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Mid-Pleistocene vermiculated red soils in southern China as an indication of unusually strengthened East Asian monsoon

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Abstract The mid-Pleistocene vermiculated red soils (VRS) from Xuancheng (Anhui Province) and Bose (Guangxi) are studied through soil micromorphological, mineralogical and chemical approaches. The results indicate a polygenetic nature of the VRS, having experienced multiple soil-forming stages. Three main stages have been recognized, attributable to distinct climate regimes. They include the formation of the homogeneous matrix of a red soil (stage 1), development of the white veins within the soil profile (stage 2), and formation of juxtaposed textural features (stage 3). The white veins, resulting from iron-depletion in the groundmass of the homogeneous matrix of a red soil, required abundant rainfall without significant seasonal desiccations. The geographically widely spread VRS south of the Yangtze River in China implies a Mid-Pleistocene extreme East Asian summer monsoon. This climate extreme might be closely linked with the changes in the strength of NADW.

Keywords: vermiculated red soil, paleosols, micromorphology, paleoclimate, mid-Pleistocene, East Asian monsoon.

A paleosol unit, referred to as vermiculated red soil (VRS), widely distributes in the region south of the Yangtze River. It is characterized by red and white veins, easy to be identified in the fields, and is usually considered a stratigraphic marker. VRS covers an area[1] of about 2.2×10^6 km^2, and extends northward to Nanyang-Tongbai-Huaihe along the middle-lower reaches of the Yangtze River, southward to the Nanling Mountains, eastward to Hangzhou, Jiaxing, Huzhou-Yixing and the Liyang mountains-Anqing-the middle-lower reaches of the Huaihe River[2], and westward to the Chengdu Plain. Recent chronological studies[3−6] consistently indicate a mid-Pleistocene age of the VRS, correlative to the S4 and S5 soil units in the Loess Plateau in northern China[4] and marine δ^{18}O stages 11—15. However, interpretations on the forming processes and environmental significance of the VRS are still controversial[1,7−13]. One view[1,7−10] considered the role of groundwater oscillations, which may have led to seasonally alternative swells (reductions) and shrinks (oxidations), and resulted in the formation of the red and white veins. However, such hydrological conditions, time-independent and local, would not explain the widely distributed VRS with specific chronology. These conditions usually yield Fe-Mn pseudogleying features absent in most of the VRS. Another view[11], still lacking plant physiology and geography support, emphasized the possible effects of roots that might absorb iron from the soil profiles, leading to partial iron-depletion, and thus the white veins. Other invoked processes include the root-induced inhomogenous oxidation-reduction conditions within soil profiles[8,9,12,13], and weathering of the heterogeneous soil parent materials[8,9,11]. The soil-forming processes and environmental significance of the VRS, therefore, need further study, which are helpful towards a better understanding on the mid-Pleistocene spatial variability of the monsoon climate in China. The VRS draws also attention of archaeologists as many VRS sections contain Paleolithic sites[6,14,15].

Two VRS sections, one from Xuancheng in Anhui Province and the other from Bose in Guangxi are comparatively studied. They both have reliable chronological data and contain archaeology sites[6,14]. The middle and upper portions of the parent materials for the Xuancheng VRS are eolian deposit while the lower portion is fluvial[4]. The Bose VRS developed on fluvial deposits. This paper aims at (1) investigating the morphological, chemical and mineralogical characteristics of the red and white veins; (2) interpreting their correspondent pedo-geological processes; and (3) reconstructing climate conditions of the VRS from regional and global perspectives.

1 Materials and methods

The 11-m thick Xuancheng section is located near the Xuancheng City (118°51′E, 30°54′N), on the second terrace (T2) of the Shuiyang River, a branch of the

Yangtze River. It consists from the top to the bottom, of a cultivated soil (~0.2 m thick), the so-called Xiashu loess (~3.8 m thick), the VRS (~6.0 m thick) and the sandy-gravel deposits of fluvial origin (~1.0 m visible thickness). Magnetostratigraphic study and luminescence dating[4] indicate an age of the VRS younger than 800 ka BP, correlative to the S4 and S5 soil units in the Loess Plateau region in northern China. The 8-m thick Bose section situates near the Xiaomei Village (106°42′E, 23°46′N), developed on the fourth terrace (T4) of the Youjiang River. From the top to the bottom, the section consists of a cultivated soil (~0.2 m thick), a red clay layer (~0.7 m thick), the VRS (~6.3 m thick) and a layer of well-sorted cobble conglomerate (~0.8 m thick). The sediments of T4 contain Paleolithic stone artifacts and *in situ* tektites[6]. The tektite event evidently occurred before the formation of T4. $^{40}Ar/^{39}Ar$ dating of the tektites yields ages of ~800 ka BP[6]. The VRS on the T4 must have developed after the formation of T4, therefore, younger than ~800 ka BP. Strong soils were also developed on the other three terraces of the Youjiang River, but lacking vermiculated features. These chronological and pedo-stratigraphic data indicate that the VRS at Bose and that at Xuancheng are chronologically correlative, formed during the mid-Pleistocene after 800 ka BP.

