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Aeolian origin of the red earth in southeast China

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ABSTRACT: A clay-like deposit known as 'red earth' is widely distributed over the terraces and high lands of the Yangtze River valley in southeast China. Its typical pedo-stratigraphical features have attracted the interest of pedologists and geologists for many years, although its origin is still debated. Here we report an analyses of the grain-size distributions, rare-earth element (REE) patterns and upper continental crust (UCC)-normalised major elemental composition of the red earth and compare them with those of the loess and other aeolian deposits in northern China. The results show that the red earth in southeast China has two or three end-member grain-size distributions, similar to the sedimentary characteristics and geochemical composition of aeolian deposits found in northern China. Together with other evidence from field observations, these results suggest that the red earth is probably of aeolian origin. On the basis of these data, we suggest that thick aeolian dusts were also deposited in the wet subtropics and that the effect of the winter monsoonal winds upon the dust transport in eastern China was more important than previously believed. Copyright © 2002 John Wiley & Sons, Ltd.

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KEYWORDS: red earth; southeast China; grain-size distribution; REE pattern.

Introduction

China is a typical monsoon-influenced region (Ding, 1994). The summer monsoon (southeastern monsoon) brings abundant moisture and heat to the continent (Chen *et al.*, 1991; Ding, 1994), and the winter monsoon (northwest monsoon) entrains and transports large volumes of dust, carrying it to east and south China and beyond (Liu *et al.*, 1982). The aeolian dust deposited on the continent thus provides a basis for the reconstruction of palaeo-wind regimes and palaeoclimates in China.

Aeolian deposits are widely distributed in China (Liu *et al.*, 1965, 1985). In the north of the country, the typical aeolian deposits have been studied extensively in the past two decades (Liu *et al.*, 1985; Kukla and An, 1989; An *et al.*, 1991; Rutter *et al.*, 1991; Ding *et al.*, 1992, 1994; Liu and Ding, 1998). Much palaeoclimatic information has been gathered by geophysical and geochemical analyses of the loess (Heller and Liu, 1982; Liu *et al.*, 1987; Kukla *et al.*, 1988; Zhou *et al.*, 1990; Ding *et al.*, 1992, 1994, 1995; Porter and An, 1995; Xiao *et al.*, 1995; Gu *et al.*, 1997; Guo *et al.*, 2000). Recently, the view that the so-called 'Red Clay', which occurs beneath the Wucheng Loess Formation, may be of aeolian origin (Liu *et al.*, 1988; Zhao, 1989; Ding *et al.*, 1998a; Lu *et al.*, 2001) has attracted some attention, resulting in valuable new grounds for understanding Cenozoic climate changes across China (Ding *et al.*, 1998a, b, 1999; Sun *et al.*, 1998a, b; An *et al.*, 2001).

In southern China, fewer studies of aeolian deposits have been reported. A clay-like deposit, known as red earth (de Chardin *et al.*, 1935; Xiong, 1944; Lee, 1975; Gong, 1983; Xi, 1991; Zhu, 1993; Zhao and Yang, 1995; Liu and Gong, 2000; Lu *et al.*, 2000; Xiong *et al.*, 2000, 2001), distributed widely over the terraces and high lands in the Yangtze River valley, has attracted the interest of pedologists and geologists for many years. This pedo-stratigraphical unit formed in southeast China, and contains one of the few records that can be used for the reconstruction of Quaternary environments. However, its origin is still debated (Zhu, 1993; Zhao and Yang, 1995). Traditionally, the red earth was believed to be a fluvial and/or eluvial deposit, but this judgment was based mainly on reworked red earth sections. A few recent studies have suggested that some red earth sequences are aeolian in origin (Yang *et al.*, 1991; Zhao and Yang, 1995; Li *et al.*, 1997, 2001; Xiong *et al.*, 1999), although there is no systematic evidence at present to support this suggestion.

The goal of this study is to compare the red earth in southeast China with the loess and other aeolian deposits in northern China in terms of sedimentary and geochemical characteristics, with the aim of improving our understanding of the origin of the red earth. The preliminary results indicate that the red earth has some properties that are consistent with an aeolian origin.

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Geological setting and stratigraphy

The red earth mainly occurs in the middle reaches of the Yangtze River valley (Xiong, 1944; Zhao and Yang, 1995) and the upper part of the Pearl River valley (de Chardin *et al.*, 1935), including the Jiangxi, Hunan, Hubei and Anhui provinces and Guangxi Zhuang Autonomous Region. This area is now situated in the wet subtropical monsoon climatic zone, with a mean annual precipitation of 1000 to 1600 mm, and mean annual temperatures of 16–18 °C. In most cases, the red earth covers the surface of Tertiary peneplains and terraces along the Yangtze River and its tributaries (Figs 1 and 2). In the Xiangjiang River valley (Xiangtan site), the red earth mantles the second through to the fourth or fifth terraces (Fig. 2). In the Jiujiang and Taihe sites, typical red earth deposits are found on the second and third terraces, there being only a brown silt deposit commonly found in the upper part of the red earth sections on the first terrace (Fig. 2).

A red earth sequence commonly consists of two pedostratigraphical units and can be subdivided into more pedogenic beds (Table 1 and Fig. 3). The lower part is a red clay layer (the typical red earth) with white and/or brown root traces, commonly about 6–12 m thick. This unit developed on clay to silty clay and is red in colour (Munsell 5YR 4/8 to 10R 3/6). In general, it exhibits a moderately developed medium subangular blocky structure with no variations evident along the sections. There are abundant clay and Fe–Mn films but no ferruginous nodules in this unit. The upper unit, a brown silt layer, is about 2–6 m thick. It has a strong brown colour ranging from 7.5YR 4/6 to 7.5YR 4/8 and always exhibits a weak coarse subangular blocky structure and no primary stratification. Few to common clay films and root traces are found in this unit. The transition between the lower unit and

