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Desert–steppe migration on the Loess Plateau at about 450 kaBP

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Abstract: According to the field investigation, observation by an electronic microscope and x-ray identification and chemical analysis, desert-steppe migration in the Loess Plateau at about 450 kaBP was studied. The data show that gypsum illuvial horizon indicating the desert-steppe environment developed in the early stage of the formation of the fifth layer loess in Shaoling tableland in Chang'an and Bailu tableland in Xi'an of Shaanxi are situated in the southern Loess Plateau. This indicates that remarkable drying occurred, a large-scope migration of desert steppe took place toward south and the climate zone migrated 5 degrees in latitude to south which is the largest migration range indicated by geochemical indexes. The desert-steppe and more wild environment distributed widely on the Loess Plateau at that time. The development of gypsum also indicates that the climate changed at 450 kaBP from monsoon climate to nonmonsoon climate in the Loess Plateau, and the region was not affected by summer monsoon and was in the cold and dry environment of nonmonsoon climate. Annual mean precipitation was about 200 mm, 400 mm less at that time than at present.

Key words: the Loess Plateau; gypsum; arid climate; large-scale migration of desert-steppe
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1 Introduction

Chinese loess has been studied by a lot of researchers and its important scientific significance is realized in restoring the Quaternary environment and correlating the climatic changes between oceans and continents (An *et al*., 1985; Kukla, 1988; Hoven *et al*., 1989; Barbara, 1995; Kemp *et al*., 1995; Liu, 1997; Kohfeld *et al*., 2003). It is thought through long time research that, the loess formed in a cold-dry climate that winter monsoon prevailed, the red-brown paleosol developed in a warm-wet climate that summer monsoon prevailed (Ding *et al*., 2000; Porter, 2001; Zhao, 2001; Guo *et al*., 2002; Zhao 2003, 2004). It is known by research that salinization occurred during the development of the fifth red-brown paleosol (Guo *et al*., 1992). According to research of predecessors (An *et al*., 1985), the first, second, fifth, sixth and ninth loess layers developed in the coldest and driest climate and desert-steppe occurred possibly in the Luochuan loess profile in the central Loess Plateau. But reliable evidence was not furnished for the development of desert-steppe at that time. Environmental changes on loess strata since 130,000 years were researched by more scientists in China (An *et al*., 1991; Xiao *et al*., 1995; Sun *et al*., 1996; Lei *et al*., 1997) and it is known that climate was the coldest and driest when Malan loess developed in the last glacial period, and steppe distribution got to Guanzhong Plain situated in the southeast Loess Plateau (Sun *et al*., 1991). However, gypsum illuvial horizon indicating desert-steppe reliably was not discovered in loess formed since 130,000 years in the central and southeast Loess Plateau. Many studies on European loess and deep sea deposit (Ruddiman, 1989) have been done abroad, and the studies were concentrated on Late Pleistocene climate change (Allen *et al*., 1993; Hughen, 1996). It was deduced on the basis of fossil animals and soil microstructure that steppe climate prevailed, but there was no desert-steppe when the loess strata

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formed (Fink *et al*., 1977). The 12th oxygen isotope climate stage corresponding to the fifth loess layer was one of the coldest three stages in the deep sea deposit (Ruddiman, 1989). However, it was not determined that the 12th oxygen isotope climate stage was colder than all other stages in the deep sea deposit. Research results show that last glacial period, especially between 18 and 15 thousand years, was the coldest and driest, many cold climate events occurred in the period (Henirich, 1988; Porter *et al*., 1995), and glacier went into North Atlantic Ocean at that time (Bond *et al*., 1992). In the last glacial period, a large scope climatic migration which is above five degrees in latitude occurred (Flint, 1971; Huang, 2000) and glacier distribution reached 47ºN in Europe. So far, that climate became colder and drier during the development of the fifth layer loess than other periods has not been discovered abroad. Consequently, migration range of the climate at that time has not been determined abroad. Precipitation during the development of loess layer changed with different areas. In the arid Lanzhou and Jingyuan of Gansu province in the northwestern Loess Plateau, the current precipitation is only 200 to 300 mm, it is very possible that there were desert-steppe and more desolate landscape in the cold-dry periods of loess development. However, in the southeast and central Loess Plateau, the current mean annual precipitation is 550 to 600 mm, there is no convincing evidence to indicate that there was desert-steppe during the loess development. Some data indicate that the vegetation was forest-steppe or more thriving vegetation when some loess layers developed in the southeastern Loess Plateau (Zhao, 2000, 2002). In recent years, the activation of dust storm indicated that loess can develop in the forest-steppe or more thriving vegetation. So more convincing evidences should be provided to prove there was desert-steppe in the southeast and central Loess Plateau. According to the field investigation and laboratory identification, the desert-steppe moving at large scope to south in the Loess Plateau at 450 kaBP was studied in the paper.

