



The fifth paleosol layer in the southern part of China's Loess Plateau and its environmental significance



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ARTICLE INFO

Article history:

Available online 10 January 2013

ABSTRACT

Through field investigations, dark red–brown lumpy ferruginous argillans (LFAs) and an underlying weathered loess layer under the fifth layer (S_5 paleosol) were discovered in the Guanzhong Plain in the southern part of the Loess Plateau in northwest China's Shaanxi Province. The ultramicrotexture of the LFAs and their mineral and chemical compositions were analyzed. Experimental results showed that mixed illite–smectite minerals comprise about 90% of the LFAs in mineral composition, with 40% SiO_2 content and high Fe_2O_3 (about 10.0%) and Al_2O_3 (about 22.5%) contents in chemical composition. Neoformed microcrystalline grains of clay minerals dominated the LFAs. The micromineral crystal grains in the LFAs were mainly plates with some degree of alignment, giving the argillans crystalline optical properties. Red LFAs and weathered loess layers under the S_5 , and the depth to which Fe_2O_3 and CaCO_3 from the S_5 have been removed, indicate that chemical weathering was much stronger when the paleosol layers formed than that at present. While the S_5 paleosol was developed, a subtropical climate prevailed in the southern Loess Plateau, with a mean annual temperature and rainfall about 4 °C and 500 mm higher respectively than that at present. The adequacy in moisture in at least 4.2 m of the gravitational water zone during the formation of S_5 was suitable for forest growth. During the warmest and moistest climate span of growth for 2.5 million years when S_5 was formed, the Qinling Mountains lost its function as a climatic boundary between the subtropical and temperate zones of East Asia, when the summer air masses crossed the Qinling Mountains and reached the Guanzhong Plain, bringing rich precipitation.

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1. Introduction

During the recent decades, much research has been implemented on various climatic parameters in the loess–paleosol sequences to reconstruct monsoonal climate changes in East Asia (Heller and Liu, 1986; Kukla, 1987; Maher and Thompson, 1995; Gallet et al., 1996; Xiong et al., 2002; Kohfeld and Harrison, 2003; Lu et al., 2004; Tang and He, 2004; Porter and An, 2005; Chen et al., 2006; Liu et al., 2007; Thomas et al., 2007; Gao and Ding, 2008). It is recognized that paleosols developed in interglacials and loess in glacials, with the former under the conditions of the weak winter monsoon strength and strong dust activity and the latter under the conditions of the strong summer monsoon intensity and weak dust storm events (Liu, 1985; An, 2000). The Chinese loess–paleosol sequence represents climate change over 2.5 million years with at

least 40 cycles (Zhao, 1988; Ding et al., 1989), and serves as one of the best records of terrestrial climate change.

Some researchers consider that the fifth paleosol (S_5) in the southern part of China's Loess Plateau was an orthic cinnamon soil with a Bt–Ck–C profile, and developed under a semi-arid climate and forest-steppe (Zhu, 1965; Lin and Liu, 1992) or a semi-humid climate (Tang, 1981; Chen et al., 2006). It appears to have undergone the strongest weathering since 2.5 Ma in the Loess Plateau, and includes thin dark red ferruginous argillans (Tang, 1981; Guo et al., 1998). These are usually characteristic of subtropical soils, so the argillans provide an evidence for soil character and strength of chemical weathering (Fink and Kukla, 1977; Tang, 1981; Fedoroff and Goldberg, 1982; Guo and Fedoroff, 1992; Zhao, 1994, 2004). Other researchers think that, because of the rather thick loess and the lack of a water-resisting layer, atmospheric precipitation can reach as deep as 50 m below ground by seeping. Nevertheless, forests cannot grow due to the absence of near-surface soil water even during the S_5 paleosol development under substantial rainfall (Zhang and An, 1994; Li et al., 2003).

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The present paper documents that red lumpy ferruginous argillans (LFAs) and weathered loess layer exist within the S_5 paleosol of the southern Loess Plateau, providing new evidence for the weathering characteristics of S_5 (Fig. 1). Based on those data, the paper then discusses the monsoon conditions during the formation of S_5 , the purpose of which is to characterize the structure and nature of the S_5 paleosol, and reconstruct the climatic and vegetation conditions.

2. Site descriptions, materials and methods

In the Guanzhong Plain, the contemporary annual mean temperature and precipitation are 12–13 °C and about 600 mm respectively. The Qinling Mountains in the southern fringe of the Guanzhong Plain serve as a climatic boundary between the subtropical and temperate zones of East Asia. The total thickness of the Quaternary loess–paleosol sequence is about 120 m in the regions of Xi'an and Baoji, two major cities in the Plain. In these profiles, red lumpy ferruginous argillans (LFAs) are found in the lower part of the S_5 layer and in the upper part of the sixth layer (L_6 , weathered loess). The Liujiapo profile is situated 9 km east of Xi'an; Shuangzhucun and Yangwancun profile are about 2 and 6 km south of Cahng'an, respectively; and the Hejiacun profile is 2 km west of Baoji (Fig. 1). Two LFA samples were collected respectively from each profile. Soil samples of $CaCO_3$ and microstructure were taken at 10-cm intervals to a depth of 5 m in the Liujiapo and Hejiacun profiles.

The LFA samples were examined by scanning electron microscope at Shaanxi Normal University to identify the ultra-microtexture. Grain size analysis used a Mastersizer 2000 laser particle analyzer (Malvern Instruments, Malvern, U.K.). The volumetric method was introduced for analysing the $CaCO_3$ content, which involves first the treatment of the soil with hydrochloric acid to produce CO_2 , and then the measurement of the volume of $CaCO_3$. Sr content was measured with an X-ray fluorescence analyzer. The Fe_2O_3 and Al_2O_3 contents were determined by spectrophotometry (Li, 1991) at Xi'an Institute of Geology and Mineral Resources of the Ministry of Land and Resources, the K_2O and Na_2O contents by flame photometry (Li, 1991), and the SiO_2 content by the K_2SiF_6 volumetric method (Li, 1991).

