

Chapter 2

Chinese Loess and the East Asian Monsoon

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Abstract This chapter offers a comprehensive review of loess studies on the Loess Plateau, and how they provide evidence for past monsoon variability. The chronological framework that has been established for the LP with the use of multiple chronometers is explained in detail. Sedimentological, paleomagnetic and geochemical climate proxies are also discussed, and the history, variability and dynamics of the paleomonsoon is described at tectonic, orbital and millennial time scales.

Keywords Chinese Loess Plateau · Loess · Paleosol · Red clay · Climate proxy · Grain size · Magnetic susceptibility · Color reflectance · Isotopic geochemistry · $\delta^{18}\text{O}$ · ^{10}Be · Geomagnetic field · C4 plant · C3 plant · Tectonic time scale · Orbital time scale · Oligocene · Holocene

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2.1 Introduction

East Asian monsoon variation, characterized by alternating dominance between cold-dry winter monsoon and warm-humid summer monsoon at the glacial-interglacial time scale, was directly driven by external solar radiation and strongly modulated by changing lower boundary conditions through interactions among atmosphere, ocean, land and the ice system. Eolian sequences on the Chinese LP indicate the onset of the East Asian paleomonsoon at least by the late Oligocene, and significant monsoon variability on tectonic to millennial time scales afterwards. Long-term evolution of the East Asian monsoon was closely related with the uplift of the Tibetan Plateau and the expansion of the northern hemisphere ice sheet, as revealed by geological evidence and numerous modeling results. High-resolution loess records demonstrate that millennial-scale monsoon variability during the last glaciation was closely related with the cold-air activities of high latitudes in the Northern Hemisphere, which was dynamically linked to rapid climate change in the North Atlantic. Future research on Chinese loess should focus on reliable chronology and sensitive monsoon proxies for both the high-resolution loess and the largely underlying red clay sequences. Furthermore, temporal-spatial variability of the East Asian monsoon system should be further investigated to understand its linkage to high- and low-latitude processes and their forcing mechanisms within the global context.

2.1.1 *Research History of Chinese Loess*

Widespread loess-paleosol and the underlying red clay sequences on the Chinese Loess Plateau are well known for their great thickness, high resolution and richness of paleoenvironmental information. Since 19th century, western researchers represented by Richthofen (1877) started to conduct loess surveys in China, and for the first time brought forward the preliminary understanding of its eolian origin based on sedimentary characteristics. In the early 20th century, Andersson (1923) studied the Hipparion fossil of Baode in Shanxi, differentiating Chinese loess into the Pliocene Baode red clay with Hipparion fossils and the Late Pleistocene Malan Loess. Then, based on vertebrate fossils, Teilhard de Chardin and Young (1930) further divided the underlying loess beneath the Malan Loess into the Early Pleistocene and Middle Pleistocene red clay. In the 1960s, on the basis of loess-paleosol stratigraphy and fossil mammal features, Liu and Chang (1962) divided the Chinese loess into the Early Pleistocene Wucheng Loess, Middle Pleistocene Lishi Loess, and Late Pleistocene Malan Loess, which laid the foundation for loess chronology studies, and further proved their eolian origin on the basis of numerous geological and biological evidence.

Since the late 1970s, based on the characteristic alternating loess and paleosol strata in loess sections, Chinese researchers have proposed the concept of the Chinese loess-paleosol sequence, and systematically discussed Quaternary environ-

mental variation (Lu and An 1979; Liu et al. 1980). Accordingly they have created a detailed stratigraphic division and nomenclature of the loess-paleosol sequences of the Loess Plateau (Lu and An 1979; Liu 1985; Kukla and An 1989; Ding and Liu 1989). On the basis of the paleomagnetic study of the Luochuan loess drilling hole, Heller and Liu (1982) established the magnetostratigraphy of Chinese loess-paleosol sequence back to 2.5 Ma. Afterwards, researchers around the world found that the Chinese loess-paleosol sequence can be well-correlated with the global ice-volume change recorded by $\delta^{18}\text{O}$ of deep-sea sediments (Heller and Liu 1984; An and Lu 1984; Liu 1985; Kukla 1987; Kukla et al. 1988; Rutter et al. 1991; Rutter 1992; Ding et al. 1995; Bloemendal et al. 1995; Liu et al. 1999a; Ding et al. 2002). This realization brought Chinese loess studies to a new stage as they became a basis for larger global environmental change research (Liu 1985) together with deep-sea sediments and polar ice cores as three pillars of global climate-change studies.