Soil micromorphology is one of the best methods in the study of paleosols. It is frequently used to identify pedofeatures resulting from various pedogenic processes, and to reconstruct the consecutive order of pedo-sedimentary events. Among the various pedofeatures, textural features (e.x. clay coatings) are particularly helpful for identifying pedogenic stages in polygenetic soils and for interpreting their forming conditions as they all have clear environmental significance[16−19]. Oriented block samples were taken from different horizons, their transitions, the red and white veins for micromorphological thin section fabrication. Bulk samples were taken to characterize their chemical and clay mineralogy properties. Twenty-nine micromorphological thin sections from Xuancheng and thirteen from Bose were studied under optical microscope. The micromorphological glossaries by Bullock et al.[20] were used for description. Clay fractions (< 2 μm) of selected samples from the red and white veins were extracted for chemical and clay mineralogy analyses. Chemical analyses were conducted on an SHIMADZU XRF-1500 sequential X-Ray fluorescence spectrometer. Oriented clay specimens was analysed using a Rigaku D/MAX 2400 X-ray diffractometer to determine the clay mineralogy assemblages. Before the XRD analyses, sub samples were respectively Mg^{2+}-saturated, Mg^{2+}-saturated and glycerol-solvated, Mg^{2+}-saturated and ethylene glycol-solvated, K^{+}-saturated at 25℃, and K^{+}-saturated and heated to 120, 400 and 550℃.

2 Results and discussions

2.1 Micromorphological, mineralogical and chemical properties of the VRS

Microscopic observations reveal that the coarse fraction of the VRS is characterized by a high dominance of quartz and crumbs of quartzite, and a lack of alterable minerals (e.x. feldspars and micas). Clay mineral assemblages at Xuancheng are dominated by kaolinite, and a small amount of vermiculite and illite (Fig. 1). These indicate a strong weathering of the parent materials, typical of tropical-subtropical humid soils. The red veins contain much goethite and hematite while the white veins are characterized by the lack of hematite and the presence of a quite small amount of goethite.

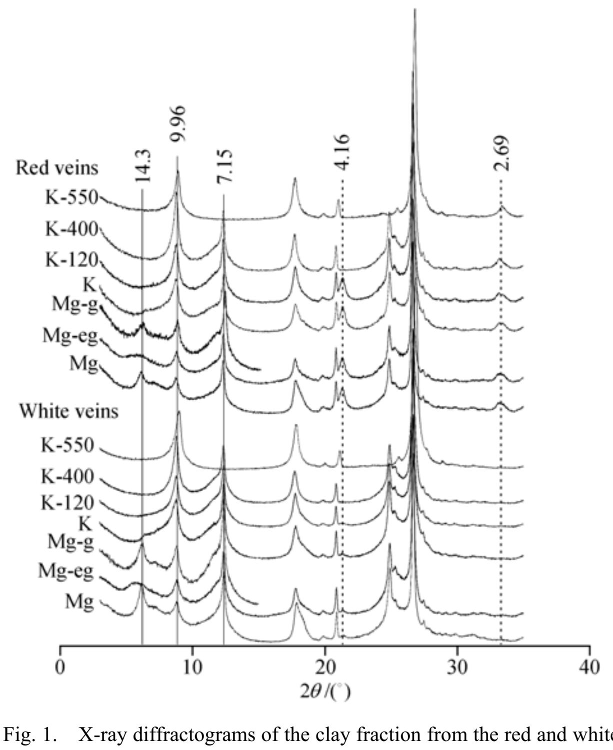

Fig. 1. X-ray diffractograms of the clay fraction from the red and white veins of the Xuancheng vermiculated red soil.

