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Pleistocene loess in the humid subtropical forest zone of East Asia

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[1] Loess deposits in Asia have been used as indicators of palaeoclimate, because they are usually found bordering deserts. This paper reports extensive and thick deposits of loess in tropical southwest China, between latitudes 18 and 23°30′N, which is 1300 km south of known, and extensively researched loess deposits in north China. The present climate of the reported loess areas is hot and humid, with mean annual rainfall of 1000–2000 mm, and vegetation of subtropical evergreen broadleaf forest. This compares with less than 400 mm rainfall and vegetation of semi-desert steppe, in areas of current loess accumulation on desert margins in north China. The source area of the loess, which is dated by optical luminescence to the late Pleistocene, from 90–222 ka, is thought to be the exposed East Asian Shelf, which was up to 140 m below present sea level during Quaternary arid phases. Recent research on the nature of the shelf environment, and the relatively large particle size of the loess, suggests a local origin. The reported loess is not interbedded with palaeosols, and small amounts of soil cover the loess, compared with well developed soils in loess in semiarid regions in north China. This is explained by elimination of the supply source by sea level rise following each arid phase, as continued dust supply appears necessary for soil to form. This preliminary report of loess in southwest China conflicts with palynological evidence, and suggests that recent reconstructions of Pleistocene aridity in east Asia may be conservative. **Citation:** Nichol, J. E., and D. W. Nichol (2013), Pleistocene loess in the humid subtropical forest zone of East Asia, *Geophys. Res. Lett.*, *40*, doi:10.1002/grl.50426.

1. Introduction

[2] The general consensus that the main sources of dust in Asia are deserts is based on a large body of work analyzing the sedimentological, mineralogical, and geochemical nature of dust deposits in China [*Zhang*, 1984; *Liu et al*., 1985; *Pye and Zhou*, 1989; *An and Porter*, 1997] Tibet [*Lehmkuhl and Haslein*, 2000], and Japan [*Nilson and Lehmkuhl*, 2001]. The main body of loess in Asia is situated between 34 and 43°N on the loess plateau of China (Figure 1), which is semiarid steppe with mean annual rainfall of 100–500 mm [*Gruenert and Lehmkuhl*, 2004], and downwind of extensive sandy and stony deserts (gobi) in northwest China at 40°N [*Liu et al*., 1985, *Zhang et al*., 1999]. Dust is still deposited there today during the outgoing winter monsoon when the climate is relatively cold and dry [*Derbyshire et al*., 1998; *Zhang et al*., 1994, 1999; *Maher et al*., 2003; *Huang et al*., 2003], but becomes incorporated into a modern soil in today's more humid conditions [*Maher et al*., 2003]. In the central and southern parts of the loess plateau the thickness of the loess ranges from 130 to 180 m, and more weathered palaeosols are interbedded with relatively unweathered loess. The loess is assumed to have been deposited during cool glacial periods of the Pleistocene when the climate in north China was arid, with sparse vegetation cover and high dust flux [*Liu et al*., 1995] and the soils to have developed under more humid interglacials. Loess has not previously been reported from humid tropical or subtropical regions, where climatic conditions are vastly different from those under which loess is known to accumulate. Although engineering surveys indicate loess deposits up to 6 m deep at 17°N at Khon Kaen in Thailand [*Phien-wej et al*., 1992], the area is drier, with a tropical savanna climate and long 5 month dry season. Here we report a 9 m deep loess section from south China at 22°N, and loess covering extensive areas of humid subtropical and tropical southwest China and northern Vietnam (Figure 1).

2. Study Area and Methods

[3] The area investigated comprises the lowlands surrounding the Gulf of Tongking, including southern Guangdong and Guangxi, and Hainan provinces of China and northern Vietnam, and extends from 18 to 23°N and 104 to 112°E. The climate is monsoonal, with mild dry winters and hot humid summers. The native subtropical evergreen broadleaf forest has been cleared for nonintensive agriculture, commonly tree crops. The climate becomes less seasonal southward, and parts of Hainan island support humid tropical Dipterocarp forest. Loess-like deposits were observed in areas of red soils and distinctive landscape patterns on satellite images (see Figure S1 in the auxiliary material).

