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Seeing beneath the farmland, steppe and desert soil: magnetic prospecting and soil magnetism

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ABSTRACT

Geophysical science offers a large range of methods that have been adapted for the detection of archaeological structures beneath the surface. Magnetometry is among others the most successful, and with respect to large survey areas, the most widely-used scientific toolkit that is used by archaeologists. New developments in instrument techniques and real-time GPS enlarged the role of magnetometer prospecting for archaeological science considerably and allow even the detailed prospecting and analysis of landscapes. An integral part of this method however should be the archaeological interpretation of the geophysical result. In this paper the rock magnetic and soil magnetic background will be discussed, which is necessary for a comprehensive understanding of survey results. The diversity of the magnetic anomalies is exemplified on the basis of selected survey results, and explains the role of magnetic prospecting in the field of archaeological science.

1. Introduction

Magnetic prospecting is among the most developed archaeological methods for the detection and mapping of archaeological sites. While the very first magnetometer measurements from Aitken (Belshé, 1957; Aitken, 1958) with proton magnetometers, pointed to the detection of thermoremanent magnetic anomalies, it turned out very soon however, that the more subtle magnetic induced anomalies are considerably more common. The great success of this prospecting method is based on the fact that worldwide almost all soils exhibit an enhancement of magnetic susceptibility in the top soils (Le Borgne, 1955, 1960; Mullins, 1977; Maher and Taylor, 1988; Fassbinder et al., 1990; Fassbinder and Stanjek, 1993; Dalan, 2008; Fassbinder and Bondar, 2013). While early measurements were done on pre-gridded areas with single sensor or single gradiometer systems smarter electronics and further developments in computer technology and satellite navigation now allows the application of multisensory instruments with real-time GPS (Becker, 1995; Gaffney et al., 2000; Trinks et al., 2013). Contemporary development took place with regard to the sensitivity of magnetometers (Linzen et al., 2009). Digital visualization techniques and fusion of data from different sources and prospecting methods combined with extensive knowledge of soil and rock magnetic parameters, allows interpretation of significant archaeological structures with great detail. A multitude of excellent prospecting results seem at first glance easy to interpret and induces many archaeologists to publish and to draw archaeological conclusions. Geophysical and namely magnetic anomalies however are not self-explanatory, but require a wide knowledge of the physical properties of archaeological sediments. In this paper I show with a range of selected case histories the variety of possible magnetic anomalies and their soil magnetic interpretation.

2. Soil magnetism and magnetic prospecting

Deviations of the intensity and/or direction of the normal Earth's magnetic field are at large and generally speaking caused by the magnetic contrast between the archaeological features and the adjacent soils and sediments. To understand magnetic anomalies it is first necessary to discriminate between induced and remanent based anomalies.

3. Magnetically induced anomalies

The enhancement of ferrimagnetic minerals in the topsoil is a common property of almost all soils worldwide (Le Borgne, 1955; Mullins, 1977; Fassbinder and Stanjek, 1993; Armstrong et al., 2012). It can be observed even on highly magnetic soils of

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volcanic origin and background (Tucker, 1952; Fassbinder and Gorka, 2009a).

Enrichment and separation of these heavy ferrimagnetic minerals can occur mechanically simply by wind or by water (Fassbinder et al., 2005), as well as by pedogenic processes in soils, but first and foremost by the heating of soils during natural fires, wood fires, and more intensively by the use of fire by anthropogenic activity. Once produced in the topsoil, these minerals end up in ditches, pits, palisades or postholes, and will generate a magnetic anomaly above the ground.

4. Formation of (ferri-) magnetic minerals in soils

Enhancement of ferrimagnetic minerals in top soils was first recognized and described by Le Borgne (1955, 1960) and ascribed to the widespread use of fire, either during forest clearance or the widespread use of fire by people. But very soon it became clear that many archaeological features previously detected by magnetometers as positive anomalies were never exposed to fire (Fassbinder, 1994). Tite and Linington (1975) showed that the climate also has a huge influence on the susceptibility due to formation of magnetic minerals in soils.

Here it must be emphasized that the distinction between magnetite and maghemite is of great importance with respect to a full understanding of site formation process. The presence of a specific mineral may give also valuable information about the fate and history of an archaeological site.