Except the color difference, the coarse minerals and microstructures of the red and white veins are essentially similar. The transitions between the red and white veins are mostly gradual (Fig. 2(a)), such that a complete clay coating may cross both (Fig. 2(b)). The only remarkable difference is the iron oxides, much more

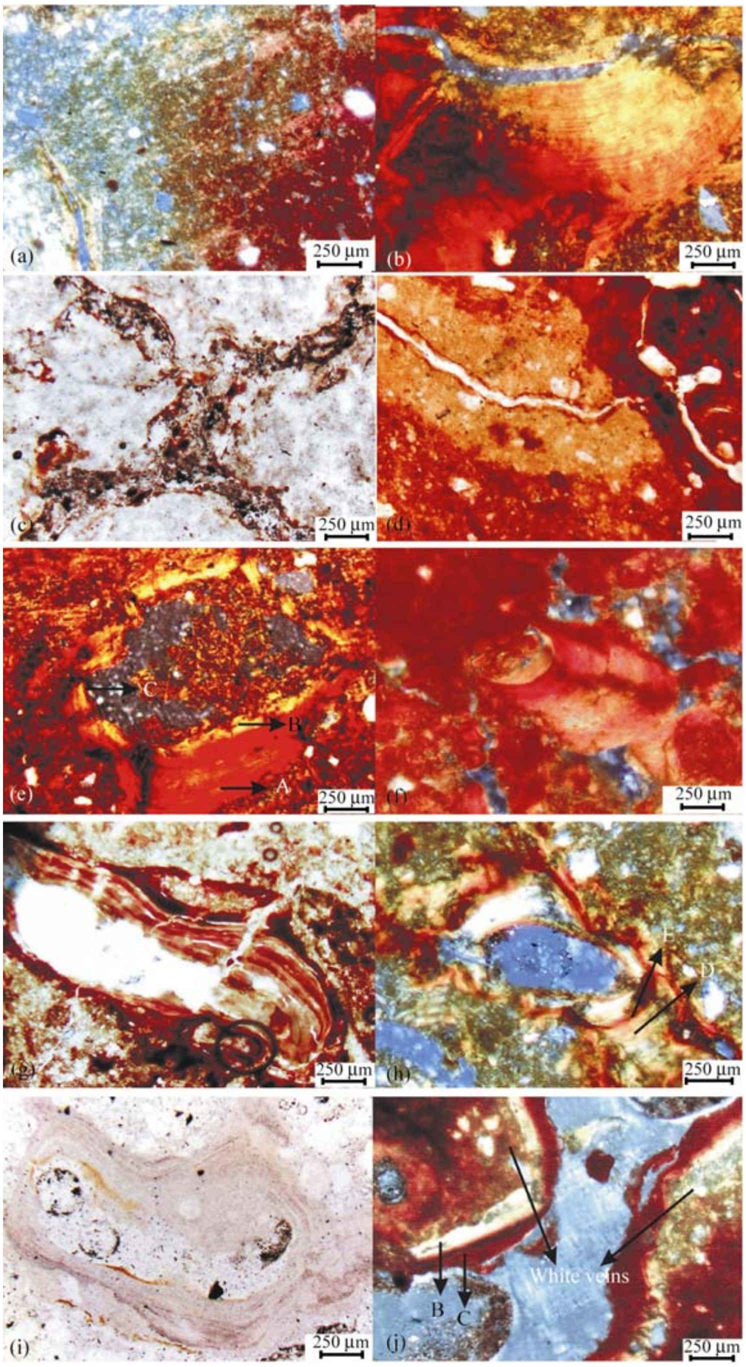

Fig. 2. Micromorphological photos of the vermiculated red soils from Xuancheng and Bose.(a) Gradual transitions between the red and white veins (Bose, cross-polarized light -XPL); (b) clay coating of type A near the boundary between the red and white veins. The portion in the white veins has lark color because of iron depletion (Bose, XPL); (c) planes in the white veins (Xuancheng, plain-polarized light - PPL); (d) planes in the white veins ended at the boundary between the red and white veins (Bose, PPL); (e) clay coatings of types A, B, and C in the red veins (Bose, XPL); (f) crescent-shaped clay coating of type A in the red veins (Xuancheng, XPL); (g) juxtaposed clay coatings of types C, D, E in the red veins (Xuancheng, PPL); (h) alternating clay coatings of types D and E in the white veins (Bose, XPL); (i) degraded clay coatings of type A in the white veins (Bose, XPL); (j) alternating clay coatings of types B and C on the planes in the white veins (Bose, XPL).

