The effects of wildfires on the magnetic properties of soils in the Everglades

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ABSTRACT: We present results of a rock-magnetic study of soils that were affected by wildfires that burned portions of the Everglades in the Spring of 2008. Soils at sites that were extensively burned exhibit a pronounced surface magnetic enhancement effect with magnetizations of surface samples up to 16 times greater than that observed at depth (>7 cm) at these sites. The increase in magnetization results from an increased abundance of a low-coercivity phase (maghemite) that occurs at the expense of the abundance of a high-coercivity phase (goethite). These results indicate that fire-induced heating caused goethite in the surface soils to convert into a more magnetic, low-coercivity phase, such as maghemite. Goethite is an excellent adsorber of phosphorus, and therefore we hypothesize that the destruction of goethite as a result of burning may have important implications for phosphorus cycling in the Everglades ecosystem. Copyright © 2010 John Wiley & Sons, Ltd.

KEYWORDS: wildfire; magnetic enhancement; goethite; Everglades

Introduction

Soils often exhibit a magnetic surface enhancement effect in that the surface soils are much more magnetic than would be expected given the magnetic properties of the soil’s parent material (Le Borgne, 1955, 1960; Mullins, 1977; Tite and Linington, 1975; Schwertmann and Taylor, 1977; Maher, 1986, 1998; Geiss et al., 2004; see Thompson and Oldfield, 1986; Evans and Heller, 1994, 2003, for summaries of literature in this area). The surface enhancement effect presents an apparent contradiction because weathering reactions generally lead to progressive oxidation of the residual minerals, which for most magnetic minerals converts them to a less magnetic phase (Mullins, 1977; Singer and Fine, 1989; Singer et al., 1996). In order for enhancement to occur, a process must take place that converts weakly magnetic iron oxides and oxy-hydroxides into more reduced, and more magnetic, mineral phases (Taylor and Schwertmann, 1974a, 1974b; Mullins, 1977; Rummery et al., 1979; Liu et al., 2003).

Wildfires are one mechanism that has been proposed to alter the magnetic properties of soils, leading to an enhancement of the surface magnetism (Le Borgne, 1955, 1960; Rummery et al., 1979; Schwertmann and Fechter, 1984; Klettetschka and Banerjee, 1995; Quirine et al., 2000; Blake et al., 2006; Oldfield and Crowther, 2007). Although the mechanisms by which fires might enhance the surface magnetization are not well documented, it has been proposed that high tempera-

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Everglades, which is the only habitat of an endangered species, the Cape Sable seaside sparrow (Pimm et al., 2002; Ross et al., 2006). We were able to take advantage of the monitoring project to collect soil cores from well-characterized sites that had been affected by the fires. Our rock-magnetic results indicate that fire-induced heating caused goethite in the surface soils to convert into a more magnetic, low-coercivity phase, most likely maghemite. Because goethite is an excellent adsorber of phosphorus in aqueous environments (Patrick and Khalid, 1974; Parfitt and Atkinson, 1976; Torrent et al., 1990; van der Zee et al., 2003), the destruction of goethite during fires likely has important implications for phosphorus cycling in the Everglades ecosystem.

**Methods**

The soils in our sampling area are shallow, usually consisting of only 10 to 15 cm of freshwater marl overlying the limestone bedrock (Nobel et al., 1996; Corstanje et al., 2006). Bedrock in the Everglades consists of a highly porous limestone, and the overlying soils contain a large percentage of biogenically precipitated freshwater carbonate with smaller amounts of clays. In this aspect these soils are very different from a more typical soil that is formed as the weathering residue from the bedrock. These soils are located in southern Everglades marl prairies that are seasonally inundated by water, being submerged for an average of three to six months every year. The seasonal drying cycle results in precipitation of iron oxy-hydroxides from the ground/surface water onto surface materials as they dry (Zhou and Li, 2001). This is the same well-recognized process that causes significant yellow-brown staining of buildings and structures in the south Florida region as irrigation waters dry on surfaces leaving an iron oxy-hydroxide precipitate.

In the Spring of 2008 two large wildfires burned portions of the southern Everglades. The Mustang Corner fire burned 15,971 ha (39,465 acres), between May 14 to June 14, 2008. The West Camp fire started on June 22, 2008 and burned 997 ha (2465 acres) (Figure 1). These fires affected vegetation survey sites in the southern Everglades, which are being studied as part of an ongoing project to monitor ecological conditions within the habitat of the Cape Sable seaside sparrow. At each of these sites vegetation data, hydrologic data, organic carbon content, iron concentration and the fire history (burn frequency and time since the most recent burn) are available.