2 Field observation of gypsum illuvial horizon in areas around Xi´an

Through the investigation of loess nearby Xi'an, the gypsum illuvial horizon was found in the upper of the fifth red-brown paleosol under the fifth layer loess in Shuangzhu profile in the Shaoling tableland of Chang'an, Renjiapo profile in Bailu tableland of Xi'an and Lujiawan profile in Hengling tableland of Lantian (Figure 1). The gypsum illuvial horizon is about 0.5 m thick, gypsum crystal grains begin to occur from a depth of 0.2 m of the fifth layer red-brown paleosol and extend into a depth of 0.7 m (Table 1). In the most concentrated layer of gypsum, the gypsum is usually lumpy. When the gypsum is in the crack, it is crystal aggregate or crystal druse, crystal aggregate are about 5 to 10 mm in diameter (Figure 2a). Some crystals developed well and occur in the form of swallow-tail twin. During the leaching and moving of $CaSO_4$, it

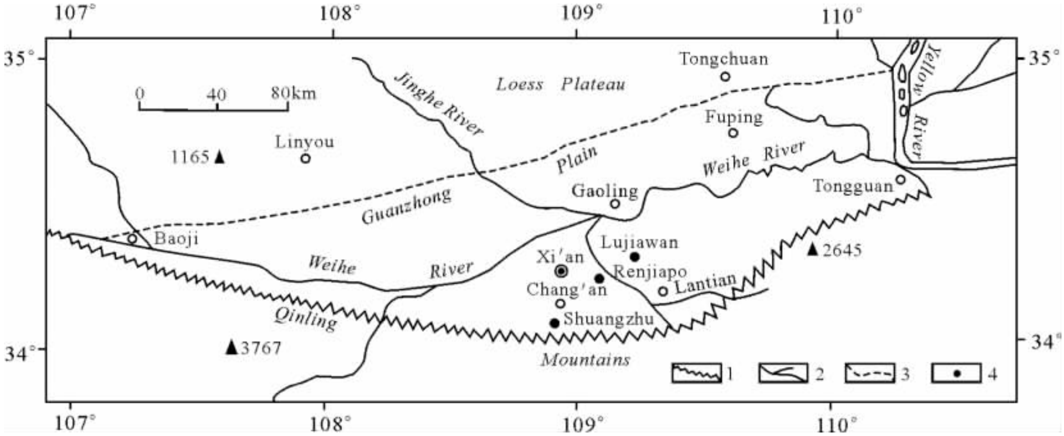

Figure 1 Location of the Guanzhong Plain and profiles studied
1. mountains; 2. river; 3. south boundary of the Guanzhong Plain; 4. profile site studied

Table 1 Distribution of gypsum in the fifth paleosol layer at Shuangzhu village in Chang'an

Loess and paleosol	Layer signal	Thickness /m	Lithological characteristics
Fourth layer paleosol	S_4	1.5	Prismatic structure and ferriferous films well developed with more clay content
Fifth layer loess	L_5	3.2	Granular and lumpy structure is main, films and spots of $CaCO_3$ developed well, and it is loose and porous.
Fifth layer paleosol	S_5	4.4	Clay content is more, prismatic structure and red ferriferous films developed. It consists of three sub-layers and gypsum crystals occur in the upper of the paleosol.