abundant in the red veins, and near-absent in the white veins. The voids in the VRS are dominated by planes, but mainly in the white veins. Some red-brownish ferruginous clay coatings, evidently developed in a latter stage, are observed on the walls of these bulky planes (Fig. 2(c), (d)). On the contrary, such features are scarce in the red veins. The white veins symmetrically developed along the sides of these planes, indicating a causal relationship of the white veins with these planes. Abundant clay coatings are observed in the VRS, and can be classified into five types. These include (A) crescent and eyebrow-like red-brownish coatings with sharp extinction and microlaminations usually occur in the red veins (Fig. 2(e), (f)), and sometimes are cut by latter planes. They became degraded into off-white or lark color in the white veins due to the iron-depletion (Fig.2(b), (i)); (B) non-laminated bright yellow coatings, limpid with sharp extinction, usually develop on the walls of the planes (Fig. 2(e), (j)); (C) dark-red non-laminated coatings with diffuse extinction form on the walls of the planes (Fig. 2(e), (j)); (D) snuff-colored non-laminated coatings with diffuse extinction along the walls of the planes (Fig. 2(g), (h)); and (E) red-brownish non-laminated coatings with diffuse extinction, along the walls of the planes (Fig. 2(g), (h)). In the red veins, the coatings of type C are juxtaposed on type B, and those of type B on type A (Fig. 2(e)). Alternations between types D and E develop on type C (Fig. 2(g)). In the white veins, the alternating types B and C are formed on the walls of the planes (Fig. 2(j)).

In both sections, except for Fe_2O_3 and Al_2O_3, the other chemical components in the clay fraction are essentially similar in the red and white veins (Fig. 3). However, the content of Fe_2O_3 in the red veins is almost ten times higher than that in the white veins. This is consistent with the X-ray diffraction and micromorphological results.

2.2 Pedogenic processes and environmental significance of the VRS

The gradual transitions between the red and white veins and their similar matrixes indicate that the two kinds of veins were formed within a previously homogeneous matrix. These are not explainable by neither heterogeneous parent materials nor the effects of roots. Micromorphological studies show an independent relationship of the white veins with roots. The white veins are usually symmetrical around the voids that are typical planes, rather than root channels. All the analyses

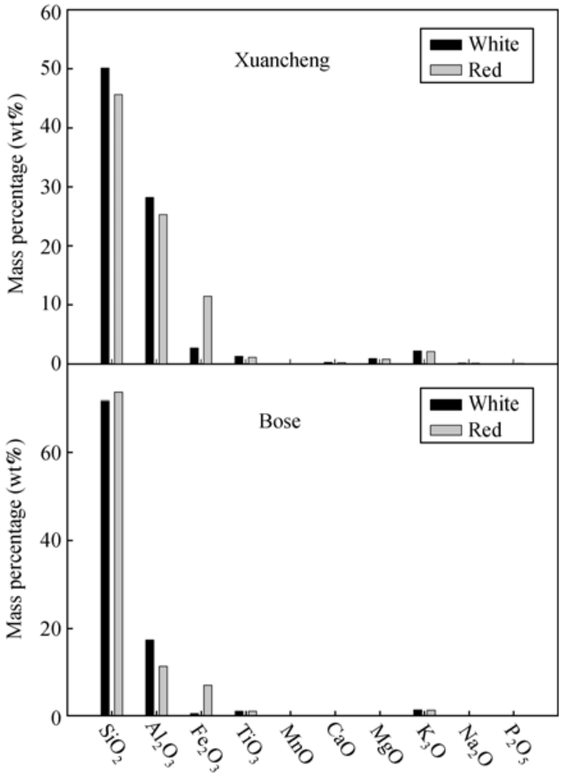

Fig. 3. Chemical analyses of the clay fraction of the red and white veins in the vermiculated red soils.

consistently show much more abundant iron oxides in the red veins than in the white veins, indicating that the white veins were formed due to partial leaching and removal of iron oxides from the soil matrixes, yielding vein features.

Several kinds of clay coatings coexist, indicating multiple clay illuvial stages under different environmental conditions. The VRS are polygenetic soils, also referred to as soil complex, developed under different climates[16,17]. The juxtaposed pedofeatures indicate that the VRS have experienced the following consecutive pedogenic processes: (1) formation of a homogeneous red soil of which the matrix contains clay coatings of type A and planes; (2) development of the white veins around the planes; and (3) formation of the clay coatings of types B, C, D, and E.

(1) Stage 1 Formation of a homogeneous red soil matrix. The dominance of quartz and quartzite, the lack of less resistant minerals in the coarse fraction, and the dominance of kaolinite in the clay fraction are all characteristics of soils under tropical and sub-tropical environments[21]. The type A clay coatings are typical of climates sufficiently wet to support a permanent and

dense vegetation cover[16]. However, the absence of gibbsite, the presence of some 2∶1 clay minerals and the abundant clay coatings in the VRS indicate a lack of tropical laterization process and moderate levels of chemical weathering. Such soils correspond to the red soils in the Chinese soil genetic classification[22]. They are formed under subtropical moist climates with evergreen latifoliate vegetation. Indeed the climate in the south of the Yangtze River must have been significantly warmer and wetter than today during the formation of the VRS because the present-day soils in the middle-lower reaches of the Yangtze River were classified as yellow brown soils[23], which developed under a cooler and drier climate than red soils.