[4] Samples were taken from 19 sites (Figure 1) at approximately 1.5 m below the surface, from fresh vertical facets such as road cuts or quarries, which appeared representative of the general landscape character. The particle size distribution (PSD) was measured by laser diffraction with a Malvern Mastersizer. The samples were first seived (<2 mm). Calcite was removed using 1N HCl acid, then dispersed using sodium hexametaphosphate solution, and stirred for 5 min, with ultrasonication for 30 s. Three to six replicate samples of each loess sample were then subjected to three consecutive 5 s runs at a pump speed of 1800 rpm. The laser diffraction values were transformed to PSD using Mie scattering model, with optical parameters of $RI = 1.52$ and $A = 0.1$.

[5] Additionally, four core samples were taken for dating from a cut at site 135 approximately 35 km south of Nanning on the Upper Pearl River. The section was at 140 m above sea

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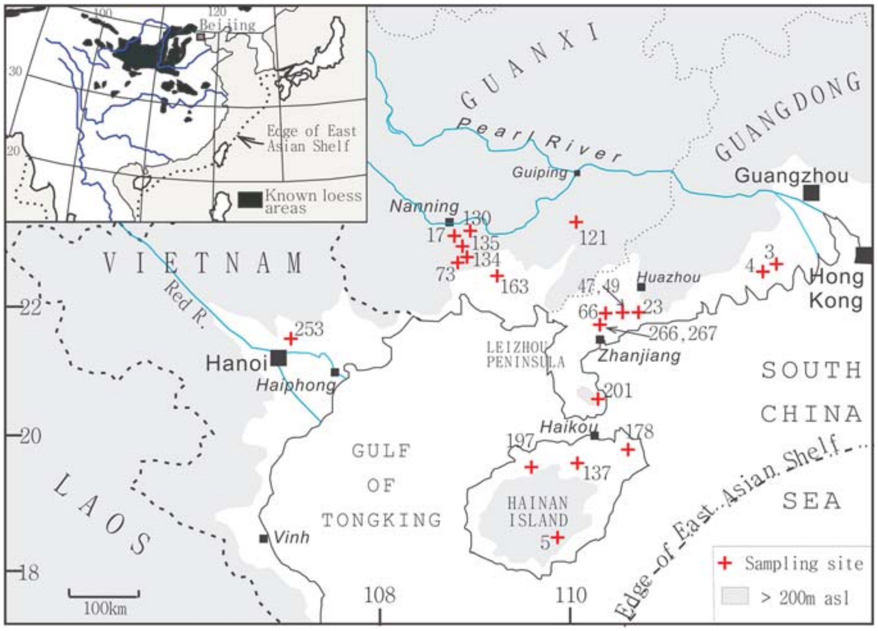

Figure 1. Sampling sites of loess deposits in south China and northern Vietnam. Data and GPS positions for the points are given in Table S1.

level, at the southern end of a low hill approximately 40 m high (Figure 2a). Geological maps and reports indicate that the site is situated near the junction between clastic sedimentary rocks and an inclined carbonate platform of Triassic age outcropping at the surface [*Li*, 1936; *Ma*, 2002; *Liang and Li*, 2005], but with considerable local complexity. The samples were taken from the vertical face of the cut at depths of 1.5, 4, 5.5, and 7 m from the top using a plastic tube inserted into the vertical wall of the cut (Figure 2b). They were then dug out individually and transported in black plastic bags for mineral analysis and dating by Optically Stimulated Luminescence (OSL) at the Research Laboratory for Archaeology and the History of Art, Oxford University. Dates are based on luminescence measurements of sand-sized quartz (90–125 m). All samples were measured in an automated Risø luminescence using a SAR post-IR blue OSL measurement protocol. Dose rate calculations are based on the concentration of radioactive elements (potassium, thorium and uranium (Table S2)) derived from elemental analysis by Inductively Coupled Plasma-Mass Spectrometry/Atomic Emission Spectroscopy. The final OSL age estimates include an additional 2% systematic error to account for uncertainties in source calibration. Dose rate calculations are based on *Aitken* [1985] (Table 1) and the OSL decay curves and dose response curves are given in Figure S2. The contribution of cosmic radiation to the total dose rate was calculated as a function of latitude, altitude, burial depth and average over-burden density based on data by *Prescott and Hutton* [1994].