3. Results

3.1. Characteristics of distribution of weathered loess and LFAs

In the contemporary soils of the southern Loess Plateau, there exists no weathered loess layer below the Bt horizon because of the limited depth of weathering under the current semi-humid

climate. The focus of the previous research on the loess–paleosol sequences was on the central Loess Plateau, and little attention was paid to the southern Loess Plateau. In the profiles discussed in this paper, the 2.3-m-thick weathered loess can be divided into three horizons (Fig. 2a and b).

The upper horizon (Cf) 0.6-m-thick below the Bt horizon is light red–brown but loessial structured, and contains thin dark red argillans with a few dark red LFAs (Figs. 2a, b and 3a–f). The light red–brown color of the weathered loess layer is formed due to the oxidation of Fe compounds and the formation of Fe_2O_3 in the weathered loess matrix itself. The middle 1.2-m-thick horizon (Cs) is dark brown–yellow and contains few red LFAs and many thin red argillans. The lower 0.6-m-thick horizon (Cl) is light grey–yellow, with a few thin LFAs (Fig. 2a). Weathering cracks are well developed in these sub-layers. A $CaCO_3$ -entitled horizon (Ck) and an unweathered loess layer (Co) appear below the weathered loess layers. The LFAs mainly occur in the Cs horizon and Cf horizon of S_5 , both of which contain vertical cracks with a length of 20–50 cm. The LFAs and weathered loess under S_5 are widespread in the southern Loess Plateau.

There exists a small thickness, usually below 0.1 mm, of argillans in the S_5 paleosol in Luochuan, Shaanxi Province, distributed in the Bt horizon and not reaching the loess layer under the paleosol layer. There exists 1–3 mm of dark red–brown argillans in the S_5 paleosol in Guanzhong Plain.

3.2. Microtexture of the LFAs and illuvium of $CaCO_3$ nodule

Using a polarising microscope, the red–brown LFAs have the optical characteristics of mineral crystals, and are characterized by well-developed crescents, strips and plates with flowed characteristics distributed in holes and cracks. On the basis of their fluted characteristics and distribution, they were formed by flowing and illuviation of clay produced in the paleosol.

The optical characteristics of thin argillans are generally thought to result from alignment of the clay particles, but it is hard to collect sufficient material for a study of the ultra-microtexture because of the thinness. Therefore, the characteristics of arrangement of clay particles, the formal features of clay particles and whether they can be labeled as new clay minerals are unclear. However, the thicker LFAs in profiles enable study by electron microscopy. Twelve LFA samples were examined with a scanning electron microscope, and they are dominated by neo-formed micrograin clay minerals (Fig. 2). It suggested that the argillans were formed during weathering under warm and moist climate conditions. The micrograins are almost regular plates with some degree of alignment (Fig. 4a–f). This preferred orientation explains why such strong birefringence is shown in the argillans.

Pure calcite crystals (Fig. 5) in nodule of $CaCO_3$ can be observed using an electron microscope. The well-crystallized well calcite formed in wet conditions.

3.3. Mineral and chemical compositions of the LFAs

There have been few studies of the mineral and chemical compositions of the thin ferruginous argillans in loess, because it is not possible to gather large, pure samples for such analysis. The discovery of abundant, relatively pure LFAs enabled determination of their chemical and mineral composition.

Tang (1981) showed that the dominant clay mineral in the thin argillans was illite, with a small amount of interlayered illite–smectite and pelhamite. Based on the X-ray diffraction data (Fig. 6) for six LFA samples from the profiles, about 90% of the clay was illite–smectite, with 5% quartz and a small amount of plagioclase and hematite.

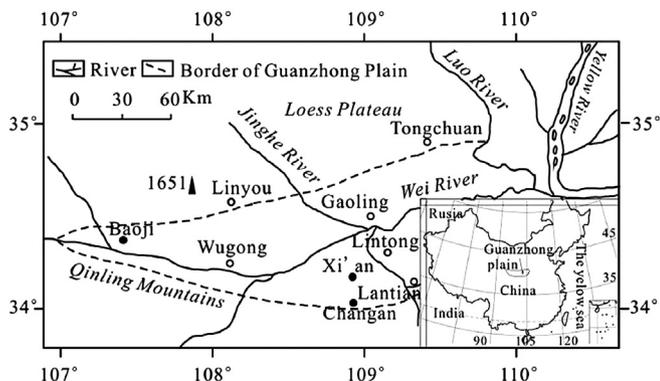


Fig. 1. Locations of the research area and the profiles.



Fig. 2. The distribution and shapes of the S_5 LFAs in samples obtained from the Guanzhong Plain of China's Loess Plateau. (a) The profile of S_5 at Liujiapo in Xi'an; (b) The profile of S_5 at Shuangzhucun in Chang'an. Bt, paleosol S_5 ; Cf, light red–brown weathered loess with red LFAs and thin ferruginous argillans; Cs, dark brown–yellow weathered loess with few LFAs and many thin argillans; Cl, light brown–yellow weathered loess sub-layer without red argillans; Ck, $CaCO_3$ nodule layer; Co, unweathered aeolian loess.