(2) Stage 2 Formation of white veins. It is evident that the white veins resulted from iron leaching and removed from the above red soil matrix. An arising question is what kinds of climate or soil hydrological conditions can lead to such iron-depletion processes.

Under surface conditions, iron may become mobile in soluble states in three cases: 1) alternating dry and wet conditions can lead to transformation between soluble Fe^{2+} and insoluble Fe^{3+}, characteristic of pseudogleying[24], yielding Fe-Mn spots, nodules, concretions, coatings or mottles in soil profiles; 2) Fe^{2+} in permanently water-saturated soils may translocate within soils, producing gray, greenish-gray or bluish-gray colors, typical of gleying soils[24]; 3) iron may be bonded to organic acids to form soluble chelate compounds, under cool-humid climates with a coniferous vegetation cover, as the case for podzolization of spodosols[24].

The mechanism of iron depletion from the white veins of the VRS clearly differs from the above three cases. Firstly, the absence of pseudogleying features in the VRS indicates a total translocation of Fe^{2+} into groundwater without resting in the soil profiles to form Fe-Mn features. The mid-Pleistocene VRS widely distributed in the areas south of the Yangtze River show strong zonal characteristics, rather than local phenomena as pseudogley soils. Secondly, gleying soils are formed under the conditions with down-fold and poor drainage, while the absence of Fe-Mn pedofeatures and presence of the red veins in the VRS indicate well-drained environments. Thirdly, VRS are characteristic of warm-moist southern China, independent of any podzolization.

Therefore, the iron-depletion processes from the white veins differ from the ordinary oxidation-reduction processes by a near complete removal of iron and their wide geographic extents in southern China. These indicate that VRS were developed under specific climate conditions that appear to have not present-day counterparts. Iron-depletion of the white veins indicates abundant rainfall leading to strong percolation of soil water without significant desiccations. Otherwise, Fe-Mn features would form. The terrace topography and the alluvial sandy-gravel parent materials, such as the conditions at Bose and Xuancheng are favorable to drainage, leading to the formation of the white veins. This provides a reasonable explanation on why VRS usually developed on well-drained parent materials. The white veins symmetrically developed along the large planes, suggesting an important role of the planes in iron-depletion by percolating water.

(3) Stage 3 Formation of juxtaposed textural features. The alternations between the yellow (types B, D) and red clay coatings (types C, E) along the walls of the planes in the white veins show that the VRS experienced several illuvial stages posterior to the formation of the white veins. Those red clay coatings were typical of warm-moist climates in tropical and subtropical zones[25,26], while the yellow ones are typical of temperate zones[16,27]. The alternations between these two kinds of clay coatings are attributable to warmer-cooler changes of climate in southern China after the formation of the white veins. These latter processes have not modified the vermiculated characteristics of the VRS. Although clay coatings are formed under relatively humid climate, the conditions, under which the red clay coatings described above were formed, should be significantly less humid than for the white veins.

The greater thickness and more abundant white veins in the VRS at Bose compared to that at Xuancheng indicate a more humid climate at Bose, as is consistent with the present-day climate pattern. This is also confirmed by the more abundant and better-developed clay coatings at Bose. The clay coatings of type A at Bose are thicker with more clear microlaminations and sharper extinction, also indicating a denser vegetation and more humid climate at Bose. Also, the red veins in the Bose VRS contain more fine particles of iron oxides, indicating a stronger chemical weathering.

2.3 VRS and East Asian monsoon

In comparison with the other pedofeatures in the VRS, the white veins correspond to the most humid climate. Development of the VRS requires two basic conditions: abundant rainfall throughout the year without clear dry season and parent materials with good drainage. The first explains the widely zonal characteristics of the VRS and the second is confirmed by our field survey that VRS is frequently underlain by sandy-gravel materials, no matter what the parent materials of the soil profiles are.

The VRS were developed in the mid-Pleistocene[4,28], correlative with the S4 and S5 soil units in the Loess Plateau region in northern China[4]. The interval from S4 to S5 contains four sub-soil units, S4, S5-1, S5-2 and S5-3[29]. S4 corresponds to MIS 11, S5-1 corresponds to MIS 13, and S5-2 and S5-3 correspond to MIS 15[29]. The S5-1 is the strongest, followed by S4 and S5-3, then S5-2[30]. The paleosol evidence from S4, S5-1 and S5-3 represents the three periods of greatest warmth of the last 1.2 Ma with S5-1 formed during the period of greatest warmth and humidity[30]. We therefore suggest, from a pedo-stratigraphic point of view, that the formation of the white veins within VRS primarily correspond to the S5-1 soil in northern China. However, white veins might also be able to form during the development of S4 and S5-3.