We collected 20 soil cores (10–13 cm long) from within the fire boundaries, and 10 cores from nearby unburned sites (Figure 1). The cores were collected in marl prairies where the major vegetation is sawgrass (Cladium jamaicense). The sampling sites are located in areas of generally uniform vegetation, however, small scale variations in topography due to microkarst features and the varying amounts of vegetative cover likely resulted in significantly different amounts of fuel for the fires at each site. This small-scale variability in fuel load suggests that the intensity of the fires likely varied on a similar scale. Therefore the distances separating our sampling localities likely far exceed the typical spatial scale of fire intensity.

Because these were wildfires, no independent, direct measures of the intensity of the fires were available. Therefore, at each site we estimated the local intensity of the fire based on the percentage of the surface area that was visibly burned in 60 m ¥ 1 m belt transects that are used as vegetation survey tracts. We collected soil cores from within these survey tracts. Previous studies suggest that only the upper few centimeters of soils are heated by surface fires (Monson et al., 1974; Iverson and Hutchinson, 2002; Raison et al., 1986). For this reason, we sub-sampled each core by taking samples from the surface, from the 2 cm depth interval and from close to the base of each core (between 7 cm to 13 cm depth).

Because most of the sites are only accessible by helicopter, we were unable to occupy the sites immediately following the fires, and had to wait until a scheduled survey in July. As a result the wet season had begun before we were able to collect the cores. Therefore it was not possible to determine how wet the soils in the sampled areas were during the fire. Nor was it possible to determine the local hydrologic history since the fire.

The samples were subjected to a suite of rock-magnetic measurements designed to identify the major magnetic miner-
als present in these soils and to constrain their relative concentrations. These measurements include initial susceptibility and frequency-dependent susceptibility made using a Bartington susceptibility meter, anhysteretic remanent magnetization acquisition and isothermal remanent magnetization (IRM) acquisition, made using a Molspin AF demagnetizer and an ASC impulse magnetizer with a coil allowing generation of impulse fields of up to 5 T. The remanences were measured on a 2G superconducting rock magnetometer equipped with DC squid sensors.

Results

Of the different rock magnetic experiments conducted, IRM acquisition curves proved to be the most useful because of the importance of very high-coercivity components (observed at fields > 3 T) that could not be detected using other types of measurements. Low field susceptibility measurements and hysteresis measurements (that only went up to 1·5 T), yielded less systematic results largely because these measurements are relatively insensitive to the high coercivity carriers that the IRM experiments show are present. In addition, the IRM acquisition experiments demonstrate that most samples contain mixtures of magnetic remanence carriers, which are more straightforward to interpret in IRM acquisition experiments (Kruiver et al., 2001; France and Oldfield, 2000) than other measurements. It is important to note that the occurrence of goethite in these samples would have gone largely unrecognized were it not for the high-field, impulse magnetizer used in this study.

Cores collected from sites characterized as having been 100% burned during the 2008 fires exhibit a large surface magnetic enhancement effect (Figure 2). Samples from the soil surface exhibit saturation IRMs that are many times (from 1·5 to 16 times) more magnetic than observed at depth in the same cores. The intensity of the magnetization varies systematically with depth in these cores. Samples from the 2 cm depth are consistently less magnetic than the surface samples, and samples from the deepest portions of the cores are even less magnetic.

The increase in saturation isothermal remanent magnetizations (sIRM) in the surface samples does not result solely from an increase in the concentration of the magnetic carrier. Instead, the composition of the magnetic carrier also varies systematically with depth (Figure 2). Deeper samples contain a progressively greater percentage of a high-coercivity carrier. In these deeper samples, the IRMs do not saturate even in impulse fields approaching 5 T, suggesting that the remanence is carried by goethite (Dunlop and Ozdemir, 1997).

Cores collected from nearby sites that were not affected by the fires exhibit very different behavior. In these cores samples from both surface and sub-surface are characterized by high-coercivity magnetizations (Figure 3). Although the surface samples are still more magnetic than those at depth in the majority of these cores, the variation with depth is less systematic. The extent of this variation likely results from variations in the burn histories of the sites, variations in the hydrology at the sites as well as variations in the soil composition.

In order to determine if the high-coercivity magnetization observed in these samples is carried by goethite or hematite,
we conducted progressive thermal demagnetization of orthogonal two-component IRMs (imparted at 5 T along the Z-axis of the sample and 0·2 T along the X-axis of the sample) (Lowrie, 1990; France and Oldfield, 2000). Results of these experiments show that the highest coercivity component is completely unblocked at temperatures of 100 °C to 125 °C, consistent with the maximum unblocking temperatures of goethite (Figure 4). In most samples the low coercivity magnetizations are completely unblocked at temperatures ranging from 500 °C to 580 °C. Changes in the slope of the thermal demagnetization curves suggests that the original low-coercivity carrier may be maghemite that alters to magnetite during demagnetization (possibly because of the presence of aluminum-substituted maghemites in the unheated samples). In one sample, the low-coercivity IRM is not unblocked until treatment at 670 °C, indicating a hematite remanence. The hematite must be formed during thermal demagnetization because there is no indication of it in the initial high-field IRM component. It is probable that maghemite in this sample was converted to hematite above temperatures of 350 °C. The offset in the trajectory of the demagnetization plot at 350 °C suggests this may indeed be the case. Extrapolation of the slope (before treatment at 350 °C) leads to a zero magnetization at approximately 580 °C. However at treatments above 350 °C the trend is systematically offset toward higher temperatures, being completely demagnetized at 670 °C.