Chemical analysis of six samples from the two profiles showed that the SiO_2 content in the LFAs ranged from 42.1 to 44.1%, Al_2O_3 from 22.3 to 23.5%, Fe_2O_3 from 10.0 to 10.4%, Na_2O 0.30%, and K_2O from 2.8 to 3.1% (Table 1). The mean SiO_2 content of bulk samples from Bt horizon was 65.2%, Al_2O_3 was 15.3%, Fe_2O_3 was 6.2%, Na_2O was 1.1%, and K_2O was 2.6%. Thus, the LFAs in samples had lower Na_2O contents and higher Al_2O_3 and Fe_2O_3 contents than those of the Bt horizon. This suggests that the weathering that produced the LFAs was strong. The higher Fe_2O_3 content of the red lumpy argillans is indicated by “ferruginous” in their name. The Fe_2O_3 content of LFAs in S_5 is similar to that of ferruginous nodules in a subtropical yellow–brown forest soil derived from a non-loess parent in Nanjing (Xiong and Li, 1987), whereas the Al_2O_3 content was 5–7% higher (Table 1). This suggests that the weathering experienced by S_5 in the southern part of the Loess Plateau was stronger than that in the subtropical yellow–brown forest soil.

Table 1
Main chemical compositions of LFAs

Sites	Layers	Samples	SiO_2	Al_2O_3	Fe_2O_3	K_2O	Na_2O
Xi'an	The lower of S_5	Lumpy argillans	43.44	22.29	9.95	3.06	0.30
Baoji	The lower of S_5	Lumpy argillans	44.06	22.31	10.23	2.82	0.28
Xi'an	The upper of L_6	Lumpy argillans	42.15	23.46	10.36	2.85	0.27
Nanjing	The lower of Ye	Ferruginous nodules	–	16.73	10.10	–	–
Nanjing	The lower of Ye	Ferruginous nodules	–	18.28	10.47	–	–

Note: S_5 is fifth paleosol, L_6 is sixth loess, Ye is Yellow–brown forest soil in the subtropics of China (Xiong and Li, 1987).

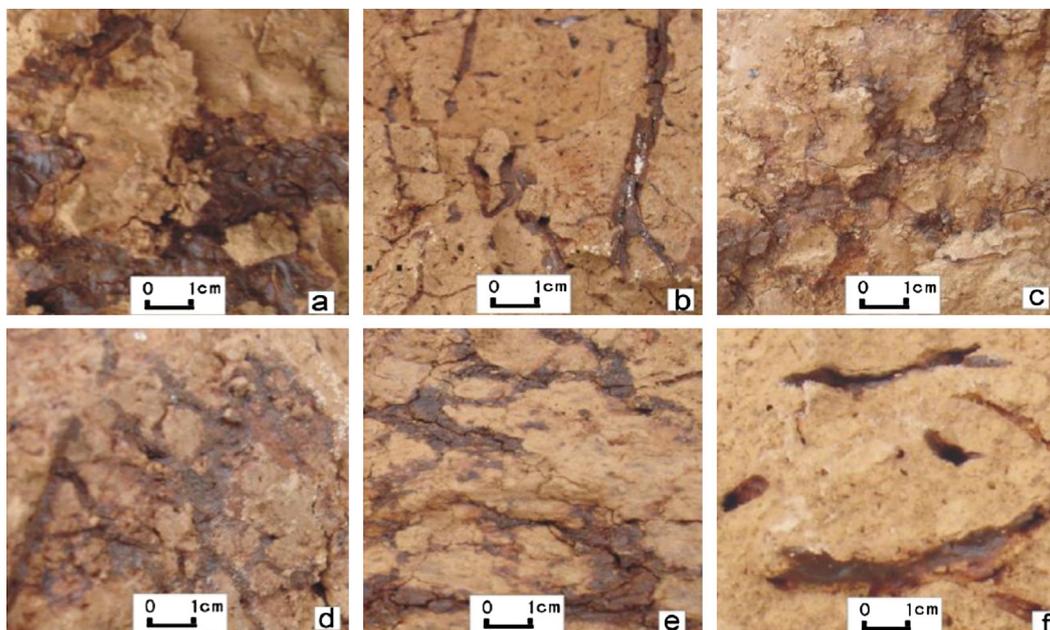


Fig. 3. Red LFAs in the L_6 loess layer that lies below the S_5 layer in the Guanzhong Plain. (a–c) Red LFAs in cracks and root holes from the Liujiapo profile in Xi'an; (d–f) Red LFAs in cracks and root holes from the Hejiacun profile in Baoji. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