3. Results

[6] The loess-like deposits were found covering extensive areas of flat or moderately sloping lowlands between 30 and 200 m elevation in Hainan Island, southwest Guangdong and southeast Guangxi provinces of China, and northern Vietnam (Figure 1). The deposits are typically reddish brown (2.5YR5/4) and are friable and porous, with massive structure, and no visible horizons, bedding planes, concretions, or pedogenic features (Figure 2b). Their field appearance satisfies several definitions of loess including "lack of stratification and remarkable ability to stand in vertical slope" [*Pettijohn*, 1957] since road cuts throughout this area are vertical. Sections show remarkable uniformity in color, texture and structure from top to bottom (Figure 2b).

[7] The deposits at most sites appear to be overlying limestone. In almost all sites the landscape forms a series of low hills with relative relief up to 40 m (Figure 2a). Field observations suggest the loess-like deposits occupy the whole thickness of the relief, although a 40 m deep section to verify this impression could not be found. Satellite images show a distinctively patterned landscape (Figure S1) similar in scale and ground plan to the rugged polygonal karst reported by *Sweeting* [1995] from north China, with polygon diameters of ~500–600 m. The patterning suggests an early phase of polygonal karst development which according to Sweeting requires a soft cover of soil or soft rock to retard surface water. Because karst has low soil forming capability, the presence of these landforms suggests an external aeolian origin, as the widespread distribution over the landscape would contra-indicate a fluvial source.

[8] The four dates for section 135 are in stratigraphic order from top to bottom with dates of 90, 117, 154, and 222 ka respectively (Table 1), although the error for the basal sample is rather large mainly due to increased scatter between multiple palaeodose measurements. This age may therefore be treated with caution. Figure 2c shows the PSD of the four dated core samples which are all well sorted and show a similar unimodal distribution. The similarity in shape of the PSD curves is surprising in view of the large differences in the dates. The top sample, 135a, dated at 90 ka +/−11 is the finest, with modal size corresponding to very fine sand, at 70–90 m. It is well sorted and compares well with many other sites examined (Table S1), where samples were taken at 1.5 m below the surface. The underlying three samples are somewhat coarser, though equally well sorted, with modes at 90–100 μm and 100–110 μm. The observed lack

