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Characteristics of the fifth paleosol complex (S_5) in the southernmost part of the Chinese Loess Plateau and its paleo-environmental significance

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ABSTRACT

The most prominent paleosol unit in the Chinese Loess Plateau (CLP) is the fifth paleosol complex (S_5) with its well-developed very thick and dark colored pedons. To provide more insight in the formation of S_5 and its environmental significance, the pedogenesis and clay mineral transformation in the S_5 of the Wugong section (Shaanxi Province) on the southernmost CLP are analyzed. S_5 at the Wugong section is essentially composed of three well-developed reddish pedons (i.e., $S_{5\text{-}1}$, $S_{5\text{-}2}$, $S_{5\text{-}3}$) which signify three glacial–interglacial climatic fluctuations during its formation. Complete decalcification in each pedon and a calcic horizon of only 30–50 cm in thickness beneath each of the three pedons suggests that after deposition the pedons developed with a relatively stable surface in a sustained warm and humid climate. Clay formation in the S_5 includes neogenesis of clay materials by in situ post-depositional weathering and mechanical migration of the fine fraction after complete decalcification.

Complete leaching of $CaCO_3$, intensive clay formation (with 60–100% higher clay content than that in the overlying and underlying loess (L_5 and L_6)) and extremely high magnetic susceptibility in the S_5 pedons reflected a warmer, more humid climate and soil environment for pedogenesis than in the 'optimum' Holocene. However, the chemical alteration of the phyllosilicate minerals was weak and restrained by the hard calcic horizon, the compact argillic horizon and the flat terrain. The major clay mineral weathering processes during the formation of the S_5 pedons at the Wugong section were depotassication, hydrolysis of primary minerals and degradation of chlorite. The pedogenesis in a loess–paleosol sequence and its pedogenic environment can best be deduced from combined data on pedogenic properties, and geochemical and mineralogical characteristics.

1. Introduction

Thick loess–paleosol sequences on the Chinese Loess Plateau (CLP) provide one of the most complete terrestrial records of the global paleoclimate and the Asian monsoon through the Quaternary period (Kukla, 1987). Loess is an eolian sediment deposited in a cold glacial period, while paleosol is the weathered equivalent of loess formed in a warm interglacial period. The loess–paleosol sequences on the CLP, reflect the balance between the accumulation rate of loess and the in situ pedogenesis after deposition controlled by the relative strength of the winter and summer monsoons (Liu, 1985). They have been developed as a consequence of this alternation between the dominance of the winter and summer monsoons that closely resemble the glacial–interglacial cycles represented by the oxygen-isotope compositions of foraminifera in deep sea sediments (Liu, 1985; Williams et al., 1988). Proxies such as grain size, magnetic susceptibility and geochemistry have been used for examining these climate changes (An et al., 1991a, b; Ding et al., 2001; Yang et al., 2006).

In most regions of the CLP the fifth paleosol (S_5) is a complex paleosol composed of three pedons, coded downwards as $S_{5\text{-}1}$, $S_{5\text{-}2}$ and $S_{5\text{-}3}$ (Han et al., 1998; Liu et al., 1990). Systematic correlations between marine oxygen-isotope curves and magnetic susceptibility variations of the loess–paleosol sequences suggest that S_5 developed from 0.62 to 0.48 Ma B.P., and was correlated with marine oxygen-isotope stages ($\delta^{18}O$) from 13 to 15 (correlative to the $S_{5\text{-}1}$, $S_{5\text{-}2}$ and $S_{5\text{-}3}$, respectively) (Heller and Evans, 1995; Kukla, 1987). The S_5, a record of climatic

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optimum during the last 1.2 Ma B.P., is the most prominent paleosol unit on the CLP, and it is characterized by its great thickness, reddish color, and well-developed clay coating (An et al., 1987). Pollen analysis in the S_5 paleosol of Xi'an and Baoji in Shaanxi Province, China has revealed that the vegetation assemblage was characterized by a combination of temperate broad-leafed trees (e.g., Quercus, Walnut and Basswood) and northern subtropical broad-leafed trees (e.g., Symplocos, Sweetgum and Pterocarya) (Zhao, 1994). Pollen evidence further signified a dominated forest landscape paleoecology and a northern subtropical condition for soil development in this region. However, based on paleo-rainfall amounts evaluated by using data of carbonate precipitation, Han et al. (1998) have suggested that in the Shijiawan and Chang'an sections located in the Guanzhong basin, grasslands dominated the paleovegetation during the development of $S_{5\text{-}1}$ and that the paleoclimatic conditions were perhaps even drier than at present (Han et al., 1998). This disparity on the paleoclimatic interpretation for S_5 is due to the different profiles studied and the limitations of the climatic indicators.

To obtain additional information, Huang et al. (2011) recently considered both paleoclimatic proxies and the mineralogical differentiation of the Holocene loess on the southernmost CLP to reveal the pedogenic environment and the pedogenesis. Mineralogical differentiation of loess and paleosol has occurred as result of eolian transportation and chemical weathering after deposition (Jeong et al., 2008, 2011). The various environmental conditions that prevailed during soil formation have determined the successive stages of the mineralogical evolution (Turpault et al., 2008). To further study the pedogenic processes and to better understand the changes of the paleoenvironment during the formation of S_5, the mineralogy and geochemistry of the clay fractions (<2 μm) of the S_5 on the southernmost CLP (Wugong section, Shaanxi Province) are analyzed and then correlated with paleoclimatic records such as, grain size, carbonate content and magnetic susceptibility. Field-observed profile characteristics of the paleosol complex in the Wugong section are consistent with the description of the S_5 in the Baoji section (Liu et al., 1990) which is 80 km to the west of the Wugong section. The Wugong section is part of a high platform and does not exhibit evidence of human perturbation or accelerated erosion. The Holocene paleosol (S_0) studied by Huang et al. (2011) and paleosol complex studied here are located at the same site of Wugong. According to ^{14}C dating of the Holocene paleosol (S_0) and field-observed consequence of loess-paleosol alternation, it can be confirmed that the paleosol complex studied is the fifth paleosol (S_5). With the comprehensive analysis together with field observations, more insight is gained in the evolution of S_5 over time and in the variations of the paleoenvironment during the formation of S_5.