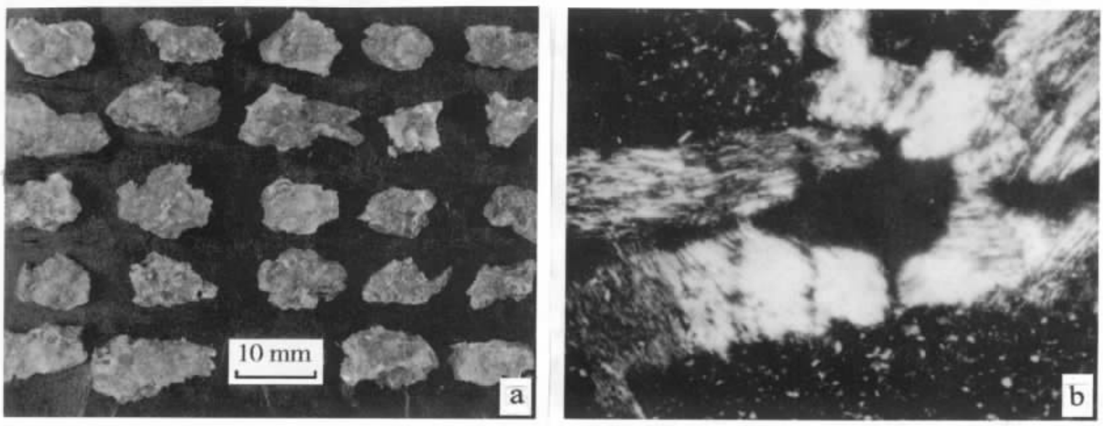

Figure 2 Shape of gypsum in the fifth layer loess in Shuangzhu profile
a. slaty gypsum crystals observed in field; b. fibrous gypsum crystal under a microscope (X50)

lends itself to the mixing of $CaSO_4$ with a little clay material of the red paleosol, there is a little red clay in the gypsum crystals, so they are very light red and translucent. The gypsum has clear glass luster, which looks like quartz with low hardness, and can be scratched by nail. There is no reaction when hydrochloric acid is added on it. It is evident that it is gypsum and is not quartz crystal grain. It is not calcite because it is not a rhombohedron. Detrital grain is less than 0.2 mm in diameter in the loess, hence the gypsum crystals developed evidently in the loess formation process. According to wider distribution of gypsum illuvial horizon in many profiles, it is known that the development of the illuvial horizon is common.

According to moving depth of $CaSO_4$ in gypsum illuvial horizon in current desert-steppe soil and desert soil (Li *et al*., 1983; Xiong *et al*., 1987), it is known that the gypsum illuvial horizon didn't develop in the process of the formation of the fifth red palaeosol, but it developed in the process of the formation of the overlying fifth layer loess. If the gypsum illuvial horizon which is distributed 0.2 m deep under the upper bound of the loess, the moving depth of the gypsum illuvial horizon can not reach 0.7 m, but only 0.4 m. Because a $CaSO_4$ illuvial horizon developing in the typical desert climate illuviates after moving to the depth of 0.2 m, it is impossible that moving depth reaches to 0.7 m.

3 Laboratory analysis and identification of samples

In order to prove the existence of gypsum, samples were identified by an optical microscope and electronic microscope and x-ray diffraction analysis and chemical analysis. On the basis of identification of 8 slides by a microscope, it is known that the gypsum identified in field is grey-white (Figure 2b) and is colourless under polarizing microscope, and its shape is fibrous