The lack of real dry seasons, as reflected by the white veins, indicates abundant rainfalls throughout the year, even in winter. Because the studied regions are within the East Asian monsoon zone, the VRS unit in southern China indicates an unusual period with extremely strong East Asian summer monsoon. According to the variations of pedogenic intensity recorded in the loess-soil sequences in northern China, this period represents the strongest monsoon intensity of the last 2.6 Ma. The clear climate fluctuations after the formation of the white veins, as reflected by the juxtaposed textural features in the VRS, appear to be consistent with the loess records in northern China. However, the pedogenic features resulting from different stages overlapped in the same soil profiles, such that their environmental significance is difficult to be resolved separately.

This mid-Pleistocene monsoon extreme documented by the VRS in southern China and the S4, S5 soils in northern China has global significance. Records from Lake Baikal reveal a continuous interglacial diatom assemblage and an apparent lack of extensive mountain glaciation in continental Siberia from MIS 15a to MIS 11, high terrestrial productivity persisting in continental Asia from MIS 15a to MIS 13, and climate contrast between MIS 12 and 11 is also significantly weaker than during more recent glacial-interglacial transitions of the late Pleistocene epoch[31]. Sapropels in the eastern Mediterranean[32] and oxygen isotope record from the equatorial Indian Ocean[33] also showed unusually strong African and Indian monsoons at 528－525 ka. Ice-records from EPICA[34] documented a lower-than-average temperature for the Southern Hemisphere during MIS 13, opposite to the warm extreme reflected by the northern hemispheric soils in China.

What might be the origin of these strong monsoons climate? Prell and kutzbach[35] showed that paleoclimatic records adjacent to India and Africa over the last 150000 years displayed four monsoon maxima which occurred during interglacial conditions and coincided with precession maxima (summer solstice at perihelion) and maxima of northern hemisphere summer radiation. From general circulation model experiments, they concluded that the spatial patterns of climate variables and their zonal and regional averages revealed that under interglacial conditions, increased northern hemisphere solar radiation produced strong East Asian summer monsoon through a larger land-ocean pressure gradient, stronger winds and greater precipitation over southern Asia. It is remarkable that around the peak of MIS11, 13 and 15, such maxima also occur. For example for these three MIS, at 60°N in June, insolation is 34, 48 and 55 Wm-2 above the present-day value of 476 Wn-2[36]. Does it mean that the conclusion of Prell and Kutzbach offering an astronomical origin to the strong monsoon in East Asia may be extrapolated to the interglacials MIS 11 to MIS 15? Apparently not.

Deep sea records[37] reveal indeed that MIS 13 and 15 are more glaciated than the following interglacials MIS 11 to 1. Moreover, ice-records from EPICA[34] document a lower-than-average temperature for the Southern Hemisphere during these interglacials, opposite to the warm extreme reflected by the northern hemispheric soils in China. The CO_2 concentration during MIS 13 and MIS 15 is also lower than during the other interglacials[38]. Actually, the amplitude of the glacial-interglacial cycles is significantly reduced before MIS 11 in all these cores with cool interglacials and cold glacials. The great warmth and humidity of the white veins, S4, S5-1 and S5-3 soils cannot therefore be easily related to global ice-volume variations as they appear to be exceptional, especially S5-1, whereas the interglacials are on the contrary much less pronounced. Although it remains to demonstrate from modeling experiments whether insolation changes can trigger a so intense East Asian monsoon during MIS 11, 13 and 15, Guo et al.[30] suggested that other factors, as the ocean circulation, might have operated during the formation of S4, S5-1 and S5-3 soils. This kind of climate extreme has indeed clear counterparts in marine δ^{13}C records[39], suggesting possible relationships with the strength of deep water (NADW) production in the North Atlantic[40,41]. Moreover, the cooler MIS13 in the Southern Hemisphere, as evidenced by the EPICA records[34], supports our explanation by the NADW strength. Stronger NADW would bring more heat from the equator and the Southern Hemisphere to the Northern Hemisphere, leading to a cooler Southern Hemisphere and a warmer Northern Hemisphere[42]. A warmer Northern Hemisphere would possibly lead to stronger monsoons.

3 Conclusions

In this study, the soil-forming processes and environmental significance of the vermiculated red soils (VRS) at Bose and Xuancheng were addressed based on micromorphological, mineralogical and chemical approaches. The results indicate three major forming-stages of the VRS, i.e. formation of a red soil matrix, development of the white veins due to iron depletion, and formation of the juxtaposed latter textural features due to alternating temperate-subtropical soil-forming processes. Formation of the white veins is crucial for the vermiculated characteristics of the VRS.

