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Magnetic susceptibility of soils along a lithotoposequence in southeast Iran

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ABSTRACT

Magnetic susceptibility (χ) is a simple and quick technique to determine soil properties and to describe soil forming processes. Knowledge about factors affecting χ data helps better interpretation. Magnetic susceptibility of soils along a lithotoposequence was studied in this research in order to investigate the effects of soil forming factors (parent material and relief) and processes on the χ content and its vertical distribution. The study area is a transect from Jiroft to Kahnooj area, south Kerman Province, Iran. Rock pediment, mantled pediment, inselberg, alluvial fan, alluvial plain, and flood plain landforms with igneous parent materials (gabbro, diorite, and granite) were selected in the area. Thirteen representative pedons on different geomorphic positions were studied. Low frequency χ (χlf) values ranged from $193.1 \times 10^{-8}\ m^3\ kg^{-1}$ to $2704.2 \times 10^{-8}\ m^3\ kg^{-1}$ in studied soils and decreased with increasing diamagnetic material contents. Mean χlf values in soils formed on gabbro, diorite, and granite parent rock were $> 1700 \times 10^{-8}\ m^3\ kg^{-1}$, $515.22 \times 10^{-8}\ m^3\ kg^{-1}$, and $352.53 \times 10^{-8}\ m^3\ kg^{-1}$, respectively. Frequency dependent χ of soils (in the range of 0.06 to 1.05%) showed that coarse multi domain grains inherited from igneous parent material were the main source of χlf in the area under study. Both increasing and decreasing trends of χlf with depth were observed. Decreasing trend of χlf with depth was due to illuviation of diamagnetic material into subsurface layers. On the other hand, increasing χlf with depth was attributed to the primary ferrimagnetic material inherited from igneous parent material. Alluvial plain ($320.44 \times 10^{-8}\ m^3\ kg^{-1}$) and mantled pediment ($328.50 \times 10^{-8}\ m^3\ kg^{-1}$) showed low values of χlf due to high amounts of soluble salts, anhydrite, and calcium carbonate investigated in these geomorphic positions. A positive significant relationship ($R^2 = 0.018$; $r = 0.27$, $P < 0.05$) between χlf and Fe_o/Fe_d activity ratio was found. Soil χlf decreased with development and relative dating of soils. Results of the study showed that soil χlf values were highly affected by parent material, relief, and soil development.

1. Introduction

Magnetic susceptibility; as a simple, quick, nondestructive, and safe technique (Dearing, 1999) has been widely used in describing soil forming factors (Lu, 2000; Blundell et al., 2009) and processes (Lu et al., 2008; Blundell et al., 2009; Lu et al., 2012a, b), soil development (Lu, 2000; Lu et al., 2008; Zielhofer et al., 2009), the origin of loess (Xia et al., 2007), fluctuation and environmental changes recorded in loess-paleosol sequences (Karimi et al., 2013), and detailed soil surveys (Siqueira et al., 2015).

The degree of magnetization of a material in response to an applied magnetic field is expressed by magnetic susceptibility (Nafeh and Brussed, 1985), and its value is a function of amount, composition, shape, and size of crystals in magnetic minerals (Dearing, 1999; Xia et al., 2007; Michel et al., 2010). Magnetite and maghemite ferrimagnetic minerals are the main source of soil magnetic susceptibility (Lu et al., 2008; Lu et al., 2012b). Soil magnetic susceptibility is affected by a wide range of factors (Blundell et al., 2009). Soil magnetic behavior in non-industrial areas is affected by soil forming factors (parent material, relief, climate, and time) and processes (Singer and Fine, 1989; Fine et al., 1992; Feng and Johnson, 1995; Lu, 2000; Alekseev et al., 2002; Owliaie et al., 2006; Hanesch et al., 2007; Lu et al., 2008; Blundell et al., 2009).