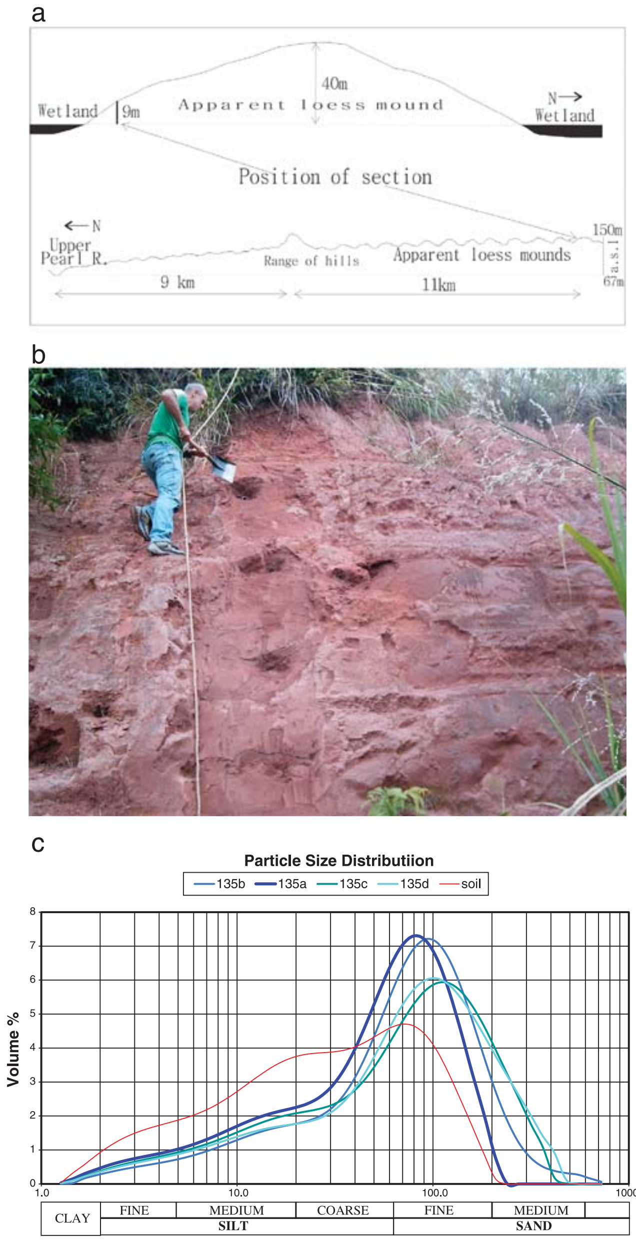

Figure 2. (a) Landscape section, and position of site 135. (b) Section at site 135 near Nanning, Guangxi Province. This site comprises reddish brown (2.5YR6/3) fine sandy silt loam. (c) Particle size distribution (μm) for four depths from a (top) to d (bottom) at site 135 and a soil layer at approximately 50 cm from the surface.

of horizons and organic content, suggests limited pedogenesis, i.e., we define this as loess, as opposed to the surface layer (2c), which is less well sorted and we define as soil.

[9] The PSD of most samples shows dominant size classes of coarse silt (40–63 μm) and very fine sand (63–100 μm) (Table S1), which fall within the sizes recognized as loess [*Liu et al.*, 1985; *Pecsi*, 1990, *Zhang et al.*, 1994, 1999; *Xiong et al.*, 2002; *Huang et al.*, 2003]. Only 3 of the 26 samples have over 30% by weight of material outside the silt and fine sand classes of 2–200 μm (column 13 of Table S1). The PSD is generally not similar to loess from the Chinese loess plateau, which is mainly finer, with modal sizes of 20–50 μm [*Sun et al.*, 2004]. However, the samples do fit well with loess in other areas attributed to local sources, such as Crouvi's PSD curves of Israeli loess from the 200 km distant Negev desert [*Crouvi et al.*, 2008]. The soil color of reddish brown observed here (Table S1) is unusual for loess, which is more commonly yellow in the arid zone of Asia [*Liu and Yuan*, 1987]. The color may indicate laterization typical of a humid tropical climate with a marked dry season. Laterization can occur in as little as 10,000 years [*Gardner and Pye*, 1981] and is assumed here to have occurred following deposition. The geochemistry is similar to loess reported for Luochan [*Chen*, 2001] and Nanjang [*Pecsi*, 1990] in north China, with similar amounts of silica, iron and aluminum, but the considerably lower proportions of CaO and Na^2O (Table 1) suggest more weathering and leaching, which would be expected in the more humid subtropical climate. The loess deposits observed throughout the region are overlain by only a thin layer of reddish brown soil containing plant roots, which is surprising as soil is thought to form rapidly in loess [*Hallberg et al.*, 1978; *Maher et al.*, 2003]. Even in semiarid regions, if pedogenesis keeps pace with deposition, modern soil will develop from contemporarily accumulated dust [*Liu et al.*, 1985; *Maher et al.*, 2003; *Sun et al.*, 1998]. Indeed the Malan loess is overlain by a 3 m deep Holocene soil with well developed pedogenic horizons. However, the Malan loess itself remains unaltered, and is not the parent material for the modern soil [*Huang et al.*, 2003].