The next phase of study arose from an analysis of the temporal-spatial distribution, stratigraphy, and biological fossil features of Chinese loess-paleosol sequences, combined with modern climatology studies. In the early 1990s An et al. (1990, 1991a) suggested that the Chinese loess-paleosol sequence was a good record of the East Asian monsoon variation. On the 10^4 -yr time scale the East Asian monsoon is alternately dominated by glacial winter and interglacial summer monsoons. An et al.'s paleomonsoon theory pushed the study of Chinese loess toward a new stage that combined it with the study of atmospheric dynamics.

In the most recent phase of study, research has been extended to the underlying red clay formation, especially the Mio-Pliocene red clay sequences (Sun et al. 1998b; Ding et al. 1999b; Guo et al. 2002). Research on the Loess Plateau revealed that the basal age of the red clay in the east of the Liupan Mountain is 6–8 Ma (Sun et al. 1997; Sun et al. 1998a; 1998b; Ding et al. 1998b; An et al. 1999; Qiang et al. 2001), and firmly established its eolian origin (Liu et al. 1988; An et al. 1991a; Ding et al. 1997; Ding et al. 1998b; Lu et al. 2001; Yang and Ding 2004; Liu et al. 2006a; Qiao et al. 2006; Li et al. 2006). However, the distribution of sources may have differed from those for the later loess. Recently, the basal age of the red-clay sequence at Shilou has been pushed back to >11 Ma (Xu et al. 2009). The oldest red-clay deposits have been found mainly on the western Loess Plateau (west of Liupan Mountain), for example, the red clay sequences of Qin'an (22–6.2 Ma) (Guo et al. 2002) and Zhuanlang (25.6–4.8 Ma) (Qiang et al. 2011).

Like the Quaternary loess-paleosol sequence, the red clay sequence appears to contain a good record of East Asian monsoon variation (Sun et al. 1997; 1998a; 1998b; Ding et al. 1999b; 2001b; Guo et al. 2002). In addition, the eolian dust-flux variation of the loess-red clay sequence can record the onset of aridification of inland Asia (An et al. 1991b). The aridification variation history of the last 7 Ma has been revised accordingly (Sun and An 2002, 2005). The discovery of the Qin'an red clay suggested that the inland Asia aridification started in the Miocene, and even back to the Late Oligocene (Guo et al. 2002, 2008; Qiang et al., 2011).

Thus, the eolian deposits on the Chinese Loess Plateau have recorded the history and variability of Asian Monsoon climate and the history of aridification of the inland Asia since the late Oligocene (An 2000; An et al. 2006; Sun and An 2002, 2005; Guo et al. 2002). Both the Monsoon and interior aridification relate not only

to late Cenozoic global cooling, but also are influenced by regional tectonic events, especially the phased uplift of the Tibetan Plateau (An et al. 2001; An et al. 2006). Further studies on the eolian sequences on the Chinese Loess Plateau, are expected to reveal not only the coupling evolution of monsoon-aridity system of East Asia, but also shed light on the dynamic mechanisms linking regional and global environmental variation on different time scales.

2.1.2 East Asian Monsoon Evolution Recorded by Chinese loess

The East Asian monsoon is an important part of global atmospheric circulation. Unlike other monsoon systems (African monsoon and Indian monsoon), the East Asian monsoon has a unique and strong mid-latitude winter circulation ('winter monsoon'). In winter and spring, cold air masses formed in the high-latitudes of central Asia move southward along the east side of the Tibetan Plateau, resulting in cold, windy and dry conditions on the Chinese Loess Plateau. The winter monsoon can extend as far south as the tropical areas in the South China Sea, and even cross the equator. As summer begins, warm and humid air originating from the tropical ocean moves northward, ultimately reaching the China-Mongolia border area ($\sim 40^{\circ}\text{N}$). This is the highest latitude reached by any monsoon system in the world, and provides indispensable precipitation for this area. The East Asian monsoon not only has a profound influence on climate in East Asia, with its clear seasonal contrast between warm-humid summer and cold-dry winters, but also dynamically links to the global climate system.