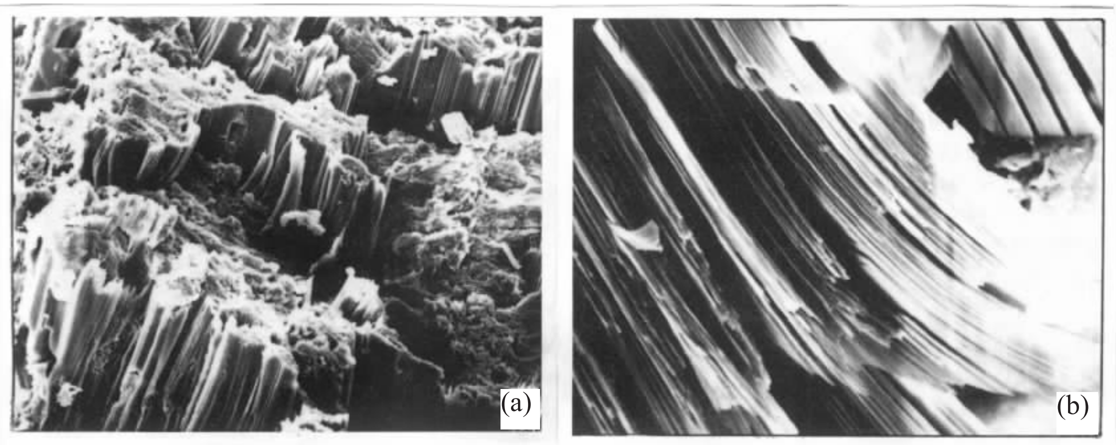

Figure 3 Gypsum crystal in Shuangzhu profile under a scanning electronic microscope
a. slaty gypsum crystal (X300); b. slaty gypsum crystal (X5000)

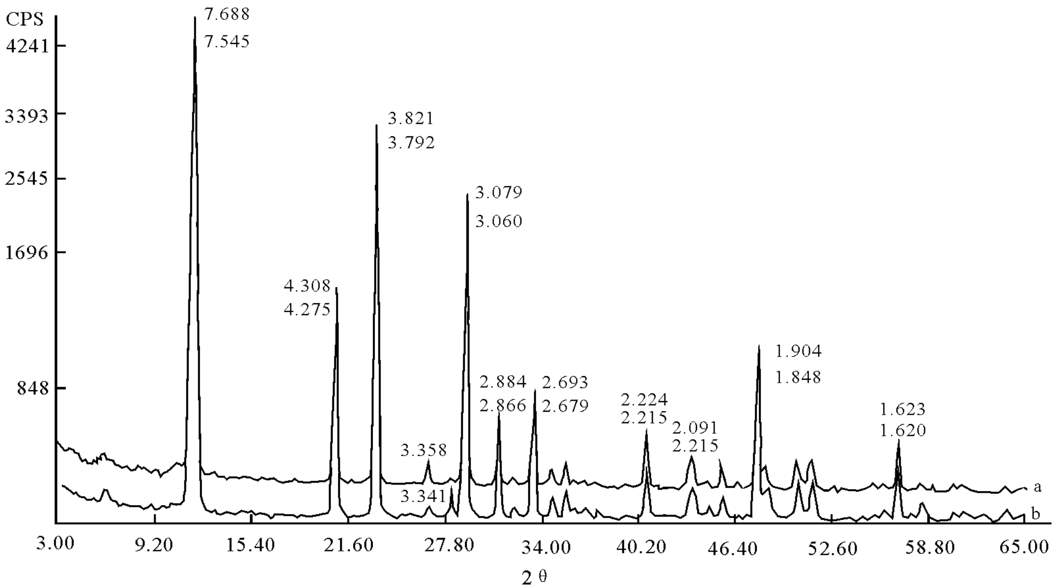

Figure 4 X-ray diffraction curves of gypsum samples
a. sample from Renjiapo profile; b. sample from Shuangzhu profile

and slaty with cleavage well developed. These characteristics show that the mineral is gypsum. According to determination of 6 samples through a scanning electronic microscope, it is known that the gypsum identified in field is slaty aggregate (Figure 3a, b). The crystal shape is the typical characteristics of gypsum.

X-ray diffraction indicated that the diffraction curves of 3 samples are the same (Figure 4) which have the characteristics of gypsum curves. Analysis of the curves indicates the gypsum content is 90% to 93% in the 3 samples, the other 7% to 10% are quartz, etc.