The white veins represent a strength extreme of the East Asian summer monsoon. During the formation of the VRS, the vast regions south of the Yangtze River were under the control of summer monsoon throughout the year. The wide spread geographic characteristics of the VRS are mainly attributable to this specific climate interval. However, good drainage of the parent materials is also necessary for VRS development.

According to the available chronology, pedo-stratigraphy and climato-stratigraphy data, the VRS in southern China are timely correlative with the S4 and S5 soils in the Loess Plateau region. Formation of the white veins in the VRS should primarily correlate with the development of S5-1 in northern China loess and a climate extreme would be closely linked with the changes in the strength of NADW.

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References

1. Xie, S. C., Lai, X. L., Yi, Y. *et al*., Molecular fossils in a Pleistocene river terrace in southern China related to paleoclimate variation, Organic Geochemistry, 2003, 34: 789－797.
2. Xu, X., The discussion about the vermiculated soil layer in the middle-lower reaches of the Yangtze River, in Quaternary Glaciers and Quaternary Geology Corpus (No.1) (eds. Committee of Quaternary Glaciers and Quaternary Geology, Chinese Geology Union) (in Chinese), Beijing: Geological Publishing House, 1984, 104－112.
3. Jiang, F. C., Wu, X. H., Xiao, H. G. *et al*., Age of the vermiculated red soil in Jiujiang area, central China, Journal of Geomechanics (in Chinese), 1997, 3(4): 27－32.
4. Qiao, Y. S., Guo, Z. T., Hao, Q. Z. *et al*., Loess-soil sequences in Southern Anhui Province: Magnetostratigraphy and paleoclimatic significance, Chinese Science Bulletin, 2003, 48(13): 1465－1469.
5. Yang, H., Zhao, Q. G., Li, X. P. *et al*., ESR dating of eolian sediment and red earth series from Xuancheng profile in Anhui province, Acta Pedologica Sinica (in Chinese), 1996, 33(3): 293－300.
6. Hou, Y. M., Richard, P., Yuan, B. Y. *et al*., Mid-Pleistocene Acheulean-like stone technology of the Bose basin, south China, Science, 2000, 287: 1622－1625.
7. Peng, B. Z., Zhao, P. H., Li, C. H. *et al*., The preliminary study on the relationship between the palaeosols and tectonic movement in the regions of Lushan, in Discussion Corpus of Chinese Quaternary Glaciers (eds. Glacier and Frozen Earth Division of Chinese Geography Union, Institute of Glacier and Frozen Earth, Chinese Academy of Sciences) (in Chinese), Beijing: Science Press, 1985, 158－160.
8. Xi, C. F., Some problems about Chinese red weathering crusts, Quaternria Sinica (in Chinese), 1965, 4(2): 42－54.
9. Xi, C. F., On the red weathering crusts of Southern China, Quaternary Sciences (in Chinese), 1991, 1: 1－7.
10. Zhu, J. J., Genesis and research significance of the plinthic horizon, Geographical Research (in Chinese), 1988, 17(4): 12－20.
11. Li, Y. Y., The discussion on the forming cause of the white veins in the quaternary vermiculated red soils in South China, Geological Review (in Chinese), 1965, 23(2): 144－145.
12. Xie, Y. Y., Wu, S. A., Preliminary studies of the quaternary sedimentary environment in Jiujiang-Lushan regions, in Geography Collections (No.13) (eds. Institute of Geography, Chinese Academy of sciences) (in Chinese), Beijing: Science Press, 1981, 106－132.
13. Xiong, S. F., Ding, Z. L., Liu, T. S., The worm-shaped veins in the red earth of South China-pedological evidence for root traces of past forest, Chinese Science Bulletin, 2000, 45(19): 1800－1804.