Although Chinese Quaternary geologists suspected that the environment of eastern China has likely fluctuated along with the strength of the East Asian monsoon variation on long (10^3 – 10^4 -yr time scales), it wasn't until the early 1990s that thorough, systematic research on the loess-paleosol sequence in central China revealed the strong correlation between the alternating layers of loess and paleosols in the Chinese Loess Plateau and fluctuations in the anti-phased East Asian summer and winter monsoons. An et al. (1991a) proposed that most of the loess was deposited during times when the East Asian summer monsoon was weakened, and did not reach as far north as the northern margin of the Loess Plateau. The dust was transported to the Loess Plateau by the northerly winds of the winter monsoon during the relatively cool and dry seasons. In contrast, the interbedded paleosols formed under the warmer, more humid summers associated with strong summer monsoons. An et al. (1991a) therefore suggested that the East Asian paleomonsoon variation has been the principal and direct driving force controlling environmental conditions in East Asia. Subsequent studies on monsoon-climate records provided by loess, speleothems, and lake and marine sediment cores, unveiled the framework and mechanisms of the East Asian monsoon climate variation during different geological periods. These lines of evidence have propelled the East Asian paleomonsoon studies to general awareness and placed the loess studies in a global context (e.g., An et al. 1990; An 2000; Liu and Ding 1998).

In recent years, studies have attempted to obtain information on the formation and evolution of the East Asian monsoon, to discover the relationship between East Asian monsoon variation and global ice volume and the uplift of the Tibetan Plateau, and to explore the global significance of the East Asian monsoon and Tibetan Plateau uplift (An et al. 2001). Paleoclimate research has already been extended spatially from the inland Loess Plateau to the marginal seas of southern China and the Warm Pool in the western Pacific (Wang et al., 2003, 2005). The range of study also has expanded to include different geological records of the northwestern inland arid area, revealing the relationship between the evolution of the East Asian monsoon and climate change at both high and low latitudes. Only through research on the response of the East Asian monsoon to the overall behavior of various factors of the global climate system, viewed through the framework of the global change, we can fully understand the mechanisms of the East Asian monsoon variability.

Loess research has revealed that the East Asian winter monsoon plays a leading role in the transportation of Asian dust and deposition of the loess-paleosol sequence on the Loess Plateau (An et al. 1991b). In winter, dust is carried by the East Asian winter monsoon blowing from inland Asia onto the Loess Plateau and deposited there, forming the loess. However, the monsoon is not the only factor driving deposition in the Loess Plateau. Recent studies on the grain-size composition of the loess have shown that high-altitude westerly circulation also influences the transportation and deposition of loess (Porter and An 1995; Sun et al. 2004; Sun et al. 2008b). The warm and humid air masses of the summer monsoon originating in the equatorial ocean episodically have promoted soil development. Based on magnetostratigraphic results and direct dating methods such as ^{14}C and luminescence dating, the basic chronology of the Chinese loess/red clay sequence has been established. By using proxy indices sensitive to monsoon variation in the loess/red clay sequence, the evolution history of the East Asian paleomonsoon has been reconstructed back to 22–25 Ma (Guo et al. 2002; Qiang et al. 2011).

The following text will review the progress of recent studies of Chinese loess and the East Asian paleomonsoon evolution from four aspects: temporal and spatial distributions of the loess, chronology, proxy indices, and the East Asian monsoon evolution on different time scales. A brief summary of the evolution characteristics and dynamic mechanisms of the East Asian paleomonsoon variability will be presented.