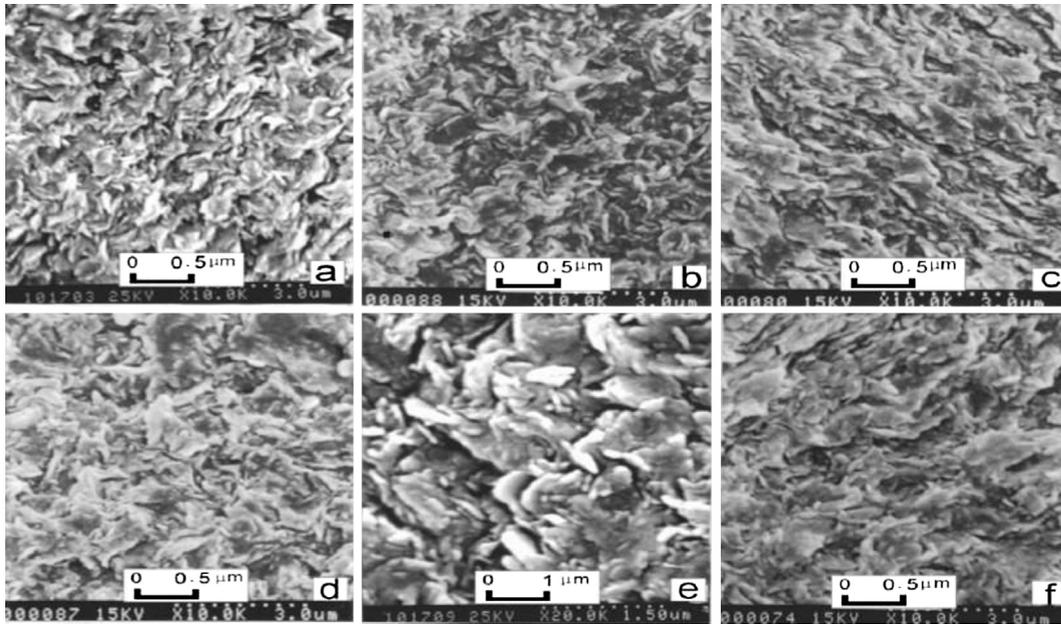


Fig. 4. The ultramicrotexture of the LFAs in the S_5 layer on the Guanzhong Plain. (a–c) Liujiapo profile in Xi'an; (d–f) Hejiacun profile in Baoji.

3.4. Removal depths of CaCO_3 and contents of Fe_2O_3 and CaCO_3

The removal depths of CaCO_3 and Fe_2O_3 are important indices used in paleoclimate reconstruction (Zhao, 1992, 2002, 2004). In well-drained soils on loess, these depth increase with increasing annual rainfall. Carbonate nodules indicate the CaCO_3 removal depth, and their CaCO_3 content is generally more than 40% (Zhao, 2002, 2004). Both the red LFAs and the thin red ferruginous argillans had high Fe_2O_3 contents, which provide evidence for the Fe_2O_3 removal depth. To eliminate the effects of continuing accumulation of aeolian dust on the removal depth, only the vertical distance

between the lower limit of the Bt horizon and the upper limit of the carbonate nodules or the lower limit of the red thin argillans was considered.

Observations show that the removal depth of CaCO_3 reaches 2.7 m from the lower border of the Bt horizon and 4.2 m from the top border of the Bt horizon to the CaCO_3 top border of the illuvial horizon (Table 2). This depth is greater than the depth of the red LFAs, because of a greater mobility of CaCO_3 than that of the colloidal Fe_2O_3 . The removal depth of Fe_2O_3 in S_5 was 1.7 m in the Liujiapo profile and 1.8 m in the Hejiacun profile (Table 2).

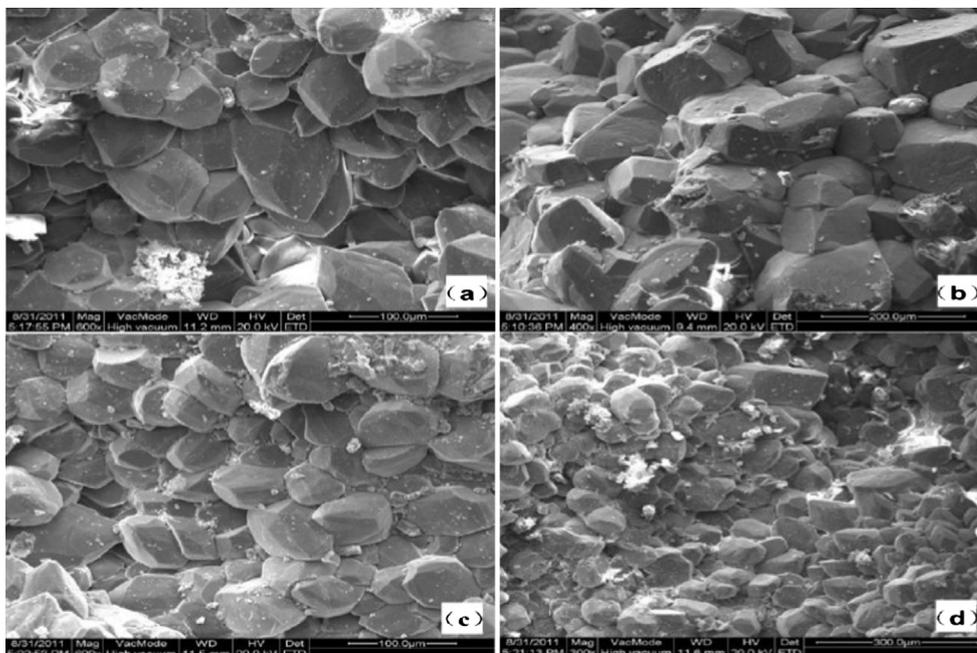


Fig. 5. Pure calcite crystals in illuvial layer of CaCO_3 below the S_5 layer at Liujiapo in Xi'an.

Table 2
Removed depth of CaCO₃ and Fe₂O₃ and R₂O₃ content in soils in different climate

Sites	Xi'an	Sihong	Hanzhong	Liuhe	Liujiapo	Hejiacun
Soil or paleosol	Mc	Ye	Ye	Ye	S ₅	S ₅
CaCO ₃ removed depth/m	0.0	0.3	0.4	2.0	2.4	2.6
Fe ₂ O ₃ removed depth/m	0.0	0.2	0.2	1.0	1.7	1.8
Thickness of weathered loess/m	0.0	0.5	0.5	2.0	2.4	2.6
Fe ₂ O ₃ content/%	4.4	5.2	5.0	5.5	5.3	5.6
Al ₂ O ₃ content/%	13.2	14.4	14.2	14.6	15.3	15.6
Mean annual precipitation/mm	600	890	900	1050	1100	1100
Mean annual temperature/°C	13	15	15	16	16	16

Note: Mc is modern cinnamon soil, Ye is modern yellow–brown forest soil, CaCO₃ removed depth is the vertical distance between lower limit of Bt horizon and upper limit of CaCO₃ horizon, Fe₂O₃ removed depth is the vertical distance between lower of Bt horizon and lower limit of red thin ferruginous argillans.