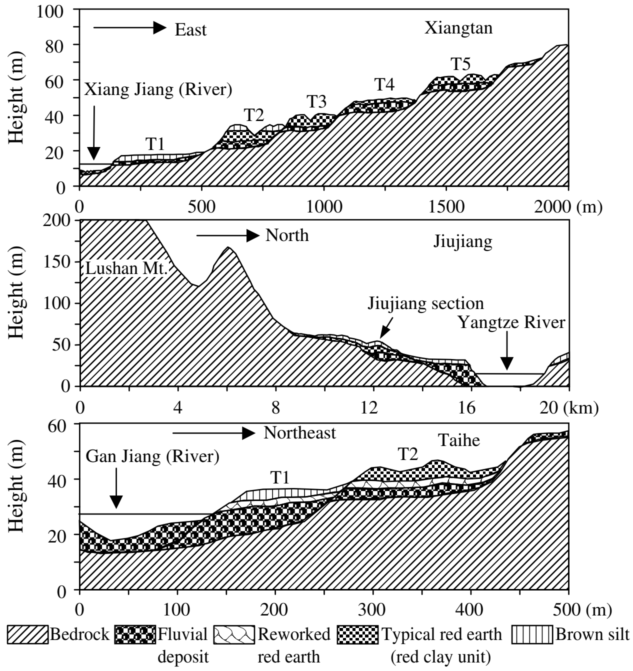


Figure 2 Terraces mantled by red earth deposits along the Yangtze River and its tributaries

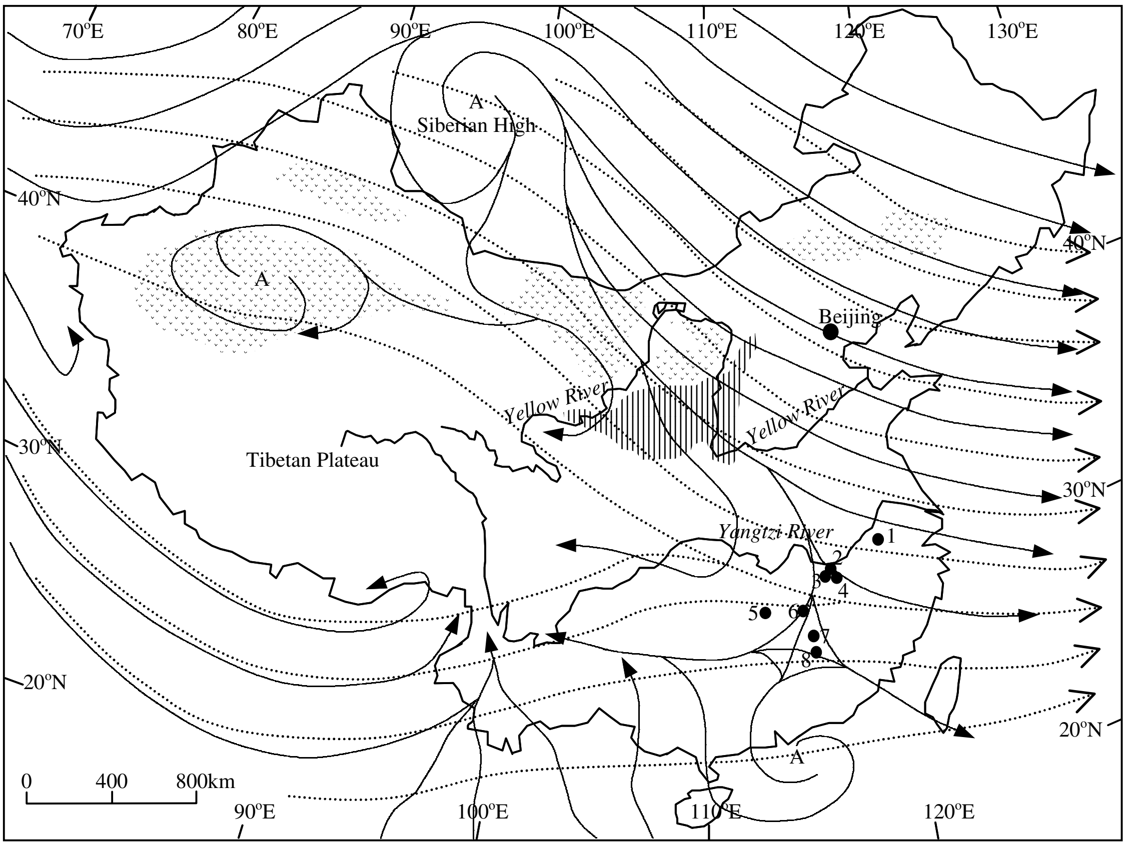


Figure 1 Location of the red earth sections (1, Xuancheng; 2, Jiujiang; 3, Lushan; 4, Xingzi; 5, Xiangtan; 6, Yichun; 7, Taihe; 8, Ganzhou) in southeast China. The solid and dotted arrows indicate the wind streamlines at the 1500 m level and at 3000 m level during January, respectively (after Ye and Gao, 1988, with permission). A: anticyclonic circulation. Winds driven by the Siberian High are responsible for the transporting of the dust from northern China to the localities in which the red earth was deposited. The areas with dots indicate deserts, and the area with vertical lines is the Loess Plateau