Comparison of IRM acquisition curves imparted before and after thermal demagnetization shows that the high-coercivity carrier (goethite) is destroyed during heating and replaced by a low-coercivity carrier with a resulting sIRM that is more than 10 times greater that the pre-heating sIRM (Figure 5). The lower coercivity component observed after heating exhibits a distributed range of coercivities; it does not saturate until treatment at 0·6 to 0·8 T. This indicates that an oxidized maghemite rather than magnetite was likely the magnetic phase created during heating.

Discussion

At burned sites in our study, surface soils show a significant increase in remanent magnetizations relative to the magnetizations observed at depth at those sites. The increased magnetizations observed in the shallow samples appear to result from an increasingly dominant low-coercivity component. The low-coercivity component exhibits both an increase in absolute intensity as well as an increase in the percentage of the total remanence in surface samples as compared with samples at depth. Unmixing the IRM acquisition curves using the techniques described by Kruiver et al. (2001), indicates that the acquisition curves from all samples may be well-fit using two magnetization components. The first component consistently has coercivities, $B_{cr}^{1}$, of 40–60 mT (consistent with maghemite) and the second component has $B_{cr}^{2}$ values of 3100–3900 mT (consistent with goethite) (Dekkers, 1989, 1990; France and Oldfield, 2000; Maher et al., 2004). Unmixing the acquisition
and may provide a way to characterize the burn history of a site in the Everglades.

A major uncertainty in this study is the lack of independent, quantitative measures of the maximum temperatures the soils experience during these fires, and the depth within the soils to which those elevated temperatures extended. The intensity of a fire depends upon a number of factors, including the fuel load, the vegetation cover in the area, and the recent hydrologic history of the site. Future studies using controlled micro-burns with thermocouples deployed with depth are required to calibrate the changes in magnetic properties directly with temperature.

Another uncertainty affecting the interpretation of our results is the variability of the local hydrological history at these sites. We were not able to sample these sites immediately following the fires, but had to wait until the wet season was well underway. As a result, some sites had experienced considerable rainfall since the fire, and the rain events may have affected the distribution of fine particles with depth. This would have the effect of overestimating the depth to which significant heating had occurred. Fires usually produce steep temperature gradients in soils with only the upper few centimeters elevated to high temperatures. The temperature gradient has been related to fuel load and soil moisture content amongst other variables (Monson et al., 1974; Iverson and Hutchinson, 2002; Raison et al., 1986). The observation of conversion of goethite to maghemite at depth might be a result of very intense heating or alternatively, it could result from downward transport of fine-grained minerals by rains that fell after the fires but prior to our sampling.

Possible effects on phosphorus cycling

Iron oxy-hydroxides, especially goethite, are known to be important adsorbers of phosphorus in aquatic systems (Parfitt and Atkinson, 1976; van der Zee et al., 1990; Chambers and Odum, 1990; Torrent et al., 1990; Patrick and Khalid, 1974). Our thermal demagnetization experiments confirm that the high-coercivity carrier in the sediments we sampled is goethite. Determining the absolute concentrations of goethite in these soils is difficult to do based on magnetic measurements because of the sensitivity of the magnetic properties to the extent of crystallinity and impurities in the goethite. Previous studies of the mineralogy of the surface soils in the Everglades indicate relatively high concentrations (Zhou and Li, 2001) that are consistent with our observations. The occurrence of goethite in these soils is particularly important because phosphorus is a limiting nutrient in the Everglades prairies and marshes (Zhou and Li, 2001). Zhou and Li (2001) have shown that the non-carbonate clays (including iron-oxides and iron-oxyhydroxides) in calcareous soils from south Florida have a strong affinity for phosphorus.

The results presented here demonstrate that heating surface soils during wildfire converts goethite to low-coercivity phases such as maghemite. We hypothesize that the destruction of goethite will release the phosphorus that had been adsorbed onto it (Patrick and Khalid, 1974; Parfitt and Atkinson, 1976; Torrent et al., 1990; van der Zee et al., 2003). Therefore these results may have important implications for the role of fires in the phosphorus cycle. The extent of goethite destruction and therefore the amount of phosphorus released likely depends on the thickness of the surface soil that is heated to high enough temperatures to cause the dehydration of goethite. This in turn depends upon the intensity of the fire. Future work studying controlled burns where we can measure the temperature profile with depth and measure phosphorus contents of
soil cores before and after heating is required to determine quantitatively the importance of this process to the overall phosphorus cycle in the Everglades.

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