According to the chemical analysis of 5 samples, the content of $CaSO_4$ in the gypsum samples collected in field is 64.4%-70.4%. Because the gypsum contains 20.93% of crystal water, the content of $CaSO_4$ is less.

The material above mentioned indicates that the semi-transparent mineral which is distributed in the upper part of the fifth paleosol is gypsum.

4 Properties of soils indicated by the gypsum illuvial horizon

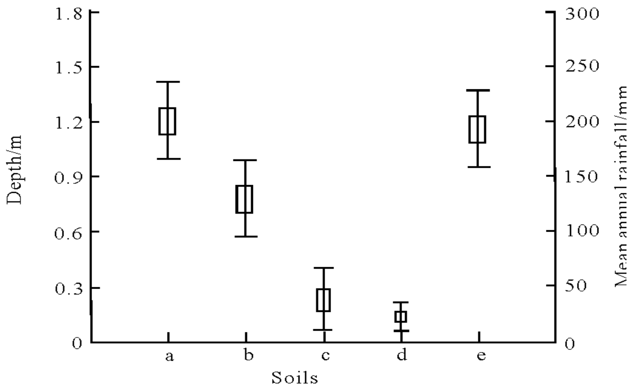

Figure 5 The distribution and mean annual precipitation during formation of the $CaSO_4$ illuvium of different soils

a. orthic cinnamon soil; b. orthic gray desert soil; c. orthic gray desert soil; d. orthic brown desert soil; e. the fifth layer loess

The gypsum illuvial horizon is the characteristic of several special soils, which can indicate the properties of soils. In order to determine soil properties by gypsum illuvial horizon, first we should know the characteristics of gypsum illuvial horizon of several modern soils. The thickness of the fifth layer loess nearby Xi'an is about 5.0 m. According to the distribution and the existing shape of gypsum in the illuvial horizon, we can identify the properties of soils. The soils with gypsum illuvial horizon in northwestern China are orthic sierozern and orthic brown soil in desert-steppe areas, orthic gray desert soil, orthic gray brown desert soil and orthic brown desert soil in the desert areas. The shape of the gypsum illuvial horizon in orthic sierozern is the nodular about 1 mm in diameter without crystal druses and coarse crystal grains, and the content of gypsum is less than 3% (Li *et al*., 1983; Xiong *et al*., 1987). The shape of gypsum in the illuvial horizon in modern orthic brown soil is part being small nodules and part being massive, coarse crystal grains. The content of gypsum is less than 10%, and the moving depth of $CaSO_4 \cdot 2H_2O$ is about 1.0-1.4 m (Figure 5a). The shape of gypsum in illuvial horizon of orthic gray desert soil is massive, coarse crystal grains, the content of gypsum is less than 15% (Li *et al*., 1983; Xiong *et al*., 1987), and the moving depth of $CaSO_4 \cdot 2H_2O$ is 0.5-1.0 m (Figure 5b). The shape of gypsum in illuvial horizon of orthic brown desert soil is similar to the one of orthic gray desert soil, but the content of gypsum is 20% to 30%, and the moving depth of $CaSO_4 \cdot 2H_2O$ is 0.1-0.4 m (Figure 5c). The shape of gypsum in illuvial horizon in rothic brown desert soil is massive or slaty, coarse crystal grains or crystal druse, the content of gypsum is more than 30% (Li *et al*., 1983; Xiong *et al*., 1987), and the moving depth of $CaSO_4 \cdot 2H_2O$ is less than 0.1 m (Figure 5d). The differences in the content of the gypsum, the shape and the moving depth are caused by different amount of precipitation. When precipitation is more sufficient, the moving depth of $CaSO_4 \cdot 2H_2O$ is greater, a part of $CaSO_4 \cdot 2H_2O$ is leached away, the concentrated amount of gypsum is less, the content is less and always exists in the form of small nodules. When precipitation is less, the moving depth of $CaSO_4 \cdot 2H_2O$ is small, the concentrated amount of gypsum is more, the content is more and occurs in the form of massive, coarse crystal grains or druse. Through separating gypsum from 20 kg earth specimen of the fifth layer loess, it is known that the gypsum illuvial horizon nearby Xi'an is 7%-12% of the volume of the earth, presents in the form of coarse crystal grains (Figure 2a) and druse, which indicates that the gypsum illuvial horizon is different from the one of the orthic sierozern, but it is similar to the one of orthic brown soil in desert-steppe areas and orthic gray desert soil in desert areas. The gypsum illuvial horizon of the fifth layer loess nearby Xi'an is distributed at 0.2-0.7 m under the lower bound of this loess layer, which shows that the greatest moving depth is more than 0.7 m. So we could at least determine that the moving depth of the gypsum illuvial horizon of the fifth layer loess is greater than that of gray desert soil, which is equal to or less than typical orthic brown soil in desert-steppe areas (Figure 5e). If we compare the gypsum illuvial horizon of the fifth layer loess with the one of orthic brown soil, it is known that the illuvial horizon comes from 0.8 m above the lower bound of the fifth layer loess. If we compare it with orthic gray desert soil, it is known that the gypsum illuvial horizon comes from 0.3 m above the lower bound of the loess. In order to obtain reliable conclusion, we choose the $CaSO_4 \cdot 2H_2O$ moving depth of orthic brown soil as the comparing standard of the $CaSO_4 \cdot 2H_2O$ moving depth of the fifth layer loess, the value is 1.0-1.5 m. This indicates that $CaSO_4 \cdot 2H_2O$ illuvial horizon of the fifth layer loess nearby Xi'an comes from 0.8 m above the lower bound of this loess layer, the greatest moving depth is 1.5 m, and the smallest moving depth is 1.0 m. The moving depth of orthic sierozen is similar to the one of orthic brown soil, so the $CaSO_4 \cdot 2H_2O$ moving depth of 1.5 m is the greatest moving depth of the soils with gypsum illuvial horizon. Because the moving depth is determined by comparing the characteristics of illuvial horizon, so the effect of wind dust accumulation during the loess development on moving depth is not taken into account. The moving depth is conservative, but the result is reliable.

