibility covariance documented here for paleosols altered by burial gleization (Figs. 2A and 3).

If not burial or original gleization, then two additional possibilities may explain the low magnetic susceptibility of Precambrian and Paleozoic paleosols. Perhaps susceptibility was degraded by recrystallization and metamorphism of magnetite and maghemite (Retallack, 1991). Or perhaps susceptibility enhancement increased through geological time with advances in weathering intensity and biological productivity, which have been predicted on other grounds (Schwartzmann and Volk, 1991). Testing of these possibilities will require study of more paleosols with a wider range of geological age and burial alteration than currently available.

The general similarity of our Precambrian paleosol susceptibility peaks to those of the Ordovician, Silurian (Fig. 1), Pennsylvanian–Permian (Soreghan et al., 1997) and Quaternary (Maher and Thompson, 1999) implies substantial atmospheric oxygenation during the late Precambrian. This is not surprising in view of supporting evidence from paleosols for substantial atmospheric oxygenation so late in the Precambrian (Rye and Holland, 1998), but does suggest a new approach to the controversial earlier Precambrian paleosol record of atmospheric composition (Ohmoto, 1997). A critical piece of information lacking at present is the atmospheric partial pressures of soil oxygen that divide susceptibility-enhanced from susceptibility-depleted soils. Because susceptibility-depleted soils include moderately well-drained profiles such as Spodosols (Maher, 1998), it is likely that this threshold is at higher partial pressures of oxygen than any past oxygen paleobarometer used for paleosols (Rye and Holland, 1998).

6. Conclusions

Magnetic susceptibility enhancement is useful for identification of some Precambrian and Paleozoic paleosols in alluvial and eolian sedimentary rocks. It is only useful for paleosols that are almost entirely red and relatively free of the green spots and mottles that are indicative of burial or original gleization. Covariance of iron content with magnetic susceptibility and surficial depletion of magnetic susceptibility ($<10\times10^{-8}$ m^3kg^{-1}) is striking in paleosols with features of burial gleization. In contrast, gleyed soils and paleosols show generally low magnetic susceptibility ($<20\times10^{-8}$ m^3kg^{-1}), varying little with large changes in iron content (up to 14 wt%) or level within the profile (down to 300 cm). Ungleyed soils and paleosols also can show covariance of iron content with magnetic susceptibility but with surface enhancement of susceptibility (5–120 $\times$ 10^{-8} m^3kg^{-1}) over a relatively narrow range of iron content (± 2 wt%). The generally low magnetic susceptibility of Precambrian and Paleozoic paleosols does not seem to be related to original or burial gleization and remains a puzzle. Perhaps it is due to burial recrystallization or lower biological productivity of such deeply buried and ancient soils.

Acknowledgements

We thank E. Oches, P. Bartlein, K. Verosub, L. Tauxe, and G. Soreghan for discussion.

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