The CaCO₃ contents of the four profiles (at Liujiapo, Shuangzucun, Yangwancun, and Hejiacun) were small (<1%) in the Bt horizon and the underlying weathered layers, but were much greater (3.6–10%) in the unweathered L₆ loess (Fig. 7a–d), indicating strong leaching of CaCO₃ from the weathered loess sub-layers. The mean CaCO₃ content of the nodules was about 60% in the underlying Ck illuvial horizon (Fig. 7a–d). In the Hejiacun profile, the CaCO₃ leaching was more intense, resulting in a low CaCO₃ content at a depth of 4.6 m in the upper part of the L₆ layer (Fig. 7d). In modern soils with secondary carbonates, the CaCO₃ horizon occurs directly beneath the Bt horizon, giving a near-zero removal depth, as in the Wangcun profile near Xi'an (Xiong and Li, 1987). These results suggest that weathering was stronger and the climate was wetter during the formation of the S₅ layer in the southern Loess Plateau than those at present.

4. Discussion

4.1. Climate and soil type during the development of the S₅ layer

Ferruginous argillans usually develop under a warm–moist subtropical or a cool–moist temperate climate (Tang, 1981; Guo and Fedoroff, 1992; Zhao, 1994, 2005) with the color of typical dark brown (poorly oxidized) in cold–moist temperate zones (Guo and Fedoroff, 1992; Zhao, 1994, 2002) and red–brown in a subtropical climate (Guo and Fedoroff, 1992; Zhao, 1994, 2002). Thin ferruginous argillans are not well developed in the brown

forest soils and cinnamon soils of the warm temperate zone in China (Li et al., 1983; Xiong and Li, 1987). Other research indicates that transparent and thick ferruginous argillans serve as the identifying feature of severely leached forest soils, and the apparent red–brown color typical of subtropical soils (Fink 1977; Fedoroff and Goldberg, 1982; Guo and Fedoroff, 1992; Zhao, 2002, 2005).

There exists a red–brown and loessial structure in the upper 0.6 m of the weathered loess matrix, which is not developed from the existence of red ferruginous argillans eluviated from overlying paleosols, but from the oxidation of Fe compounds and the formation of Fe₂O₃, further indicating an effect of weathering. In modern soils in northern China, there is neither red–brown color in the Bt horizons (Li et al., 1983; Xiong and Li, 1987) nor red–brown weathered loess underlain by unweathered parent materials. On the contrary, oxidization and reddish deposits are common in the upper parts of parent materials overlain by modern yellow–brown forest soils in the subtropics in south China (Li et al., 1983; Xiong and Li, 1987). Thus, the weathered layer with red–brown matrix appears to be a feature of subtropical soils developed under relatively high temperatures.

The lower limit of the LFAs and the thin ferruginous argillans of S₅ are about 1.0 and 1.7 m below the bottom of the Bt horizon, respectively. These removal depths are greater than in the yellow–brown forest soil in the Hanzhong area (Table 2) and Sihong area (Table 2), where the mean annual temperature is 15 °C and the mean precipitation is 890 mm/y (Table 2; Li et al., 1983; Xiong and Li, 1987). The depth is also slightly greater than that in the subtropical yellow–brown forest soil in the Liuhe area of Jiangsu province (Table 2), where the mean annual temperature is 16 °C and the precipitation 1050 mm/y (Li et al., 1983; Xiong and Li, 1987). The removal depth of CaCO₃ (Table 2) further suggests a greater weathering intensity of the layers that contain LFAs than that of the yellow–brown forest soil at Liuhe. The thickness of the weathered loess in the S₅ layer is also greater than that in the subtropical yellow–brown forest soil in the Hanzhong, Sihong, and Liuhe areas (Table 2, Fig. 8b) and less than that in the Jurong area (Fig. 8a). This suggests that the mean annual temperature and precipitation would have been at least 16 °C and 1100 mm/y during the development of the S₅ layer. These values are 4 °C and 500 mm/y higher than those in the Guanzhong Plain. Thin ferruginous argillans are common in the Bt horizons of the Chinese loess sequence, except in paleosols that developed between 0.52 and 0.47 Ma (Kukla et al., 1988; Ding et al., 1994), but LFAs have developed only in the S₅ layer since 2.5 Ma. This suggests that the period during which S₅ developed was the warmest and moistest period since 2.5 Ma. Other climate proxies indicate a warmer and moister climate

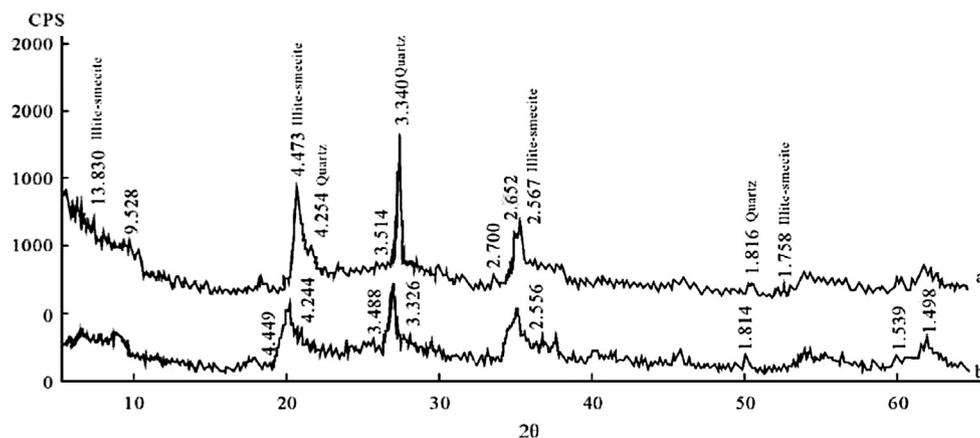


Fig. 6. X-ray diffraction curves for samples from the S₅ layer LFAs obtained from the Guanzhong Plain. X-ray diffraction curves are for samples from (a) the Liujiapo profile in Xi'an and (b) the Hejiacun profile in Baoji.

