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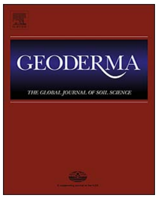

Relationship between magnetic properties and reddening of tropical soils as indicators of weathering

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ABSTRACT

This study evaluates the use of magnetic properties as an indicator of weathering of tropical soils. Soil samples collected across the tropical belt were analysed for magnetic susceptibility and its frequency dependence. Frequency dependence is caused by superparamagnetic (SP) ferrimagnetic nanoparticles, which are commonly attributed to neoformation during soil forming processes. Magnetic properties are compared to the redness rating of soil colour, which is related to the hematite content and is an established proxy for soil weathering. The investigated samples comprise material of different weathering stages from unweathered and weathered rock to subsoil and strongly weathered topsoil. They cover a broad variety of parent materials: ultrabasic, basic, intermediate, acid igneous rocks, clays and clay slates, phyllites and sandstones. The results show that soil reddening, magnetic susceptibility and in particular frequency-dependent susceptibility generally increase with proceeding weathering. However, there is a lithologic overprint and the parent material has to be taken into consideration. Soils stemming from acid igneous rocks, clays, clay slates and phyllites show a positive correlation between reddening and susceptibility or frequency dependent susceptibility, rendering these properties suitable for indicating weathering. In contrast, soils stemming from ultrabasic, basic and intermediate igneous rocks and sandstones show no significant correlation. The reason is the strong lithogenic overprint of ferrimagnetic minerals including SP particles, which commonly occur in these rock types.

1. Introduction

1.1. Lateritic soil formation

Laterites, (ferralsols, plinthosols or oxisols FAO, 2006; NRCS, 2006) are one of the most widespread soil types in the humid tropics. They are the outcome of long-lasting and intense chemical weathering processes under humid conditions under variable soil moisture regimes. Laterites are generally characterised by the following features: strong weathering of silicates; the release of Fe and Al ions forming new minerals such as gibbsite and Fe oxides (predominantly goethite and hematite) (Tardy and Roquin, 1992) and the prevalence of kaolinite. Laterites are formed from different geologies (e.g. silicate rocks and limestone) and their composition and properties are strongly controlled by the chemical composition of the parent rock (Schellmann, 1981).

1.2. Reddening

Hematite is a main constituent of lateritic soils and is responsible for their characteristic red colour (Torrent et al., 1983; Fontes and Carvalho, 2005), and is an indicator of weathering state (Schwertmann, 1993). The neoformation of hematite from the dehydration of ferrihydrite requires elevated soil temperatures and low water activity (Schwertmann, 1993). Typical laterites are therefore different to strongly weathered soils under permanent humid soil moisture regimes which favour goethite over hematite formation (Fontes and Carvalho, 2005), where in this case, hematite content is not a suitable proxy for weathering. The verification of the paragenetic formation of maghemite and hematite was accomplished by Torrent et al. (2006, 2010a).

1.3. Soil magnetic susceptibility

Soil magnetic susceptibility is caused by the presence of ferrimag-

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netic Fe and Fe/Ti Oxides such as magnetite, titanomagnetite and maghemite that are stable in soils and can accumulate due to their resistance to weathering. The absolute value of susceptibility is proportional to the amount of ferrimagnetic minerals and is also influenced by the mineral particle size. Grain sizes depend on the provenance and conditions of formation. Macro-sized multidomain (MD) ferrimagnetic minerals tend to be of lithogenic origin (formed during the crystallisation of igneous rocks), derived from the weathering of ultrabasic and basic igneous rocks. In contrast, ultrafine grained ferrimagnetic minerals are thought to form mainly during pedogenesis (Maher and Taylor, 1988). These minerals are superparamagnetic (SP) and show frequency-dependence of magnetic susceptibility. This behaviour is based on the relaxation of the SP minerals which gives rise to a time decay of magnetisation termed magnetic viscosity (Néel, 1949). Thus, quantifying this property can potentially provide a proxy for soil formation and weathering in certain environments.

1.4. Ferrimagnetic mineral formation and co-formation of hematite

Ferrimagnetic minerals of pedogenic origin form during weathering and soil genesis by geochemical or bacterial processes. There are several theories describing these processes. The first describes ferrihydrite transforming to magnetite via partial dehydration and oxidation in the presence of excess Fe^{2+} ions in solution (Schwertmann, 1988; Dearing et al., 1996). Subsequently, magnetite may oxidise to maghemite. This pathway requires the sufficient release of Fe from the parent material through hydrolysis and subsequent dissolution by Fe-reducing bacteria. When a critical concentration of Fe^{2+} is reached, it will be oxidised. These transformations are facilitated by wetting and drying cycles in soils with corresponding changes in water activity, pH and redox conditions.