Lithology of parent material strongly influences soil magnetic susceptibility (Lu, 2000; Magiera et al., 2006; Camargo et al., 2014). Close relationship between soil magnetic susceptibility and parent material lithologies in soils of China and central Europe was reported by Lu (2000) and Magiera et al. (2006), respectively. Surface soils developed on sedimentary rocks showed higher magnetic susceptibility compared to subsurface horizons in both researches mentioned above. However, higher values of magnetic susceptibility in soils developed on igneous rocks were investigated and an increasing trend of magnetic susceptibility with depth was found compared to soils on sedimentary rocks.

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Moreover, De Jong et al. (2000b) and Blundell et al. (2009) reported that soil magnetic susceptibility varies with the slope position due to some factors such as texture and drainage class. Studying three catenas in Saskatchewan, Canada, De Jong et al. (2000b) concluded that soil magnetic susceptibility decreased downward the slope. They reported that anaerobic biochemical processes (signs of gleying and high Fe_o/Fe_d ratios) could probably destroy the ferrimagnetic minerals and cause further decrease of magnetic susceptibility values in lower slope positions.

Meanwhile, soil magnetic signals could also be influenced by climatic conditions (Lu, 2000; Blundell et al., 2009; Lu et al., 2012a) and type of plants (Lü et al., 2001). Temperature and precipitation increased the magnetic susceptibility values of surface soils (Lu, 2000). Besides, De Jong et al. (2000a) reported the highest formation rate of pedogenic ferrimagnetics in more humid soil zones. Rainfall was also reported as the driving factor for hydrolysis reactions and the release of Fe from primary minerals by Dearing et al. (2001). Warm-wet subtropical climate of Yun-Gui Plateau could induce a strong degree of chemical weathering, produce the pedogenic magnetite/maghemite and hematite, and thus increase the magnetic susceptibility values of calcareous soils up to $6000 \times 10^{-8}\,m^3\,kg^{-1}$ (Lu et al., 2012a). The effect of the C3 and C4 plants on the magnetic susceptibility of Chinese soils was studied by Lü et al. (2001). The ability of C3 and C4 plants to enhance magnetic susceptibility signal of soils was different in their report. The capability of C4 plants to increase magnetic susceptibility signal of soils was much greater than C3 plants.

Besides, like other soil properties, magnetic susceptibility is also time dependent (Blundell et al., 2009) and can be a suitable index of soil development (Lu, 2000; Lu et al., 2008). Lu (2000) studied the magnetic susceptibility of soils formed along chronosequences on marine and alluvial deposits. He showed that soil magnetic susceptibility increased with increasing soil development due to pedogenic formation of ferrimagnetic particles. In another study, Lu et al. (2008) concluded that magnetic susceptibility of soils formed on basalt parent material decreased with soil development due to weathering of primary magnetic minerals. Studying soils on Quaternary loess- Tertiary red clay of Chinese Loess Plateau, Hu et al. (2009) reported that Fe_o, Fe_o/Fe_d, and magnetic susceptibility of soils decreased with increasing soil age. However, no relation was reported between magnetic susceptibility of a soil chronosequence and absolute dating of soils formed on basalt parent material of Hainan Island tropical area, China (Huang, 1999). Moreover, no positive significant correlation between magnetic susceptibility and soil age in soils of Slovenia in age range of 5 ka to 1.8 Ma was reported (Vidic and Verosub, 1999).

Soil forming processes affect the values and vertical distribution of magnetic susceptibility. De Jong et al. (2000b) reported that biogeochemical processes and displacement of magnetic or diamagnetic components of soil may increase or decrease the magnetic susceptibility of soil horizons. Calcium carbonate, water, and organic material are examples of diamagnetic material (Alekseev et al., 2002). Carbonate illuviation and organic matter accumulation at the surface may alter the magnetic susceptibility of a horizon compared to other horizons which could be attributed to increase and/or decrease in concentration of soil magnetic components (Hanesch et al., 2007). Owliaie et al. (2006) concluded that magnetic susceptibility of eluvial horizons in Kohgilouye area was higher than illuvial horizons.