The oldest age of the fifth layer loess is about 460 ka BP (Liu, 1997). The research results indicate that the loess development thickness of in the Loess Plateau is about 0.5 m per 10 thousand years (Liu, 1997; Zhao 2002). So it is deduced that the gypsum illuvial horizon of the fifth layer loess developed at about 450 kaBP.

5 The climate environment during development of the fifth layer loess

There are many indexes which can restore the paleoclimate, but the indexes which can strictly indicate climate conditions are less. For example, sporo-pollens are possibly destroyed by microorganism, carried and mixed by wind and water, and vegetarian develops in certain changing range of climate, the animal can move, the chemical composition and particle size can reflect only the relative change of climate. However, the formation and reservation of gypsum need strict climate conditions, which develops in the arid and extreme arid climate area (Li *et al.*, 1983; Xiong *et al.*, 1987), and can indicate quantitatively the climate conditions. If the soil classification (Figure 5) indicated by the gypsum illuvial horizon of the fifth layer loess nearby Xi'an is known, we can accurately recover the precipitation at that time. Orthic sierozern and orthic brown soil are desert-steppe soil, the annual mean precipitation in their development areas is 200-300 mm and 150-280 mm (Li *et al.*, 1983; Xiong *et al.*, 1987), and orthic gray desert soil is desert soil, the annual mean precipitation in its development area is 100-200 mm (Li *et al.*, 1983; Xiong *et al.*, 1987). Orthic gray brown desert soil and orthic brown soil are most weakly developed soils, the annual mean precipitation in their development area is less than 100 mm (Figure 5). Because the gypsum illuvial horizon of the fifth layer loess indicates that the development level of loess layer is similar to or weaker than the one of orthic brown soil, the soil represented by this gypsum illuvial horizon corresponds to brown soil in desert-steppe areas or weaker than the soil, the annual mean precipitation during development of the loess layer is about 150-250 mm (Figure 5). The modern mean annual precipitation is about 600 mm in areas around Xi'an. It is evident that the annual mean precipitation is about 400 mm less at that time than at present in areas nearby Xi'an.