Table 1 Macromorphological features of the red earth sections in southeast China

Section	Unit	Depth (cm)	Texture[a]	Matrix	Mottles[b]	Structure[c]	Coating[b,d]	Root traces[b]	Lower boundary[e]
Jiujiang	Brown silt	0–186	Sc	7.5YR 4/6	f	1, c, sbk	f	f	g
		186–310	Sc	5YR 4/8	f	2, m, sbk	f, cl	f	c
		310–440	Sc	7.5YR 4/4	c-m, 2, 7.5YR 3/1	2, m, c, pr, sbk	f, c, cl	f	g
		440–649	Sc	7.5YR 4/6	c, 3, 7.5YR 3/1	c, sbk	f	f	g
	Red clay	649–736	Sc	5YR 4/8	c, 3, 5YR 3/1	2, m, sbk	c, m, 5YR4/4, cl	c	g
		736–919	Cs	10R 4/8	c, 3, 7.5YR 5/8	2, m, sbk	m, 10YR4/4, cl, fe	a	g
		919–1129	Cs	10R 4/6	c, 3, 5YR 7/6	2, m, sbk	a, 10R3/4, cl, fm	a	g
		1129–1558	Cs	10R 3/6	c,3, 10YR 7/1	2, m, sbk	a, 10R4/3, fm, cl	a	a
Xuancheng	Brown silt	0–36	Sc	7.5YR 4/6		1, f, gr		c	d
		36–81	Sc	7.5YR 4/8		2, c, m, sbk	c, 5YR 5/4, cl	c	g
		81–126	Sc	5YR 3/6	c, 2, 2.5YR 2/1	2, c-m, sbk	m, 2.5YR 4/3, cl	f	g
		126–153	Sc	7.5YR 4/6		1, f-m, gr		f	g
	Red clay	153–396	Sc	5YR 4/8	c,3, 2.5 YR 2/1	2, f-m, sbk	m, 2.5YR 3/6	f	g
		396–432	C	2.5YR 4/8		1-2, m, sbk	c, 7.5YR4/4, cl	f	d
		432–495	Sc	2.5YR 4/6	c, 3, 2.5YR 2/1	2-3, f-m, sbk	c, 5YR4/6, cl	f	g
		495–567	Sc	5YR 4/8		2, m, sbk	c, 2.5YR 3/6, cl-fe	f	g
		567–639	Sc	5YR 4/8		2, c-vc, sbk	c, 2.5YR 3/6, cl, fe	c	c
		639–738	Sc	7.5YR 4/6		1, m-c, abk		c	c
		738–837	Sc	2.5YR 4/6	c,3, 2.5YR 2/1	1-2, c, sbk	c, 2.5YR 4/8, cl, fe	c	c
		837–936	Sc	7.5YR 5/6	c, 3, 2.5YR 4/4	1, c, abk		c	c
		936–1032	C	2.5YR 4/6		2-3, f-m, sbk	c, 2.5YR3/3,cl,fe	c	g
		1032–1068	C	2.5YR 4/6		1, c, abk-sbk	c, 2.5YR 3/3, fe	c	c

[a] c = clay; s = silt.
[b] f = few; c = common; m = many; a = abundant; 1 = fine; 2 = medium; 3 = coarse; f = faint; d = distinct; p = prominent.
[c] 0 = structureless; 1 = weak; 2 = moderate; 3 = strong; vf = very fine; f = fine; m = medium; c = coarse; pr = prismatic; gr = granular; abk = angular blocky; sbk = subangular blocky.
[d] cl = clay coating; fe = Fe oxide coating; mn = Mn oxide coating; fm = Fe oxide and Mn oxide coating.
[e] a = abrupt; c = clear; g = gradual; d = diffuse.

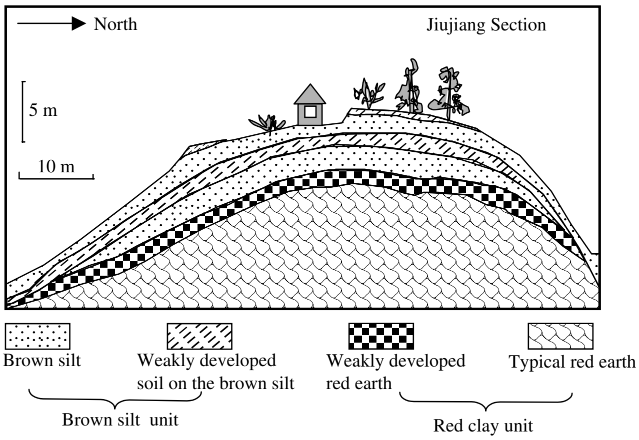


Figure 3 The Jiujiang section exposed by a recent roadcut

the upper unit is apparently discontinuous, probably reflecting interruption by erosional events (Fig. 3). The upper unit has been completely removed by erosion in some areas.

The age of the red earth has not been clearly determined. Some magneto-stratigraphical studies have shown that the upper part is of a normal polarity, whereas the lower part displays reversed polarity (He *et al.*, 1992). Electron spin resonance (ESR) age estimates for a 12-m-thick red earth show that the base of the section in Anhui Province was deposited about 0.82 Ma ago (Zhao and Yang, 1995). Many palaeolithic artefacts have been recovered from red earth sections in Hunan, Anhui Province and Guangxi Zhuang Autonomous Region (Hou *et al.*, 2000). An age estimate from tektites in the Bose section in Guangxi revealed that the red earth (reticular mottled red clay) may be as old as 0.8 Ma (Hou *et al.*, 2000), suggesting that it was deposited in the middle to late Pleistocene.

Analysis and results

For this study, eight red earth sections were investigated and sampled (Fig. 1). Analyses of the grain-size distribution, magnetic susceptibility, rare-earth elements (REE) and major elemental concentrations were conducted.

The grain-size distribution was determined with a Malvern Mastersizer laser particle analyser after ultrasonic treatment, and for the loess and red clay samples, a pretreated method (Lu *et al.*, 2001) was used to remove the organic matter and carbonate. Magnetic susceptibility was measured with a Bartington MS2 susceptibility meter. Major elemental composition was obtained by ICP-9000 after treatment with acid. The REE and trace element abundances were measured by Inductively coupled plasma-mass spectrometer (ICP-MS) with indium (In) as an internal standard. The samples were digested with a $(HF + HClO_4 + HNO_3)$ acid solution. The analytical precision is about 10% for replicate analysis of reference samples. The REE results are normalised to chondrite (Masuda *et al.*, 1973), and the major element concentrations are normalized by average upper continental crust (UCC) concentration (Taylor and McLennan, 1985).