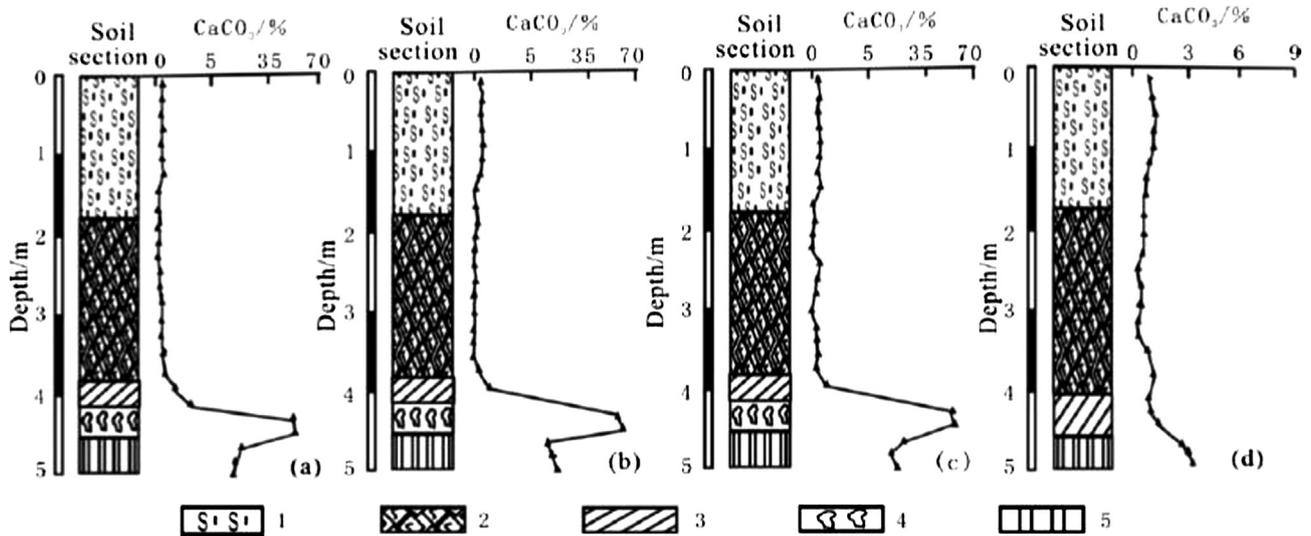


Fig. 7. Variations in the CaCO_3 content in the weathered sections of the fifth layer (S_5 , paleosol) in the Guanzhong Plain: (a) Liujiapo profile in Xi'an, (b) Shuangzhucun profile in Chang'an, (c) Yangwancun profile in Chang'an, and (d) Hejiacun profile in Baoji; 1. paleosol S_5 ; 2. Light red-brown weathered loess with red LFAs and thin ferruginous argillans; 3. Light brown-yellow weathered loess sub-layer without red argillans; 4. CaCO_3 nodule layer; 5. Unweathered aeolian loess.

during this time (Guo and Fedoroff, 1992; Maher and Thompson, 1995; Chen et al., 2006).

4.2. Reduced influence of the Qinling Mountains on climate during S_5 development

Modern rainfall in the southern Loess Plateau results from the movement of warm and moist air masses from south of the Qinling Mountains during the summer and autumn. The present rainfall in

the north is much less than that in the south owing to the blockage of air masses by the Qinling Mountains. In the western and northern parts of the Loess Plateau, it is about 600 mm/y, similar to or less than that in the southern Loess Plateau, whereas in areas beyond Qinling Mountains, it is more than 800 mm/y (Li et al., 1983; Xiong and Li, 1987; Zhao, 1994). During the interglacial epoch in which S_5 developed, however, the wet climatic zone appears to have migrated northward. The rainfall in the southern Loess Plateau was greater than today because more moist air