2. Materials and methods

2.1. Field description and sampling

The Wugong section (N 34°19′17″, E 108°07′08″) is situated on the southernmost Chinese Loess Plateau (CLP), at an elevation of about 500 m a.s.l. (Fig. 1a). The present day average annual temperature and precipitation are 12–14 °C and 650–750 mm, respectively. The climate type of this region is a warm temperate semi-humid continental monsoon climate. In Chinese soil taxonomy, the modern zonal soil in this region is Eum-Orthic Anthrosols (Cooperative Research Group on Chinese Soil Taxonomy, 2001).

The fifth paleosol complex (S_5) is essentially composed of three well-developed reddish pedons ($S_{5\text{-}1}$, $S_{5\text{-}2}$, $S_{5\text{-}3}$ numbered downward) of 1.8, 1.8 and 1.5 m in thickness, respectively (Fig. 1b, c, d). The carbonate nodule horizons of 30–50 cm in thickness beneath the pedons can easily be recognized, making them useful as a stratigraphic marker between pedons (Fig. 1b, c, d). Profile characteristics of the field observations are summarized in Table 1. Vertically oriented samples were collected at 20 cm intervals from the $S_{5\text{-}1}$ and $S_{5\text{-}2}$, and at 10 cm intervals from the $S_{5\text{-}3}$. From the adjacent overlying and underlying loess (L_5 and L_6, respectively) four samples were taken at 20 cm intervals. Also from each of the three calcic horizons a sample was collected.

2.2. Analytical methods

2.2.1. Soil physicochemical properties

The samples were air dried, crushed and passed through a 0.25 mm sieve for soil magnetic susceptibility measurement and through a 2 mm sieve for carbonate content and particle-size distribution measurements. The magnetic susceptibility (M_S) was measured by a Bartington MS-2B susceptibility meter at low-frequency (0.47 kHz/χ_{lf}) and recorded in SI unit (10^{-8} m^3/kg) (Zhou et al., 1990). Soil calcium carbonate was determined by using the Chittick apparatus (Dreimanis, 1962). For further analysis the samples were pretreated for further analysis with acetic acid solution buffered with sodium acetate (pH = 5.0) to remove the calcium carbonate and with 10% H_2O_2 solution to remove organic matter. Suspensions were then washed several times with distilled water to remove excess ions and to assist dispersion of the clays. Silt and clay were separated from the sand fraction (2–0.05 mm) by wet-sieving through a 0.05 mm sieve. The silt fraction (0.05–0.002 mm) was separated from the clay fraction (<0.002 mm) by sedimentation under gravity (Gee and Bauder, 1986). The clay fraction was washed and centrifuged repeatedly with double deionized water and anhydrous alcohol to remove the excess salts. The sand, silt and concentrated clay fractions were dried and weighed to obtain the percent of each fraction.

The chemical composition of the selected clay samples was determined by wavelength dispersive X-ray fluorescence spectrometry (WD-XRF, PW4400) at the State Key Laboratory of Loess and Quaternary Geology of the Institute of Earth Environment, Chinese Academy of Sciences in Xi'an. To perform the analysis a 0.6 g clay sample was mixed with 6 g of dry lithium tetraborate ($Li_2B_4O_7$) and fused into a 32 mm diameter glass bead. Calibrations were done with 28 nationally certified reference materials of soil (GBW07401–GBW07416 and GBW07301–GBW07312). Analytical accuracy was checked by parallel analysis of two national standards (GSS-8 and GSD-12), and amounted to 1–2%.

2.2.2. Soil mineralogy

Mineralogical measurements of the clay fractions were carried out by X-ray diffraction (XRD). Prior to the XRD measurement free Fe-oxides and amorphous Al-phases were removed by dithionite–citrate–bicarbonate (DCB) extraction (Mehra and Jackson, 1960; He et al., 1994). For the XRD measurements specimens of the clay samples were saturated with magnesium (Mg) or with potassium (K) and mounted as slurries on glass slides. Air-dried Mg-saturated samples were analyzed at 25 °C after solvation in glycerol for 24 h (Mg–glycerol). Air-dried K-saturated samples were X-rayed at 25 °C before and after heating at 300 °C and 550 °C for 2 h (K-25 °C, K-300 °C, K-550 °C). Another specimen of clay was treated in 6 M HCl to remove possible chlorite and saturated with K and X-rayed at 25 °C (HCl-K). The 3° to 30° (2θ) range was scanned stepwise at a scanning speed of 1° (2θ) min^{-1} by using a Bruker D8 X-ray diffractometer (CuKα radiation generated with 40 kV accelerating potential and 40 mA tube current).

Identification of the clay minerals was based on the comparison of the XRD patterns obtained under the five different measurement conditions: Mg–glycerol, K-25 °C, K-300 °C, K-550 °C and HCl-K. Illite is recognized by its 1.0 nm peak in all treatments. Smectite is identified by the presence of a 1.8 nm peak in the Mg–glycerol sample and the absence of this peak in all K-saturated samples. Vermiculite is identified by the presence the 1.4 nm peak in the Mg–glycerol sample which is absent in the K-25 °C sample. Chlorite maintains a 1.4 nm peak after heat treatment of 2 h at K-550 °C. Kaolinite is identified by the presence of a peak at 0.71 nm in the