Grain-size distribution

The grain-size distribution of seven red earth sections was determined at 5-cm intervals. The grain size in these sections

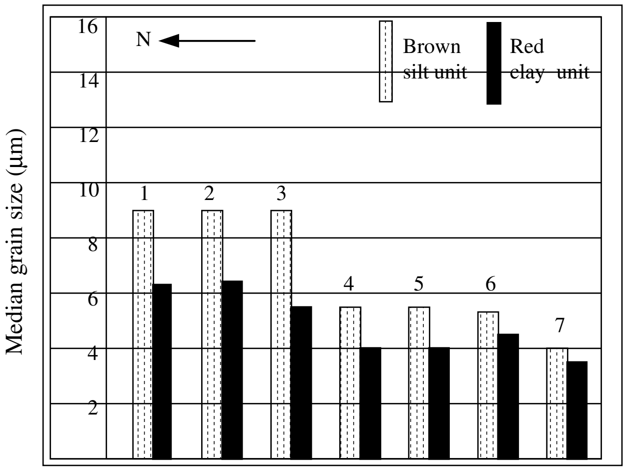


Figure 4 Spatial variations in average ($n = 50$) median grain size of the red earth in southeast China (1, Xuancheng; 2, Jiujiang; 3, Xingzi; 4, Xiangtan; 5, Yichun; 6, Taihe; 7, Ganzhou)

shows broadly consistent trends over a broad area. The average median grain size (M_d) for the brown silt unit decreased from 8.5 μm in the north (Xuancheng) to 4 μm in the south (Ganzhou), whereas the red earth unit median grain size decreased from 6.5 μm to 4 μm (Fig. 4).

The sequential variations in median grain size and magnetic susceptibility of the Jiujiang, Lushan and Xuancheng red earth sections are illustrated in Fig. 5. The magnetic susceptibility of these three sections shows some similarities in both long-term trends and short-term variability. This may imply that the magnetic susceptibility records of the red earth sections can be used as a stratigraphical correlation tool as in some loess sections. The M_d for the entire sequence ranges from 5 to 10 μm, and is much finer than the loess deposits in the clay loess zone (<15 μm) of the Loess Plateau (Liu *et al.*, 1965). The sections also show a down-core shift in the M_d and the percentage coarse fraction (e.g. >63 μm). In the lower part of the section (the red clay unit, i.e. 7–16 m for Jiujiang section, 6–16 m for Lushan section), the M_d ranges from 5 to 7 μm and the coarse fraction (>63 μm) is negligible. In the upper part of the section (the brown silt unit), the M_d is 7–10 μm and the percentage coarse fraction can reach 1–2%. The limited amount of the coarse grain fraction (>63 μm) through the section indicates a very small input of proximal particles in the red earth deposits.

A comparison of the grain size distribution of aeolian deposits from northern China and the red earth from southeast China was undertaken in order to clarify the relationship between the red earth and the loess. The red earth samples commonly display a bimodal or polymodal distribution, with the coarsest mode composed of 8–15.6 μm grains (Fig. 6A and B). The fine mode of 1–2 μm is also apparent in all the red

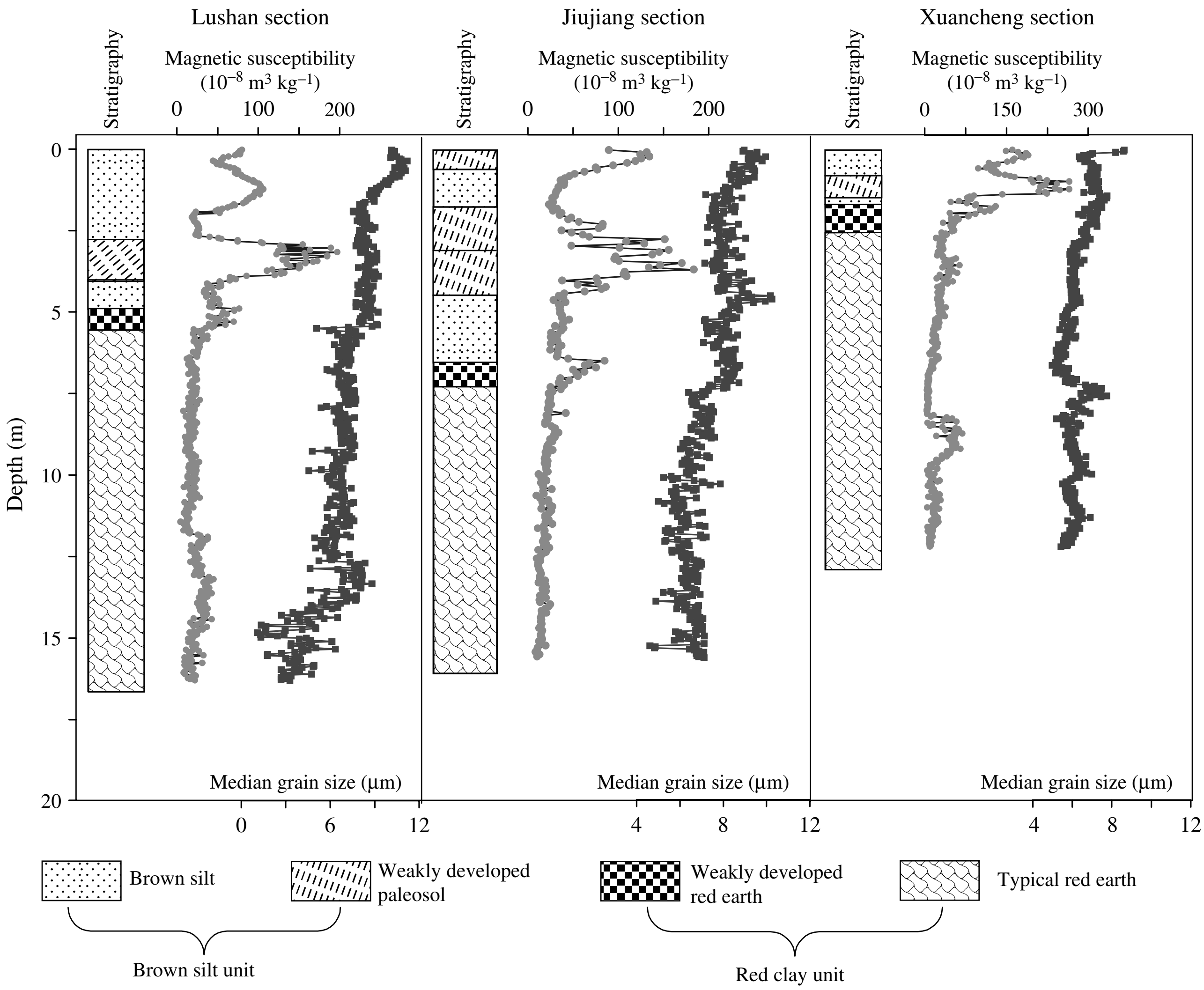


Figure 5 Pedostratigraphy and the variations in grain size and magnetic susceptibility with depth at the Lushan, Jiujiang and Xuancheng sections