[10] The error limits of the ages reported here, are coincident with lower sea levels in the Sulu Sea varying between −45 m, to −130 m as estimated by *Linsley* [1996] and *Chappell and Shackleton* [1986] from oxygen isotope records (Table 1). The dates of around 90 k and 117 ka are also coincident with peaks of coarse-grained dust in the Chinese loess-palaeosol profiles [*Zhang et al.*, 1994], and with cold events in northern China, indicated by terrestrial deposits from ice cores in Greenland and the north Atlantic [*An and Porter*, 1997]. The date of 154 ka is also consistent with a marked cold event during the last glaciation, diagnosed from Antarctica ice core data [*Petit et al.*, 1999] and with Marine Isotope Stage (MIS) 6. All four dates recorded fit within MIS glacial phases 2, 4 or 6, if the error limits are invoked for the samples dated at 117 and 222 ka.

[11] These results, combining particle size, physico-chemical properties, massive structure, landform and age, lead us to define the deposits as loess of local origin. The dominant size classes of coarse silt of 40–63 μm and very fine sand of 63–100 μm, which are similar to Israeli loess [*Crouvi et al.*, 2008], are mainly carried in short term suspension within 1500 m of the ground [*Tsoar and Pye*, 1987] and are unlikely to have travelled over very long distances.

4. Explanation

[12] Sea level in East Asia during the late Pleistocene was up to 140 m lower than present [*Chappell and Shackleton*, 1986; *Voris*, 2000; *Bintanja et al.*, 2005] and due to the shallowness and steep outer edge of the East Asian shelf, the area exposed at only half of this lowering, i.e., 70 m was almost as extensive as at the maximum, and the Sunda shelf was still exposed. The Red and Pearl rivers carrying large quantities of alluvium and silt flowed across the shelf [*Yim et al.*, 2006; *Sun et al.*, 2000; *Wang et al.*, 1999; *Zhao and Li*, 1990], and farther south, the Mekong emerged to the

Table 1. Age, Dose Rate, Equivalent Dose, and Geochemistry of Major Oxides (wt %) of Dated Deposits, Compared With Two Sites on the Chinese Loess Plateau

Analyte Symbol	Nanjang [*Pecsi*, 1990]	Luochan [*Chen*, 2001]	Sample Point 135a	Sample Point 135b	Sample Point 135c	Sample Point 135d
Estimated age (ka)			90 +/−11	117 +/−15	154 +/−24	222 +/−50
Dose Rate (Gy/ka)			2.56 +/−0.18	2.47 +/−0.17	2.45 +/−0.20	2.89 +/−0.18
Equiv. Dose (Gy)			230	290	444	544
SiO_2	71	67	71.5	72	76.3	77
Al_2O_3	15.7	14	14.0	14.1	11.4	11.4
Fe_2O_3	5.8	4.5	5.5	4.5	4.4	3.3
MnO	0.08	0.7	0.04	0.10	0.03	0.02
MgO	1.49	2.2	0.86	0.98	0.78	0.83
CaO	0.9	1.05	0.06	0.06	0.05	0.12
Na_2O	1.34	1.75	0.08	0.10	0.11	0.11
K_2O	2.2	3.2	1.38	1.71	1.93	2.10
TiO_2	0.81	0.75	0.82	0.64	0.73	0.49

Sunda shelf. The winter monsoon winds reaching the study area from north-central China crossed the shelf for over 600 km, and the summer monsoon winds reaching south-west China were also mostly over land (Figure 3). With an anticyclone situated over the Pearl River Delta near Hong Kong in January (Figure 3a) the dry monsoon from north central Asia would approach Hainan Island and the Leizhou Peninsula from ENE [*Central Meteorological Bureau*, 1979], parallel to the coast and over the exposed sea bed. Winds would then veer to easterly, then southeasterly over the exposed Gulf of Tongking, to be drawn northward then northeastward toward Nanning and Guiping in the Upper Pearl valley (Figure 1). It is likely that anticyclonic conditions persisted into spring and early summer during Quaternary glacial phases [*Li et al*., 1988; *Pye and Zhou*, 1989]. Furthermore, due to the greatly reduced size of the South China Sea [*Huang et al*., 1997], and loss of warm water input from the Indian Ocean, the summer monsoon would have been much drier [*Wang and Sun*, 1994; *Hoddell et al*., 1999; *Wang et al*., 1999; *Chen et al*., 1997]. It would have approached the study area across dry land, including the exposed shelf from southern Borneo across Indo-China to Nanning, a distance of over 4000 km over land, and would thus have been much drier than today. The loess reported here is thought to be unrelated to the loess reported from the semiarid region of north Thailand, which is not within the trajectory of winter monsoon winds crossing the shelf (Figure 3a). Dry winter winds reaching north Thailand would have travelled 500 km over land as well as the 1500 m Annamite mountain range. The Thai loess is reportedly thinner (up to 6m deep) and redder than that reported here, and appears to be finer (*Phien-wej et al*., 1992), although no dates, and few quantitative data are available.