Orthic brown soil does not develop in the modern Loess Plateau, but it develops on the Inner Mongolia Plateau and middle and west of Ordos Plateau between 38° and 40°N (Figure 6) (Li *et al.*, 1983). Because glacial climate migrates from south to north when climate becomes cold, the development of gypsum illuvial horizon in the Xi'an area (34°15'N) in the south edge of the Loess Plateau indicates that the climatic zone moved 5 degrees in latitude toward south (Figure 6). The precipitation in development area of orthic brown soil is scarce, because such kind of area is rarely affected by the summer monsoon. 39°N is the northwesternmost limit that modern East Asian summer monsoon reaches (Wang, 1990). So the Loess Plateau was not affected by summer monsoon and was under the nonmonsoon climate condition during the development period of the gypsum illuvial horizon nearby Xi'an. Even if the fifth layer loess has the properties of orthic sierozern, nonmonsoon climate would also prevail at that time. The subtropical climate moved to the north at great range in the Loess Plateau at about 500 kaBP (Zhao, 2001) and was

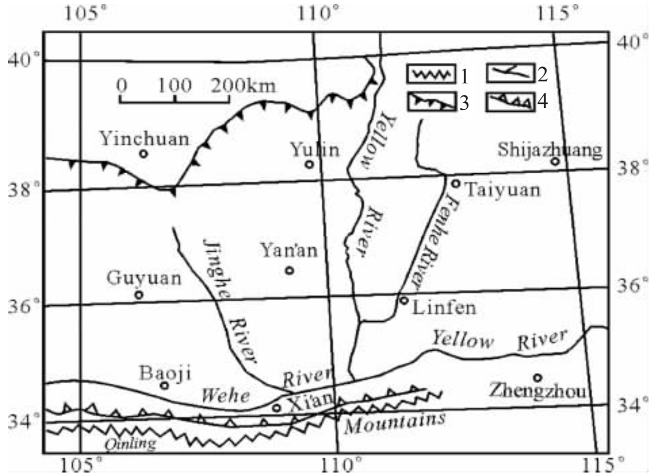

Figure 6 Migration of orthic brown soil and climate at about 450 kaBP in the Loess Plateau
1. mountains; 2. river; 3. south boundary of current orthic brown soil and north boundary of current summer monsoon; 4. south boundary of orthic brown soil and isoline of rainfall about 200 mm at 450 kaBP

the warmest and wettest period of the Loess Plateau since 250 kaBP. But after 500 kaBP, the large-scale southward movement of desert-steppe took place at early stage of the fifth loess's formation, which indicates that the great climate fluctuation occurred. The reason for this great climate fluctuation at that time is worthy of investigation.

So far, the gypsum has not been found in other loess layers in the middle and south of the Loess Plateau, its development is the indicator of extreme arid climate and also represents the change from monsoon climate to nonmonsoon climate.

6 Conclusions

On the basis of the above mentioned researches, we can obtain the following:

(1) At the early stage of the fifth layer loess's formation at about 450 kaBP, there was extreme dry climate in the Loess Plateau, the large-scale southward movement of the climatic zone took place, a move of 5 degrees in latitudes to south.

(2) At about 450 kaBP, the typical desert-steppe moved to the south-east edge of the Loess Plateau, the environment of the central and northwestern parts of the Loess Plateau is even more desolate.

(3) At about 450 kaBP, the climate character changed from monsoon climate to nonmonsoon climate. This area was almost effected by summer monsoon and became the arid and cold nonmonsoon climate area, and annual mean precipitation of the southeast of the Loess Plateau was then about 200 mm, 400 mm less at that time than at present.

(4) The development of the gypsum illuvial horizon of the fifth layer paleosol indicates that the soil developed in areas around Xi'an corresponds to orthic brown soil or more weakly developed soil at about 450 ka BP.

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