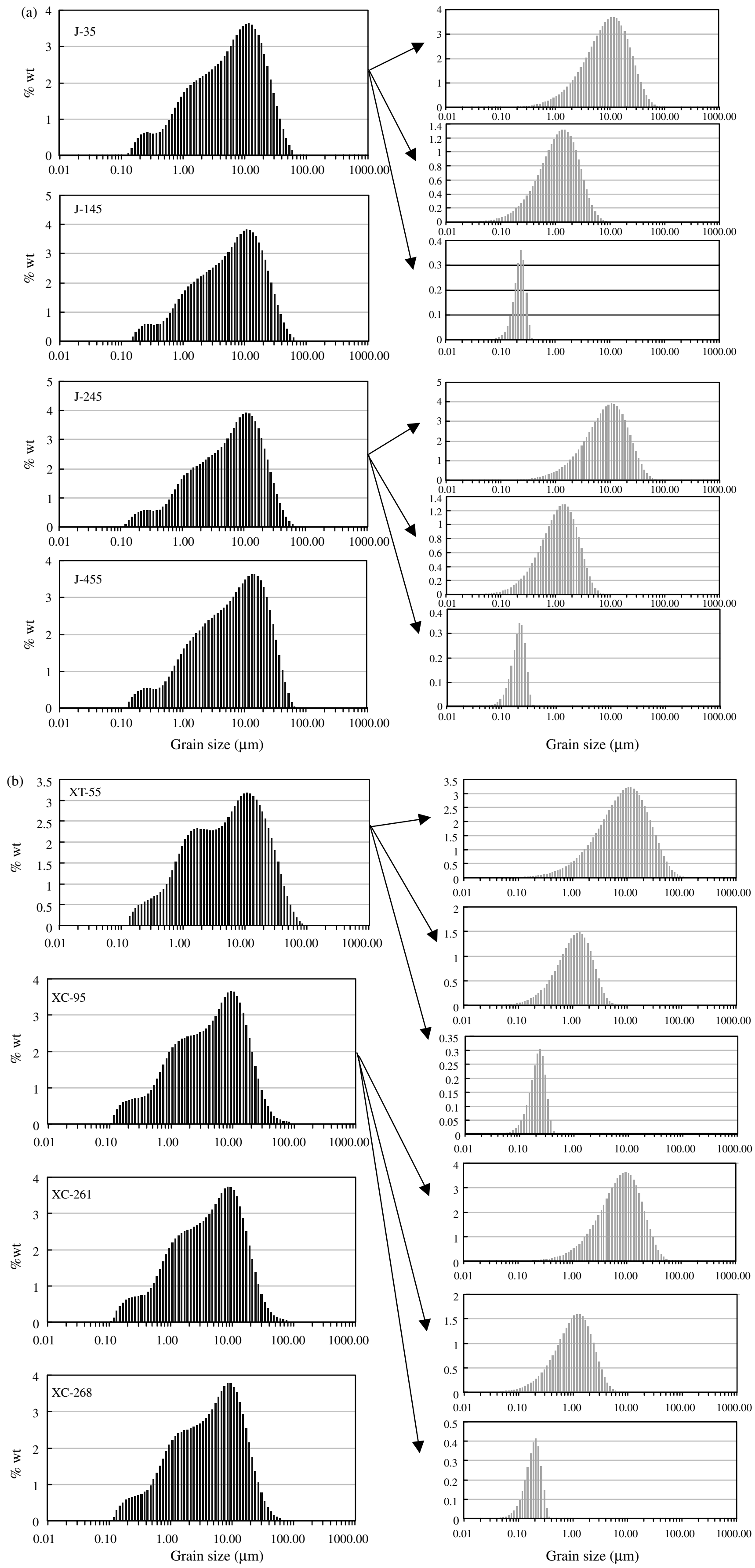
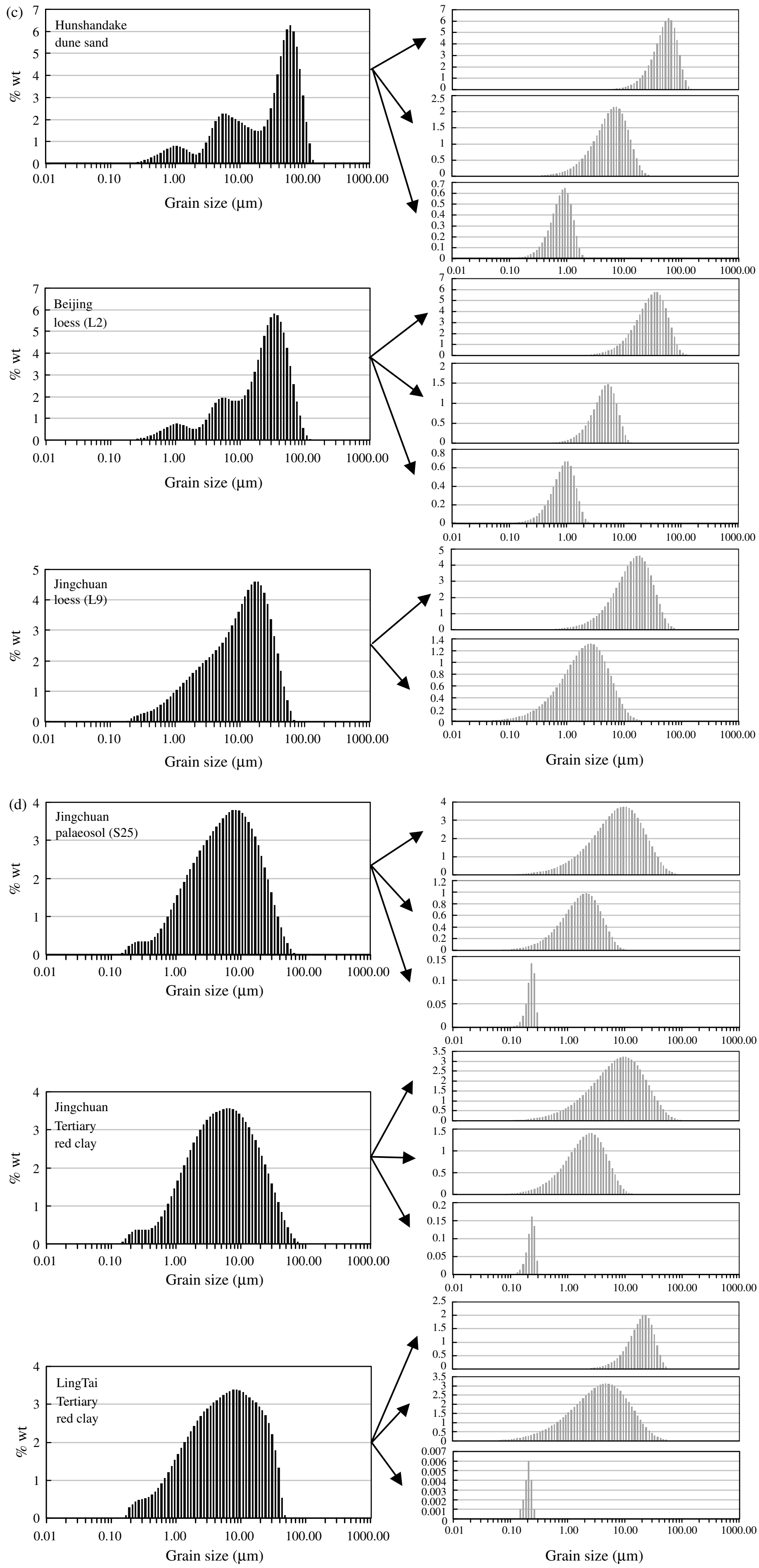