Le Borgne (1955, 1960) ascribed the formation of maghemite either to:

- 1) fermentation, with reduction by the decomposition of organic materials in anaerobic soils, followed by re-oxidation to maghemite during dry weather periods under aerobic conditions
- 2) by natural and anthropogenic fire:
- $\alpha - Fe_2O_3 \Rightarrow Fe_3O_4 \Rightarrow \gamma - Fe_2O_3$ hematite ⇒ magnetite ⇒ maghemite
- reduction ⇒ oxidation

Both processes start with hematite, have magnetite as an intermediate phase, and should finally yield maghemite. Synthesis experiments and observations in nature, however, indicate that the processes forming maghemite are different and more complex. Four precursors are known for maghemite:

a) Magnetite inherited from parent rock or sediment oxidizes (partially) to maghemite. These maghemites usually have grain sizes in the range of millimetres. This process has been observed, e.g., for titanomagnetites (Fitzpatrick and Le Roux, 1976).
b) Depending on the particle size, lepidocrocite ($\gamma - FeOOH$) dehydrates between 260 °C and 300 °C to maghemite (Scheffer et al., 1959; Schwertmann and Taylor, 1979).
c) In the presence of organic matter, goethite is transformed to maghemite during bush fires (Schwertmann and Fechter, 1984; Anand and Gilkes, 1987; Stanjek, 1987).
d) Siderite ($FeCO_3$) oxidizes readily to maghemite when it is gently heated (Van der Marel, 1951; Schwertmann and Heinemann, 1959).

However, it has not yet been observed that hematite may act as a precursor for maghemite or magnetite. Apart from the fact that hematite is not always present in soil, where maghemite was found, it has not been conclusively shown yet that hematite can be reduced to magnetite under natural pedogenic conditions. Mineral assemblages (Anand and Gilkes, 1987; Stanjek, 1987) as well as calculations (Scotter, 1979) suggest that the maximum temperatures reached in top soils during burning are about 300–400 °C, where a reduction of hematite by reducing agents such as organic carbon is unlikely.

The formation of magnetite in soils and sediments is still discussed controversially in the literature (cf. Oldfield, 1992; Dearing et al., 1997), new research however seems to prove both processes (Maher, 2011). Two pathways for its pedogenic formation are proposed:

a) Inorganic: In synthesis-experiments the controlled oxidation of ferrous iron yields magnetite (David and Welch, 1956). This inorganic formation may also take place in soils (Maher and Taylor, 1988).
b) Biologically: The biologically controlled formation of magnetite by soil bacteria has been observed by Fassbinder et al. (1990). The intracellular magnetite crystals formed may be arranged in chains and have similar size and shape to magnetite that was extracted from soils. Furthermore dissimilatory iron-reducing bacteria such as GS-15 (Lovley et al., 1987) may form magnetite extracellular in soil.

The formation of greigite (Fe_3S_4) in soil can occur by two path ways:

a) Inorganic: It was shown that greigite can be produced by syntheses-experiments under controlled conditions (Uda, 1965).
b) Biologically controlled: Evidence of magnetotactic greigite bacteria was found by Mann et al. (1990). Evidence of biologically unidentified soil bacteria was reported by Stanjek et al. (1994) and Fassbinder and Stanjek (1994).

The formation and transformation process of iron oxides in soils is a rather complex interrelation between geochemistry, temperature, temporary weather conditions and climate (Schwertmann, 1988, Maher, 2011). A simplified sketch illustrating the different pathways of the formation and transformation process for magnetite and maghemite that may occur in natural soils and sediments is shown in Fig. 1.

Examples of archaeological sites where the resulting magnetic anomalies can be explained by the induced magnetization of the features are shown from archaeological sites in the Nile Delta (Becker and Fassbinder, 1999). The mud brick walls are made from materials of different magnetic susceptibilities. This explains why they show up in some areas as a positive (black) anomaly marked by red arrows, but in other areas as a negative (white) anomaly

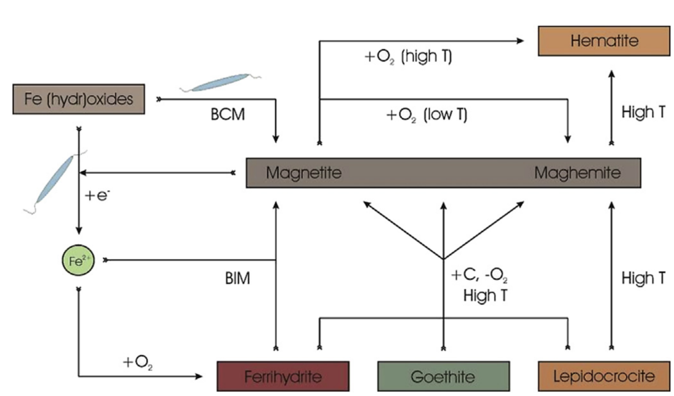

Fig. 1. Sketch of the possible formation pathways of maghemite and magnetite in soils (BIM = Biologically Induced Magnetite, BCM = Biologically Controlled Magnetite; after Stanjek, 1999, unpublished pers. communication and Schwertmann, 1988).