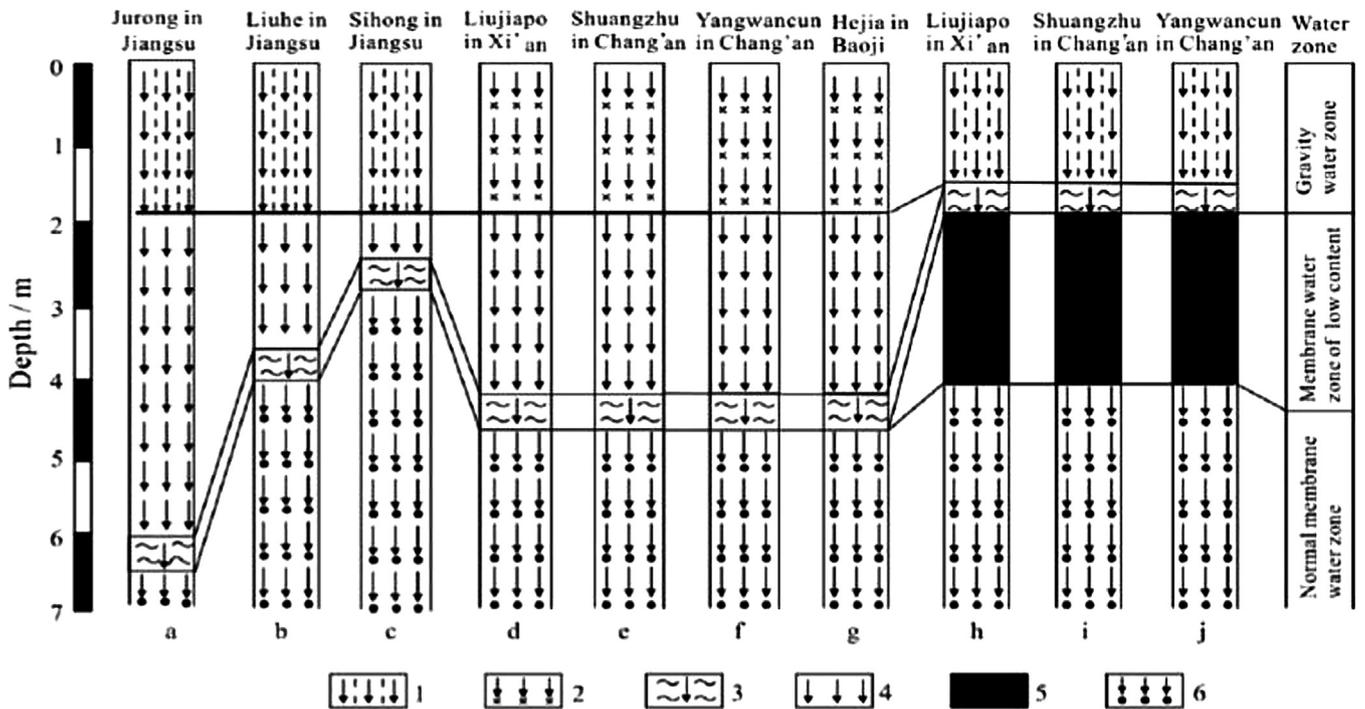


Fig. 8. Vertical distribution of soil water in subtropical South China and the Guanzhong Plain. (a–c) Weathered section of yellow-brown subtropical forest soils in South China; (d–g) Weathered section of the S_5 paleosol in the Guanzhong Plain; (h–j) Modern soil sections in the Guanzhong Plain. Lithologies include: (1) the Bt horizon of modern soils in the gravitational water zone, (2) the Bt horizon of the S_5 paleosol in the gravitational water zone, (3) the illuvial CaCO_3 horizon (Ck) in the gravitational water zone, (4) the weathered parent material horizon in the gravitational water zone, (5) the dry earth layer in the membrane water zone, and (6) the unweathered parent material horizon in membrane water zone.

masses crossed the Qinling Mountains in the summer and autumn. The formation of the red–brown weathered loess layers and LFAs in S_5 , in the southern Loess Plateau suggests that areas in the south and north of the Qinling Mountains experienced a moist subtropical climate during that epoch. Therefore, the Qinling Mountains failed to function as a climatic boundary due to a stronger summer monsoon at hot time. The altitude of Qinling Mountains is similar to that of today during the formation of the S_5 paleosol, so strong summer monsoon cannot be taken as evidence that the altitude of the Qinling Mountain was lower. Studies indicate that summer monsoon was strong during the development of the paleosols, thanks to the increasing temperature of Quaternary interglacial periods (An, 2000).

4.3. Nature of the soil water during S_5 development

The nature of soil water can be determined by the removal depth of chemical components in soil profiles. CaCO_3 contents in the Bt horizon are low in the S_5 profiles with some samples at almost zero, and the CaCO_3 illuvial horizon in S_5 (Ck) lies 2.2 m under the Bt horizon (Table 2, Fig. 2a and b). This indicates that soil water caused strong solution of the CaCO_3 at the time of formation of the S_5 layer. The removal of CaCO_3 may occur under alkaline, neutral, or acidic soil water conditions (Li et al., 1983; Liu, 1985; Xiong and Li, 1987; Marion, 1989; Zhao, 1992, 2002, 2004, 2005). However, the water was more probably neutral or acidic if the removal depth of the CaCO_3 illuvial horizon was 2.2 m lower than that at the bottom of the Bt horizon. With the currently alkaline soil water in North China, the CaCO_3 illuvial horizon closely follows the bottom of the Bt horizon (Li et al., 1983; Xiong and Li, 1987; Zhao, 1994, 2002). In sections of weakly acidic brown forest soils in North China and of acidic yellow–brown forest soils in South China, the CaCO_3 illuvial horizon lies 1 m or less from the bottom of the Bt horizon (Li et al., 1983; Xiong and Li, 1987; Zhao, 1994, 2002). Because the removal depth of the CaCO_3 illuvial horizon is less than 1 m, the soil water would have been weakly acidic. Acidic rainwater resulted in the acidic soil water in an acidic soil. The CaCO_3 illuvial horizon in S_5 lies 2 m below the bottom of the Bt horizon, which indicates that the soil water should have been acidic at that time.

The removal depth of Fe_2O_3 provides further evidence of the nature of the soil water. The eluviation and removal of Fe_2O_3 occur under weakly acidic conditions (Li et al., 1983; Xiong and Li, 1987; Zhao, 1994, 2002, 2005), not under alkaline conditions. For example, Fe_2O_3 in an alkaline orthic cinnamon soil is not commonly removed, but is weakly exuviated in a weakly acidic brown forest soil (Li et al., 1983; Xiong and Li, 1987; Zhao, 1994, 2002). It is obviously removed in an acidic yellow–brown subtropical forest soil (Li et al., 1983; Xiong and Li, 1987). The Fe_2O_3 in the S_5 profile was removed 1.7 m below the bottom of the Bt horizon, supporting the hypothesis that the soil water was weakly acidic during the middle and late stages of S_5 development. A long period of acidic precipitation resulted in acidic soil water during the development of S_5 .