Figure 6 Grain-size distribution (left) and partitioning of end-member distributions (right) for the red earth from southeast China and the loess and other aeolian depostis from northern China. (A) Red earth samples from the Jiujiang section (sample numbers J-35, J-145, J-245 and J-455). (B) Red earth samples from the Xiangtan (sample number XT-55) and Xuancheng sections (sample numbers XC-95, XC-261 and XC-268). (C) Samples of dune sands and loess from northern China. (D) Samples of palaeosols and Tertiary red clays from northern China. (E) Comparison of grain-size distributions between the typical red earth (sample number TH-25) and fluvial reworked red earth samples (sample numbers TH-35, TH-46 and TH-53) from the Taihe section



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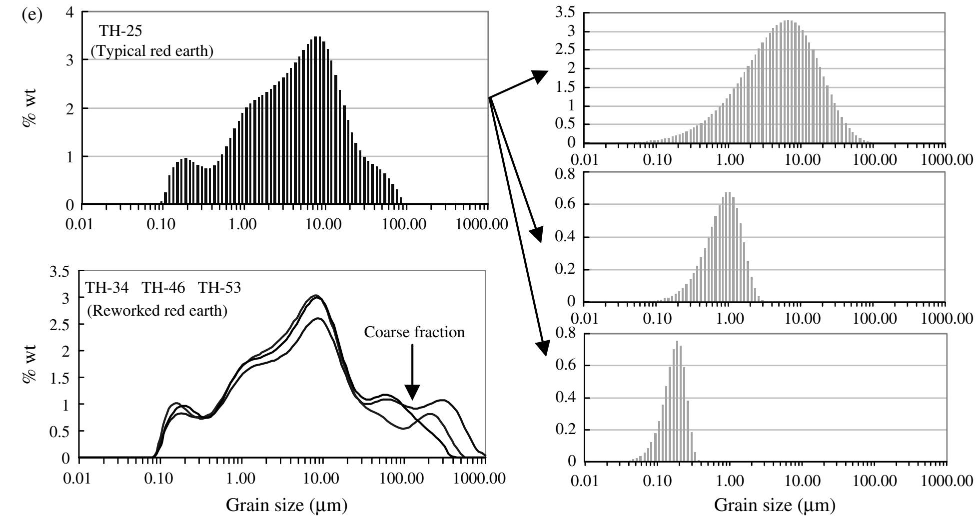

Figure 6 (*Continued*)

earth samples, and a finest mode composed of <0.5 μm grains is present in concentrations of less than 2%. Calculations based on Weibull distribution functions (Sun *et al.*, 2000) show that the grain-size distribution of the red earth can be subdivided into two or three end-member distributions (Fig. 6A and B). This partitioning of grain sizes suggests that distinct processes of transport and weathering are responsible for the grain-size distributions of the red earth. It can be seen that the grain size distributions of the palaeosols and the Tertiary red clay samples from northern China are similar (Fig. 6D). The loess and dune sand samples also can be subdivided into two or three end-members (Fig. 6C). The difference between the red earth and the loess lies in the fact that the finest mode apparent in the red earth is absent in both loess and dune sand.

It is commonly observed that the aeolian dust sampled at continental sites exhibits a markedly bimodal and sometimes polymodal grain-size distribution (Pye, 1987). Recent studies also suggest that the loess and other aeolian deposits in northern China consistently show a bimodal or polymodal grain-size distribution (Sun *et al.*, 2000; Lu *et al.*, 2001). The similarity between grain size distributions of the red earth, the loess–palaeosol series and the Tertiary red clay suggests an origin for the red earth of southeast China very similar to the loess and other aeolian deposits of northern China. It is difficult to examine the origins of each end-member in the grain-size distributions. For the two coarse populations in the red earth samples, the transporting wind systems, e.g. the winter monsoon winds and the westerlies, may have been the controlling factors (Sun *et al.*, 2000). Previous study has shown that for the Malan loess the mode and concentration of the coarsest grain-size component decrease from north to south across the Loess Plateau (Liu *et al.*, 1985; Ding *et al.*, 1995; Sun *et al.*, 2000), suggesting a north–south transport gradient. The fine population with a 2–4 μm mode is similar to the aeolian sediments sampled from the North Pacific (Rea and Hovan, 1995), implying that the westerlies are probably the major transporting agent (Sun *et al.*, 2000). The finest population with a mode <0.5 μm, common in the red earth, is found only in the palaeosols and the Tertiary red clay. This population may be derived from the breakage of soil aggregates (Pye, 1987) and/or weathering after deposition. The relatively low content of the finest population (less than 2%) indicates that weathering has no obvious influence on the grain-size distribution for the red earth and aeolian deposits of northern China.