14. Yang, D. Y., Li, X. S., Lu, H. Y. *et al*., Loess in Xuancheng prefecture of Anhui Province and palaeolithic culture, Journal of Geomechanics (in Chinese), 1997, 3(4): 85—89.
15. Huang, W. W., Evidence for early man's activities from the lateritic beds of south China, Quaternary Sciences (in Chinese), 1991, 4: 373—379.
16. Fedoroff, N., Clay illuviation in red Mediterranean soils, Catena, 1997, 28: 171—189.
17. Kemp, R. A., Micromorphology of loess-paleosol sequences: A record of paleoenvironmental change, Catena, 1999, 35: 179—196.
18. Mccarthy, P. J., Martini, I. P., Leckie, D. A., Use of micromorphology for palaeoenvironmental interpretation of complex alluvial palaeosols: An example from the Mill Creek Formation (Albian), southweatern Alberta, Canada, Palaeogeography, Palaeoclimatology, Palaeoecology, 1998, 143: 87—110.
19. Srivastava, P., Parkash, B., Polygenetic soils of the North-Central part of the Gangetic plains: A micromorphological approach, Catena, 2002, 46: 243—259.
20. Bullock, P., Fedoroff, N., Jongerius, A. et al., Handbook for Soil Thin Section Description, England: Waine Research Publication, 1985, 1—152.
21. Xu, J. Q., Jiang, M. Y., Yu, S. F. *et al*., The minerals of the tropical and sub-tropical soils in south China, in Collection of Chinese Red Soils (eds. Li, Q. K.) (in Chinese), Beijing: Science Press, 1983, 41—73.
22. Xiong, Y., Li, Q. K., Chinese Soils (in Chinese), Beijing: Science Press, 1987, 39—84.
23. Chinese Soil Survey Office, Chinese Soils (in Chinese), Beijing: Chinese Agricultural Press, 1998, 164.
24. Zhu, H. J., He, Y. G., Soil Geography (in Chinese), Beijing: Higher Education Press, 1992, 90—131.
25. Fedoroff, N., Rodriguez, A., Micromorphologie des sols rouges de Tenerife et de La Palma (Iles Canaries), Comparaison avec les sols rouges méditerranéens, in Micromorfologia de Suelos (eds. Delgado M.), Espana: Granada, 1978, 887—928.
26. Cremaschi, M., Paleosols and Vetusols in the Central Po Plain (Northern Italy)—A Study in Quaternary Geology and Soil Development, Milano: Edizioni Unicopli, 1987, 306.
27. Kemp, R. A., Genesis and environmental significance of a buried middle Pleistocene soil in eastern England, Geoderma, 1987, 41: 49—77.
28. Zhao, Q. G., Yang, H., A preliminary study on red earth and changes of quaternary environment in south China, Quaternary Sciences (in Chinese), 1995, 2: 107—116.
29. Liu, T. S., Loess and Environment (in Chinese), Beijing: Science Press, 1985, 347.
30. Guo, Z. T., Liu, T. S., Fedoroff, N. *et al*., Climate extremes in Loess of China coupled with the strengh of deep-water formation in the North Atlantic, Global and Planetary Change, 1998, 18: 113—128.
31. Alexander, A., Douglas, P., Williams, F. *et al*., Muted climate variations in continental Siberia during the mid-Pleistocene epoch, Nature, 2002, 418: 65—68.
32. Rossignol-Strike, M., Paterne, M., Bassinot, F. C. *et al*., An unusual mid-Pleistocene monsoon period over Africa and Asia, Nature, 1998, 392: 269—272.
33. Bassinot, F. C., Labeyrite, L. D., Vincent, E. *et al*., The astronomical theory of climate and the age of the Brunhes-Matuyama magnetic reversal, Earth and Planetary Science Letters, 1994, 126: 91—108.
34. EPICA community members, Eight glacial cycles from an Antarctic ice core, Nature, 2004, 429: 623—628.
35. Prell, W. L., Kutzbach, J. E., Monsoon variability over the past 150000 years, J. Geophys. Res., 1987, 92: 8411—8425.
36. Berger, A., Long-term variations of daily insolation and Quaternary climatic changes, Journal of Atmospheric Science, 1978, 35(12): 2362—2367.
37. Imbrie, J., Hays, J. D., Martinson, D. J. *et al*., The orbital theory of Pleistocene climate: Support from a revised chronology of the marine $\delta^{18}O$ record, in Milankovitch and Climate, Part 1 (eds. Berger, A., Imbrie, J., Hays, J. D. *et al*.), D. Reidel, Dordrecht, 1984, 269—305.
38. Wolff, E., Kull, C., Chappellaz, J. *et al*., Modelling past atmospheric CO_2: Results of a challenge, EOS, 2005, 86 (38): 341—345.
39. Raymo, M. E., Ruddiman, W. F., Shackleton, N. J. *et al*., Evolution of Atlantic-Pacific $\delta^{13}C$ gradients over the last 2.5 m.y., Earth and Planetary Science Letters, 1990, 97: 353—368.
40. Boyle, E. A., The role of vertical chemical fractionation in controlling late Quaternary atmospheric carbon dioxide, J. Geophys. Res., 1988, 93: 15701—15714.
41. Duplessy, J. C., Shackleton, N. J., Fairbanks, R. G. *et al*., Deep water source variations during the last climatic cycle and their impact on the global deep-water circulation, Paleoceanography, 1988, 3: 343—360.
42. Broecker, W. S., The great ocean conveyor, Oceanography, 1991, 4: 79—89.

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