The role of some soil forming factors and processes on the vertical distribution of magnetic susceptibility has widely been reported in the prior literature. However, the relationship between vertical distribution of natural diamagnetic materials (such as $CaCO_3$, gypsum, anhydrite, and more soluble salts) in arid and semi-arid soils and vertical distribution of soil magnetic susceptibility related to soil formation processes was not studied. Since vertical distribution of soil magnetic susceptibility is highly depended to the increase, decrease, translocation, and transformation of magnetic and diamagnetic materials in a pedon, the present research aimed at 1) determining soil magnetic susceptibility related to soil forming factors (parent material and relief) and processes (calcification, salinization, gypsification, and anhydritification), and 2) studying the capability of magnetic susceptibility as a suitable tool in soil genesis and classification studies.

2. Material and methods

2.1. Field studies

The study area is a transect from Jiroft (about 688 m asl) to Kahnooj (about 506 m asl) area, south Kerman Province, Iran (Fig. 1). Mean temperature and precipitation of the area are 25.8 °C and 174 mm, respectively. Soils of the area were dominantly covered by varnished desert pavement without considerable vegetation cover and non-cultivated. Igneous parent material with diorite, granite, and gabbro compositions were dominant from geological point of view. Besides, gypsiferous and calcareous evaporites were also found (Babakhani et al., 1992). Rock pediment (pedon 1), mantled pediment (pedons 2, 3, 4, 7, and 12), inselberg (pedon 5), alluvial fan (pedons 8, 9, and 10), flood plain (pedons 6 and 13), and alluvial plain (pedon 11) were among dominant landforms studied (Fig. 1). A total of 13 representative pedons (at least one pedon on each landform) were described and sampled (Schoeneberger et al., 2012) along the lithotoposequence (Fig. 2). Soils were classified according to WRB classification system (IUSS Working Group WRB, 2015).

2.2. Laboratory studies

Soil samples were air dried, crushed, and passed through a 2 mm sieve. Soil magnetic susceptibility (χ) was measured in low (0.46 kHz, χlf) and high (4.6 kHz, χhf) frequencies using a Bartington instruments MS2 magnetic susceptibility system with an MS2B sensor. The percentage of frequency dependent magnetic susceptibility (χfd %) was calculated using Eq. (1) in order to study the size of magnetic crystals in soils and the abundance of pedogenic ferrimagnetic in SP-SSD (~0.03 μm) boundary (Dearing, 1999).

$$\%\chi fd = 100\,[(\chi lf - \chi hf)/\chi lf] \quad (1)$$

where χfd is the frequency dependent magnetic susceptibility, χlf is the low frequency magnetic susceptibility, and χhf is the high frequency magnetic susceptibility.

Pipette method was used for particle size analysis (Gee and Bauder, 1986). Jenway pH and EC meters were used to measure the pH of saturated paste and EC of saturated extract. Back titration method was used for $CaCO_3$ determination (Nelson, 1982). Gypsum plus anhydrite were measured by acetone method (Nelson, 1982), and gypsum was investigated by oven (Artieda et al., 2006). Anhydrite was calculated by the subtraction of oven from acetone data (Wilson et al., 2013). Walky-Black method was used for organic matter determination (Nelson and Sommers, 1982). Sum of crystalline and non-crystalline iron (pedogenic iron, Fe_d) was analyzed using citrate-bicarbonate-dithionate (Mehra and Jackson, 1958) and acid ammonium oxalate (Schwertmann, 1973) was used to extract non-crystalline iron (Fe_o). An AAS Vario atomic absorption was used for Fe determination of extracts. Statistical analyses of data were performed by SPSS 16 software.

3. Results and discussion

3.1. Magnetic properties of soils formed on igneous rocks

3.1.1. Magnetic susceptibility (χlf)

Tables 1 and 2 show selected physical, chemical, and morphological properties of studied soils. The χlf range of soils (Table 1) was from $193.1 \times 10^{-8}\,m^3\,kg^{-1}$ (C2 horizon, pedon 4) to $2704.2 \times 10^{-8}\,m^3\,kg^{-1}$ (C4 horizon, pedon 13). The high χlf values of soils were attributed to magnetic particles originated from igneous parent material (Lu, 2000; Lu