[13] The shelf environment is sandy [*Sun et al*., 2000] and *Zhao and Li* [1990] report sand dunes on the sea bed, with the sediments becoming finer landwards. This may have resulted from the loss by deflation of fine particles from a succession of juxtaposed interstadial beaches [*Yim et al*., 2006] and alluvial fans as the coastline advanced and retreated over the shelf. In spite of the dynamic nature of fluvial and aeolian processes, and immature soils, exposed coastal sites generally become well vegetated within one or two decades, unless climate is prohibitive. This is evidenced by several 20 year old reclaimed land sites in Hong Kong which are currently covered by tall grass, shrubs and trees up to 15 m tall. If however, climate was prohibitive to a full vegetation cover, the shelf may have become a source area for dust, similar to *Pye*'s [1995] description of dust being

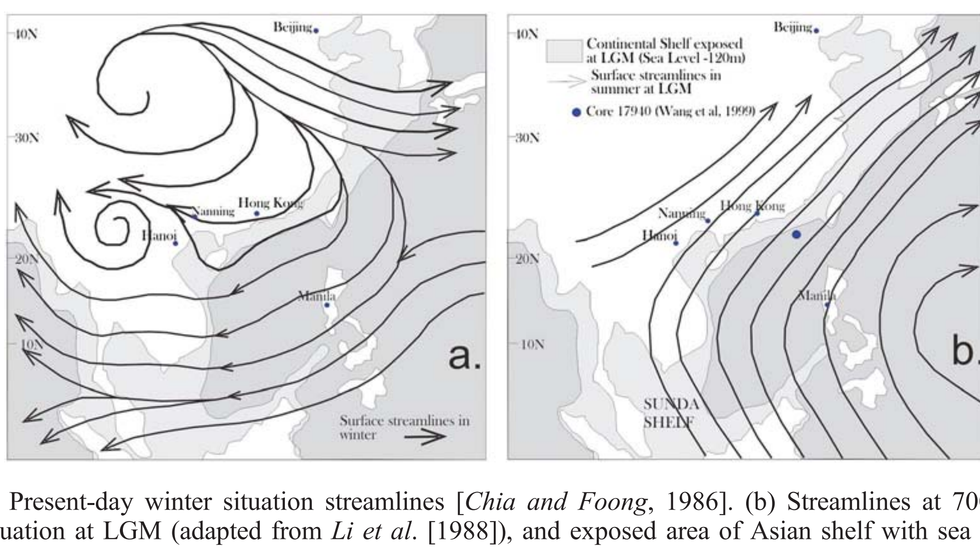

Figure 3. (a) Present-day winter situation streamlines [*Chia and Foong*, 1986]. (b) Streamlines at 700 Mb estimated for summer situation at LGM (adapted from *Li et al*. [1988]), and exposed area of Asian shelf with sea level at –120 m [*Voris*, 2000].

blown some considerable distance from a source area, such as a wadi, fan or dry lake bed, toward a semiarid margin where the vegetation cover is sufficiently thick to trap the dust. In such a situation loess may form if accumulation is fast enough and/or climate arid enough to inhibit soil formation. Pye's description of sand dunes and sand sheets forming immediately adjacent to the source and slowly migrating downwind [*Pye*, 1995] are represented in our case by the widely researched "Old Red Sands of Guangdong", (which are fossilized coastal dunes of Pleistocene age) along the coasts of south China [*Zheng and Wang*, 1998]. Such a sequence of downwind fining is represented by three samples from east to west across Hainan island (Figure S3). Sample 178 at a coastal site (Figure 1), comprising loamy sand, grades into sandy loam (sample 137), then silty clay loam (sample 197) over a distance of 150 km westwards.