A second theory assumes pedogenic enhancement of ferrimagnetic minerals in tropical and subtropical soils also occurs in conjunction with pedogenic hematite formation (Torrent et al., 2006). Warm to hot and sub-humid to humid climates favour the dehydration that is necessary to transform ferrihydrite to hematite (Schwertmann, 1988). The model suggests transformation occurs with intermediate steps producing ferrimagnetic minerals: ferrihydrite – SP (superparamagnetic) maghemite (i.e. nanosized ferrimagnetic minerals) – SD (ferrimagnetic single domain) maghemite – hematite (Torrent et al., 2006). The intensity of each step of the pathway varies according to the pedoclimate and degree of weathering. This means that rates of ferrihydrite and maghemite formation are relatively fast compared to hematite formation in permanently moist but not saturated soils. In contrast, tropical soils undergoing seasonal drying tend to exhibit a faster hematite formation. However, Torrent et al. (2010b) stress that such processes are highly complex and should be carefully evaluated and compared only when formed on similar parent materials.

The transformation pathways for ferrimagnetic minerals and hematite are in agreement with the general conditions that favour the formation of laterites where various mechanisms of hydration and dehydration create sequences of minerals in different hydration states (Tardy and Roquin, 1992). Thus laterites provide a key environment to investigate the use of magnetic measurements as indicators of soil formation and development.

While it is common to regard the visible Fe oxides such as hematite and goethite as products and indicators of soil development it is still rare to use the ferrimagnetic iron oxides for that purpose. It has been demonstrated that the presence of the magnetic iron oxide fraction of soils is also a widespread phenomenon that responds to and reflects soil forming processes (Mullins (1977); Maher (1986). The advantage of using magnetic susceptibility as an indicator for soil development is that this property provides a quantitative measure of the amount of ferrimagnets and is relatively easy to measure.

Many investigations of magnetic properties have been conducted in soils of temperate or subtropical regions, only very few analyses are available for tropical soils. It is generally assumed that an increase in soil magnetic susceptibility occurs with an increasing age of the soil and with climate being warmer and wetter (cf. Singer et al., 1996; Torrent et al., 2010a). Therefore deeply weathered lateritic soils are suitable environments to verify the relationship between soil formation and soil magnetic properties.

The aim of this study is to i) investigate the potential of ferrimagnetic compounds as a proxy for soil formation and weathering in tropical environments, ii) identify if magnetic susceptibility is a result of pedogenic neoformation or if there is a significant lithogenic overprint and iii) investigate the relationship between soil reddening and magnetic susceptibility according to different parent rock types.

2. Materials and methods

2.1. Soil samples

The soil samples originate from the geoscientific collection of the Federal Institute for Geosciences and Natural Resources (BGR) in Hanover, Germany. The sample collection ($n = 1475$ samples) includes lateritic soils and their siliciclastic parent material from tropical regions. Samples were collected from the field at the beginning of the 1970s. These laterites are classified as Ferralsols and Plinthosols (FAO, 2006) or Oxisols (NRCS, 2006). The samples were originally collected to investigate mineral alterations under intense tropical weathering and the genesis of mineral deposits (Schellmann, 1974). At the time of collection the samples were air-dried, mechanically crushed to < 2 mm and homogenised. Since preparation they have been stored in an air-dried state in the sample archive of the BGR in plastic boxes under constant indoor climate.

A sub-set of 506 samples was selected and includes topsoil and subsoil from various depths, in addition to weathered and unweathered parent rocks (Table 1). Table 1 also lists the countries of origin of the samples and parent rock type based on the original field description. The classification of the igneous rocks was made by consulting available geochemical data of the samples which resulted in basic gabbro being classified as ultrabasic.

Table 1
Overview of the investigated material, including number of samples, country of origin and parent rock material. Ultrabasic igneous rocks: *gabbro*, *phonolite*, *serpentinite*; Basic and intermediate igneous rocks: *amphibolite*, *andesite*, *basalt*, *olivine-feldspar-basalt*, *charnockite*, *diabase*, *dolerite*, *gabbro*, *gneiss*, *phonolite*; Acid igneous rocks: *charnockite*, *dolerite*, *gneiss*, *biotite-gneiss*, *granitic gneiss*, *granite*; Clays/clay slates: *pisolite*, *slate*, *shale*, *quartzitic slate*, *clay slate*, *carbonaceous clay*, *tertiary sediments*; Phyllites: *phyllite*; Sandstones: *sandstone*, *quartzite*.

Origin	Ultrabasic	Basic/ Inter-mediate	Acid	Clay/ Clay slates	Phyllites	Sand-stones	Σ
Australia		9	39	26		10	84
Brazil	21	30	9	11	14		85
El Salvador		10					10
Ghana			17	10	7	9	43
Guatemala	8						8
Hawaii		19					19
India		9	36	10			55
Madagascar	15	16	16				47
Mexico			4				4
New Caledonia	20						20
Philippines	8						8
Puerto Rico	21	4					25
Sri Lanka		4	20				24
Uganda		8	22	16			46
Venezuela	13	8	7				28
Σ	106	117	170	73	21	19	506