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Establishing fire incidence in temperate soils using magnetic measurements

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Abstract

Natural, unburnt topsoil samples from the Cotswolds region of England and samples from archaeological contexts in the UK and Hungary, some of which are known to have been affected by burning, have been used to identify a distinctive magnetic 'signature' linked to the effects of fire on magnetic properties. A combination of bulk, low field (χ_{lf}) and frequency dependent (χ_{fd}) magnetic susceptibility and normalized anhysteretic remanent magnetization (χ_{ARM}) measurements have been used on both unburnt and experimentally burnt samples from the Cotswolds and on the archaeological samples. Complementary determinations were made for both sets of samples of the maximum potential susceptibility (χ_{max}) and, hence, percentage fractional conversion (χ_{conv}), which provides independent evidence of burning. The results show that the ferrimagnetic mineral assemblages produced as a result of fire have a significantly finer grain size than those arising from weathering and soil formation alone. Burning thus gives rise to a distinctive envelope of values on a bilogarithmic plot of χ_{ARM}/χ_{fd} versus χ_{ARM}/χ_{lf}. Such a diagram provides a convenient basis for identifying magnetic signatures in soils, archaeological materials and palaeosols that have arisen mainly through burning.

Keywords: Fire; Soils; Archaeology; Magnetic properties; Palaeosols

1. Introduction

One of the earliest contributions to what has become known as environmental magnetism was Le Borgne's (1955, 1960) demonstration that burning led to enhanced soil susceptibility. Subsequent studies showed that the magnetic minerals arising as a result of enhancement through burning include fine-grained ferrimagnets which, depending on the conditions of heating and cooling, could be either non-stoichiometric magnetite, or maghemite (Mullins, 1977; Longworth et al., 1979). Rummery et al. (1979) were able to show that strongly enhanced ferrimagnetic mineral signatures in the surface sediments of Llyn Bychan, N Wales, could be linked to catchment fires during the year preceding sampling and also that the magnetic signatures from well-documented forest fires that occurred during the late 1940s in the Landes region of SW France persisted in sediment profiles from the Etang de Biscarosse and the Etang de Sanguinet at least until 1977. All these studies relied on measurements such as magnetic susceptibility (χ) or saturation isothermal remanent magnetization (SIRM) which are indicative of increased magnetic concentrations. No attempt was made to establish any kind of magnetic 'fingerprint' indicative of burning.

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In addition to the role of fire, several other mechanisms have been proposed that enhance soil susceptibility by increasing the concentration of 'secondary', fine-grained ferrimagnets. These mechanisms range from the widespread effects of natural soil formation, where this involves alternations between reducing and oxidizing conditions (Mullins, 1977; Maher and Taylor, 1989), to localized iron sulphide (greigite) formation under persistently reducing conditions (Fassbinder and Stanjek, 1994).

As a first step towards identifying a magnetic signature linked to fire, Oldfield (1994), following Maher (1988), proposed a basis for distinguishing between secondary, fine-grained ferrimagnets formed in soil, whether by burning or by natural soil formation, and those produced by magnetotactic bacteria. This distinction rests on the much greater extent to which the latter comprise stable single domain (SD) grains capable of retaining a strong magnetic remanence. As a result of this, magnetite produced by magnetotactic bacteria has a high anhysteretic remanent magnetization (ARM), often expressed as susceptibility of ARM (χ_{ARM}). By contrast, secondary soil 'magnetite' is relatively richer in finer magnetic grains. Among these latter, grains with diameters close to the boundary between SD and superparamagnetic (SP) behaviour (ca. 0.02 μm) show peak values for frequency dependent susceptibility (χ_{fd}). Even finer grains within the SP range show peak values for low frequency susceptibility (χ_{lf}). It follows from this that within magnetic assemblages dominated by grain sizes in the SD range and finer, χ_{ARM}/χ_{lf} and χ_{ARM}/χ_{fd} increase with increasing grain size. Although the two quotients can be used separately, a convenient way of plotting both (as in the figures in the present study) is on a bilogarithmic diagram using them as axes. By means of this type of diagram, the envelope of values for sediments dominated by bacterial magnetite can be clearly distinguished from that within which both soil sources and sediments dominated by the erosive input of secondary pedogenic ferrimagnets fall (Oldfield, 1994). It has also been possible to use the envelopes of quotient values to differentiate between catchment soil sources, and sediment assemblages that are partly derived from them but also include bacterial contributions (van der Post et al., 1997; Oldfield and Wu, 2000).

From the results published so far, however, no clear distinction has emerged between fine-grained secondary magnetite produced by burning and that produced by weathering. The envelope of values for catchment sources and fine-grained, predominantly detrital sediments reported in Oldfield (1994), and used to provide contextual background to the present results, includes samples from a wide range of environmental contexts, some of which may have been burned.

In the present study we explore the possibility that burning may give rise to a magnetic 'signature' sufficiently distinctive from that arising from weathering alone to allow its detection where it has been the dominant mechanism responsible for magnetic enhancement. The approach used builds on that outlined in Gedye et al. (2000). They show that the sediment record from Lago di Origlio, a small lake in southern Switzerland, includes several horizons containing strong evidence in the charcoal record for burning in the catchment. Each horizon is marked by magnetic mineral assemblages which, by virtue of their dominance by SP and transitional SP/SD grains, can be distinguished from the intervening layers, irrespective of whether these are dominated by bacterial magnetite, or by catchment-derived assemblages rich in haematite. What the results from Lago di Origlio are unable to do is to demonstrate conclusively the extent to which the fine-grained magnetite associated with fire incidence comes predominantly from burnt soils or simply reflects enhanced surface erosion in the wake of the fire. In the present study we seek to develop a basis for distinguishing between the two, initially in soils. Such a distinction may be helpful in:

- archaeological studies, where demonstration of *in situ* fire can aid interpretation of specific contexts (e.g. Crowther, 2003, in press);
- research on loess-palaeosol sequences, where there has been some debate about the processes giving rise to magnetic enhancement in the buried soil layers (e.g. Kletetschka and Banerjee, 1995; Maher and Thompson, 1999); and
- both erosion and fire history studies, provided any demonstrable distinctions can be made against the background 'noise' of magnetic variability arising from other processes responsible for changes in magnetic mineral assemblages (see e.g. Gedye et al., 2000; Blake et al., 2006).

The study also uses the percentage fractional conversion (χ_{conv}) of a sample (viz: χ_{lf}/χ_{max}, where χ_{max} is the maximum potential susceptibility of a sample) as an independent means of assessing the likely extent to which soils have been affected by burning (Tite and Mullins, 1971; Crowther, 2003).

Two complementary sets of samples were analysed. The first comprises modern topsoils from the Cotswolds