By comparing the grain-size distributions, typical aeolian red earth samples can be distinguished from other samples derived from the mixing of red earth and fluvial deposits. For example, the fluvially reworked red earth samples in the Taihe section have an apparent coarse fraction >100 μm in addition to the red earth population (Fig. 6E).

REE patterns and UCC-normalised plots

Previous studies have shown that the mineral composition of the red earth in southeast China is similar to the north China loess (Luo, 1990; Yuan and Gong, 1990) with an occasional appearance of some unstable minerals including biotite, hornblende and augite. To confirm this suggestion, the REE and major element composition of the red earth samples from Jiujiang section were analysed. As shown in Fig. 7, all REE patterns for the red earth are similar to those characteristic of bulk continental crust (Taylor and McLennan, 1985), with enriched LREE and consistent negative Eu anomalies. These features are similar to the published results for the north China loess and Tertiary red clay (Ding *et al.*, 1998a; Gallet *et al.*, 1998). The average Eu* ratios (Eu/Eu*) of these red earth samples is 0.6119, within the range for loess (0.6–0.8) (Gallet *et al.*, 1998). The results also display a variation in absolute abundance of REE within the section. For example, in the upper part of the section (the brown silt unit), the concentration of ΣREE is 151.6 ppm, whereas in the lower part it decreases to 75.26 ppm. This depletion in absolute abundance of REE is probably a result of weathering.

The UCC-normalised plots for the red earth samples are shown in Fig. 8. Most elements show the UCC distribution, but some display positive or negative anomalies. The negative anomalies for Sr, Na, Ca, Mg, K and U seem to be related to intensive chemical weathering before and after deposition of the red earth. The positive anomalies for Ti can be explained by relative enrichment arising from depletion of other mobile elements.

These features are similar to those of the loess in many regions (Gallet *et al.*, 1998), thus indicating that the red earth also originates from well-mixed and multicyclic sediments. It may have the same source as the loess of northern China.