[14] The lack of horizons and pedogenic features here compared with up to 33 alternating loess and soil layers on the semiarid loess plateau in north China is remarkable, but may be explained by differences in source areas. Loess in north China had a continued dust supply from neighboring deserts throughout interstadials including the Holocene, from which a modern soil is currently being formed [*Maher et al*., 2003]. According to Maher, soil formation there during the Holocene has been accompanied by continuous accumulation of dust, and stronger soil development occurred during periods of higher loess accumulation, thus soil development may need a continuous dust supply. However, the loess reported here lost its supply source on reestablishment of sea levels at the start of each interstadial, thereby removing a necessary input, thus soil may not have formed in existing loess during interstadials when the shelf was covered.

5. Palaeoclimatic Implications

[15] The deflation of large amounts of sediment from the shelf suggests that the shelf (at least in southwest China and Gulf of Tongking) must have remained unvegetated, similar to desert surfaces, for extended periods during the last glacial period (220–12 ka, or MIS stages 2, 4, and 6), because deflation is unlikely from a vegetated surface. Furthermore, the reported loess extending for distances of 200 km inland from the coast, suggests that the climate during arid phases of the late Pleistocene was inimical to soil formation. Although some vegetation would have been necessary to trap the loess, it must have been sparse for large distances inland. For pedogenesis, a rainfall regime of around 600 mm is required. For example, *Huang et al*. [2003] report the current development of luvisols, and arable farming practices in regions of the southern loess plateau where annual precipitation is 600 mm. On the other hand, loess is actively accumulating on the western edge of the loess plateau where mean annual rainfall is 200–400 mm [*Maher et al*., 2003]. The implied decrease in rainfall of up to 1000 mm from present levels in this area of south China appears to conflict with other palaeoclimatic reconstructions.

[16] Evidence from pollen samples in deep sea sediments [*Wang et al*., 1999; *Sun et al*., 2000], sea bed surveys [*Zhao and Li*, 1990], a peat bog in Taiwan [*Liew et al*., 1998] and volcanic crater lakes on the Leizhou Peninsula [*Mingram et al*., 2004] suggest an open forest-grassland vegetation for the south China region. The mismatch is comparable to *Broecker et al*.'s [1988] observations from deep sea core 17964 off the Sunda shelf in Southeast Asia, where large sediment inputs during the last glacial cycle suggest aridity, whereas pollen data indicate tropical rain forest.

6. Conclusion

[17] The loess reported here represents preliminary findings of loess in a humid subtropical region, and more field surveys and dates are required to establish better relationships with other sites. However, the climatic aridity implied by the loess appears to conflict with pollen data indicating forest-grassland in coastal south China including the exposed East Asian shelf during the last glacial period. These problems may be due to greater temporal [*Fang et al*., 1999; *An*, 2000] and spatial [*Sun et al*., 2000] variability during the glacial period, giving rise to steeper ecological gradients and time sequence compared with today. For example *Sun et al*. [2000] conclude that an enhanced winter monsoon during the last glaciation brought greater aridity to the northern shelf of the South China Sea, but greater moisture to the Sunda shelf in the south. This is evident from Figure 3, which shows the Sunda Shelf in the path of wet winds in both summer and winter, but dry land winds year-round for the northern shelf around the Gulf of Tongking. Although parts of the study area support tropical moist forest today, with Dipterocarps in Leizhou and Hainan, moisture rapidly declines westward and drought is common. Such variability gives rise to ambiguity in the absence of high-resolution proxy records. Now that more accessible sedimentary data are available for southwest China, more comprehensive and higher resolution survey and dating may help resolve the apparent mismatch between sedimentary and palynological evidence.

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