4.4. Depth distribution of gravitational water during the development of S_5

Soil water is directly utilized by plant growth and vegetation development, and influences vegetation type. Some researchers consider that because very large thickness of loess, the lack of aquitards in loess strata and the infiltration depth (about 50 m) of atmospheric precipitation caused soil water deficiency, the thick loess region is unsuitable for the development of forests (Zhang and An, 1994; Li et al., 2003). However, based on the research of the soil micro-structure, some researchers have inferred forest vegetation

(Tang and He, 2004). Therefore, the type of vegetation during S_5 formation is an unsolved problem, and study of palaeosol water content plays a key role in revealing the type of vegetation at that time.

Based on the content of CaCO_3 and water condition needed to form CaCO_3 illuvial horizon, water content in the soil profile at that time can be determined. Moving downwards through the soil from the water aeration zone, water passes through three zones: the gravitational water zone, membrane water zone and saturated groundwater zone (Yang and Shao, 2000). Because gravitational water with high content in the soil possesses solubility and chemical transport capacity, the depth of the gravitational water plays a decisive role in vegetation development (Yang and Shao, 2000; Zhao et al., 2007, 2008). Although early researchers generally believed that soluble salts could be dissolved by membrane water, more recent research suggests that the effect is weak. Previous research found that membrane water could not dissolve insoluble CaCO_3 and also form CaCO_3 illuvial horizon by precipitation (Zhao, 1999, 2004). The effect of membrane water on the S_5 palaeosols lasted about 450 ka (Sun and Zhao, 1991; Guo et al., 1998), but the content of CaCO_3 is low in the layer of Bt (Fig. 7), which shows that membrane water transport has no effect on it. Membrane water represents water characterized by a low volumetric water and slow movement (Huang et al., 1998; Zhao et al., 2007, 2008), which explains the weak dissolution ability. However, gravitational water forms when soil moisture is greater than field capacity. The field capacity in the Southern Loess Plateau is typically around 20% (Yang and Shao, 2000) and any content exceeding this value may produce gravitational water, which moves quickly down to the groundwater zone. The high content and fast movement of this water explains why it possesses the abilities of dissolution and transport. The pure calcite crystals (Fig. 5) in CaCO_3 nodules indicate sufficient gravitational water.

Two factors may account for the illuviation of CaCO_3 and Sr in the S_5 palaeosols. One is that, while downward infiltration of the solution occurs, the acidic water becomes alkaline, and CaCO_3 and Sr precipitate when their concentrations become supersaturated. Under such conditions, the lower limit of the CaCO_3 and Sr deposition distribution should be shallower than that of the gravitational water. The other factor is that, while the solution infiltrates downward, soil moisture content decreases and the gravitational water changes into membrane water when the moisture content is lower than about 20%. Deposition of CaCO_3 and Sr happened due to the inability of dissolution. Under such conditions, the lower limit of the CaCO_3 and Sr deposition should be equal to that of the gravitational water zone. It is conservatively assumed that the illuviation of CaCO_3 and Sr occurred under the latter conditions. Even so, the depth of the gravitational water could have reached at least 4.2 m when S_5 developed, which is not only much greater than the about 2 m depth of the gravitational water of the modern soil in the Central Shaanxi Plain, or Guanzhong Plain (Yang and Shao, 2000; Zhao et al., 2008) (Fig. 8h–j), but also greater than those of subtropical yellow–brown soil profiles at Sihong and Liuhe in South China's Anhui Province (Table 2, Fig. 8b and c). Soil water content at a depth of 4.2 m exceeded 20% and could have totally satisfied the demand of the development of forest when S_5 developed. Therefore, it can be justifiably affirmed that the type of vegetation in the Guanzhong Plain of Shaanxi was forest when S_5 developed.

5. Conclusions

The conclusions below can be drawn based on the present study on the S_5 paleosol layer in the Guanzhong Plain of the southern part of China's Loess Plateau:

- (1) Neo-formed microcrystalline grains of clay minerals dominate the lumpy ferruginous argillans (LFAs). These microcrystalline grains are mainly regular plates, with some degree of alignment, which explains why the argillans show crystalline optical properties. The LFAs in the S₅ layer were composed of about 90% mixed illite–smectite clays and 5% quartz with an ultra-microcrystalline texture and a high Fe₂O₃ content. The LFAs were formed by illuviation of neo-formed clay minerals as a result of strong chemical weathering under warm and moist subtropical climate conditions.
- (2) The S₅ layer in the southern Loess Plateau, formed between 0.52 and 0.47 Ma, is a subtropical yellow–brown forest soil, but not the cinnamon soil formed under a semi-arid climate as was believed in the past.
- (3) Stronger chemical weathering than at present took place when the S₅ layer developed in the southern Loess Plateau. The presence of LFAs indicates that the soil water was weakly acidic.
- (4) The red LFAs, the characteristics of the weathered loess, and the removal depths of CaCO₃ and Fe₂O₃ all indicate that a subtropical climate prevailed during development of the S₅ layer in the southern Loess Plateau when the annual mean temperature and precipitation were about 4 °C and 500 mm higher than at present.
- (5) The CaCO₃ and Sr profiles in the weathered loess layer indicate that the gravitational water reached a depth of at least 4.2 m with more than 20% water content in the soil above the 4.2 m depth, adequate for sustainable forest growth.
- (6) During the development of the S₅ layer, the Qinling Mountains appeared to have lost its function as a climatic boundary in East Asia, when the warm–moist air masses from south of the mountains crossed the mountains into the southern Loess Plateau more frequently than they do at present.

Acknowledgements

This research was co-funded by the National Natural Science Foundation (Grant No: 40672108) and the State Key Laboratory of Loess and Quaternary Geology, Chinese Academy of Sciences (SKLLQG1021).

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