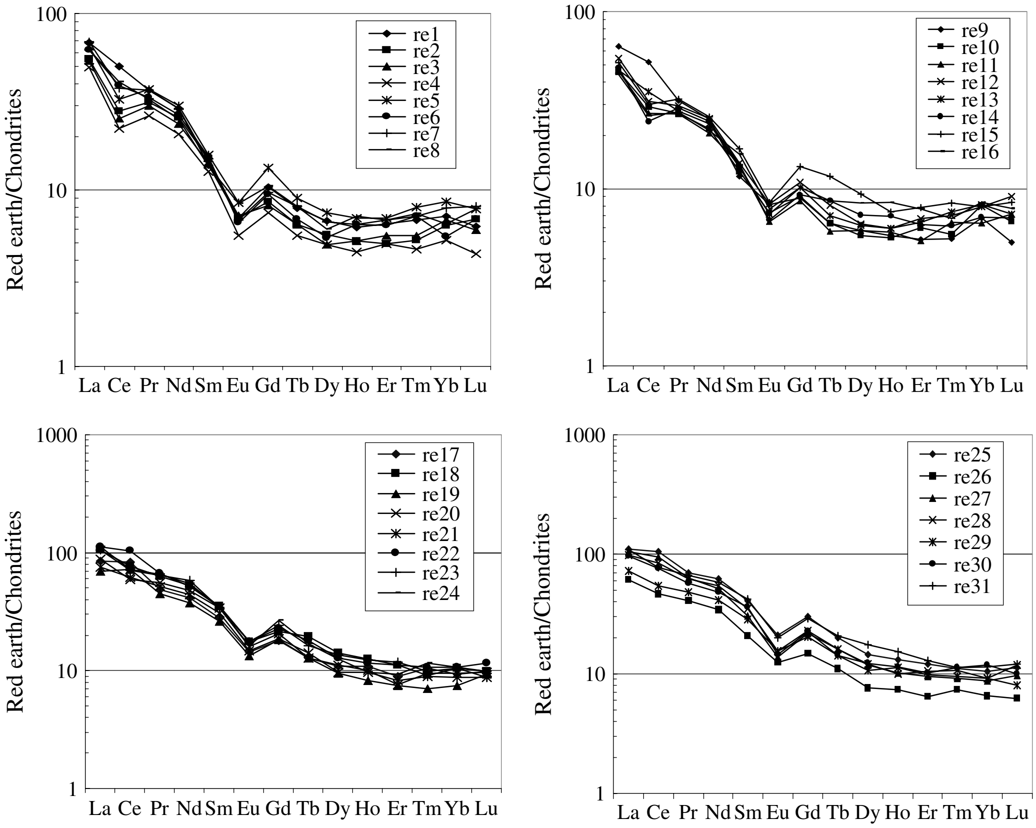

Figure 7 The REE patterns of the red earth in the Jiujiang section

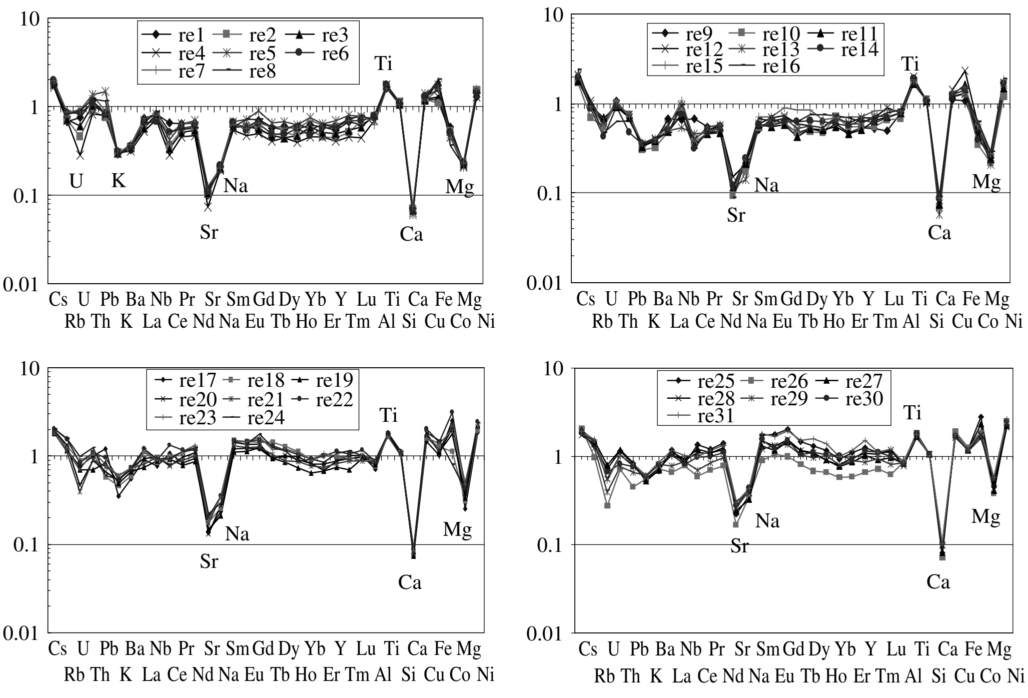

Figure 8 The UCC-normalized plots of the red earth in the Jiujiang section

Discussion and conclusion

From field work and the results described above, the following points emerge.

1 As with the loess deposits in northern China, the red earth covers a variety of relief forms.
2 The grain size of the red earth displays a bimodal or polymodal distribution, similar to the loess–palaeosol and other aeolian deposits across northern China.
3 Most of the red earth sections are unstratified and free of pebble stringers and the typical red earth can be distinguished from the fluvially reworked red earth by comparison of grain-size distributions.

4 The REE patterns and UCC-normalised distributions of the red earth are identical with those of typical north China loess.
5 Modern-day deposition of wind-blown dust derived from northwestern China can be observed in the study area.

These lines of evidence suggest that the red earth in wet subtropical southeast China, as with the north China loess, is of aeolian origin.

It has been shown that the history of dust deposits in China (Ding *et al.*, 1998a, 1999) and in the Pacific Ocean downwind of East Asia (Rea *et al.*, 1998) can be traced back to the Miocene or even earlier. The main agents responsible for transporting dust from source areas to depositional regions are the westerlies and the winter monsoon winds over East Asia (Chen *et al.*, 1991; Ding, 1994). The former is mainly responsible for high-level dust transportation, whereas the latter influences only near-surface dust transport.

Recent studies suggest that before 2.6 Ma the winter monsoon winds were less effective in transporting dust from the deserts to the Loess Plateau, and the westerlies were probably the main transporting agent (Ding *et al.*, 1998a). Global cooling, the onset of extensive glaciation in the Northern Hemisphere and uplift of the Tibetan Plateau (Raymo *et al.*, 1989; Ruddiman, 1997; Shackleton *et al.*, 1995), caused the Siberian High, and thus the winter monsoon winds over East Asia, to strengthen after 2.6 Ma. As pointed out in previous studies, the strengthening of the winter monsoonal winds can be partly traced from down-core variations in loess thickness and grain size in the Loess Plateau (Liu *et al.*, 1985; Ding *et al.*, 1995), and from the stepwise increases in the loess-covered areas in China during the Quaternary (Liu *et al.*, 1985). For example, the Early Pleistocene loess (Wucheng Loess Formation) is found only as a restricted deposit in the valleys of the Jinghe River, Luohe River and in the southwestern part of Shanxi Province. However, the Middle Pleistocene loess (Lishi Loess Formation) extends from Qinghai in the west to Shandong Province in the east, covering an extensive area in northern China. The Late Pleistocene loess (Malan Loess Formation) covers a more extensive area, including the Yangtze River Valley (Nanjing) (Liu *et al.*, 1985). These stepwise extensions in the loess-covered areas are probably related to increases in the aridity of inner Asia (Liu *et al.*, 1985) and/or to the strengthening of the winter monsoonal winds over East Asia.

Evidence from other records also suggests an aridification during the Pliocene–Pleistocene. Pollen data revealed that there is an expansion of the drought-resistant genus and species belonging to Chenopodiaceae, Compositae, Ephedraceae, Tamaricaceae and Zygophyllaceae in northern China (Li, 1991), indicating an intensified arid condition during the Pliocene–Pleistocene. In the Qaidam Basin, the late Pliocene–Pleistocene arid conditions were featured by the thick saline lake deposits (Wang *et al.*, 1999). In the northwest of China, the Pliocene–lower Pleistocene molasse formation (the Xiyu Formation, indicating a relatively humid climate) was replaced by the middle and upper Pleistocene Gobi gravel deposits, which imply the formation of extensive deserts in the northwest basin interiors (Liu *et al.*, 1996). The higher accumulation rates of the loess compared with Tertiary red clay (Ding *et al.*, 1999; An *et al.*, 2001) and the increased fluxes of windborne dust into the central North Pacific (Janecek and Rea, 1983; Rea, 1994) all suggest a trend toward drier climates in the Asian interior.

For the mechanism of the aridification in the Asian interior, uplift experiment results suggest that uplift of the Tibetan Plateau is the main cause (Ruddiman and Kutzbach, 1989; Manabe and Broccoli, 1990; Broccoli and Manabe, 1992, 1997; Kutzbach *et al.*, 1997). Another model result (Ramstein *et al.*, 1997) points out that the retreat of the Paratethys plays as important a role as uplift of the Tibetan Plateau in shifting the central Asian climate from temperate to continental conditions.

The red earth is a widely distributed pedo-sedimentary unit of Middle Pleistocene age in southeast China, adding new evidence in favour of an increase in aridity in the interior of the Asian continent. Several lines of evidence, including the sedimentological and geochemical data described above, suggest a likely aeolian origin. This implies that wind-blown dust deposits may have started to accumulate in southeast China as early as the Middle Pleistocene. Thus these results support the suggestion that there may have been a marked increase in aridity in northern China in the Middle Pleistocene with strengthening winter monsoonal winds becoming increasingly effective in transporting dust from north to south China.

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