2.2 Temporal and Spatial Distributions of Chinese Loess

Chinese loess is deposited over an area of $\sim 630\,000\text{ km}^2$, or 6.6% of China (Liu et al. 1985). It is mainly located between 33 and 47°N, and 75 and 127°E, north of the Qinling, Qilian and Kunlun mountains, from Xinjiang through Gansu, Shaanxi, Shanxi, Henan, western Liaoning, to the Songliao Plain. The loess area is arc-shaped, protruding toward the south. The sandy deserts of Horqin and Otindag in northeastern China, Mu Us, Tengger and Badain Juran deserts in Inner Mongolia, Taklimakan and Gurbantunggut deserts in northwestern China border it on the north

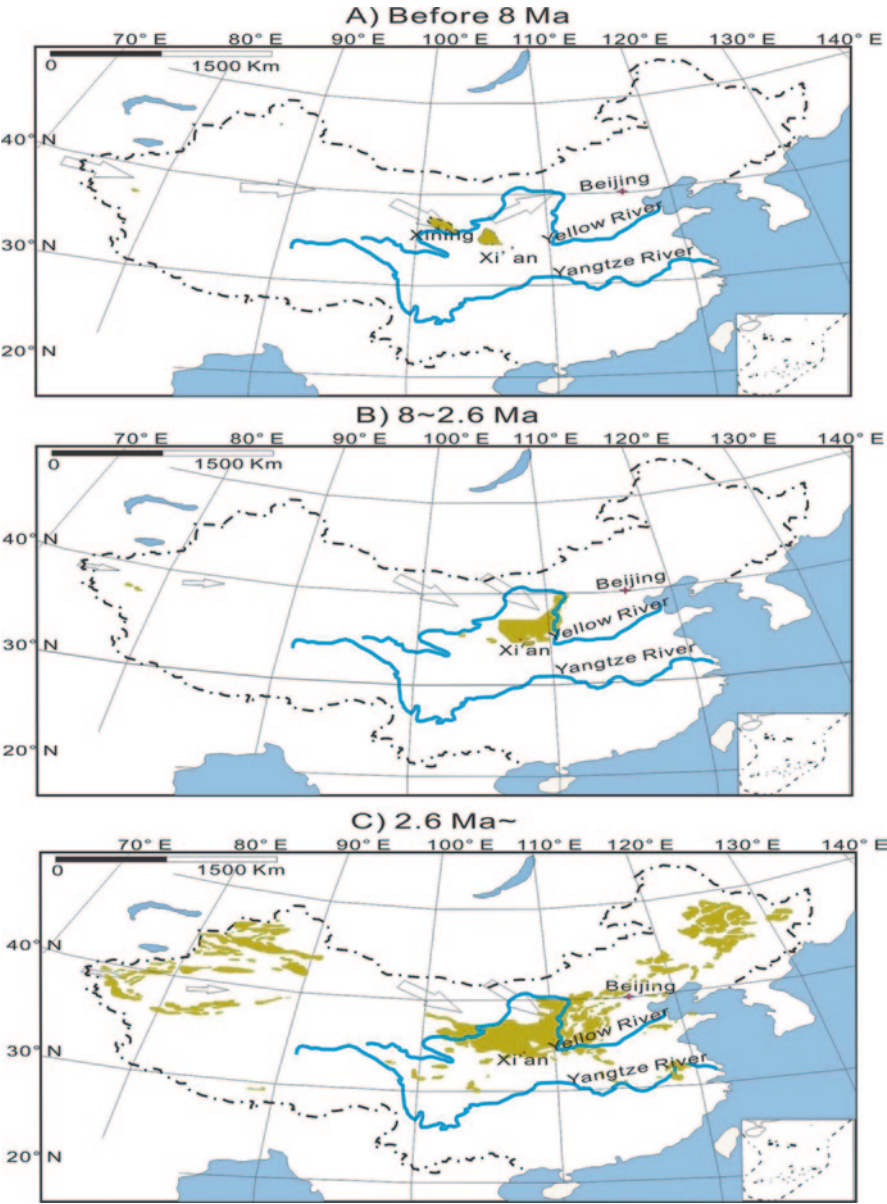


Fig. 2.1 Distribution of loess-paleosol and red clay sequences over northern China

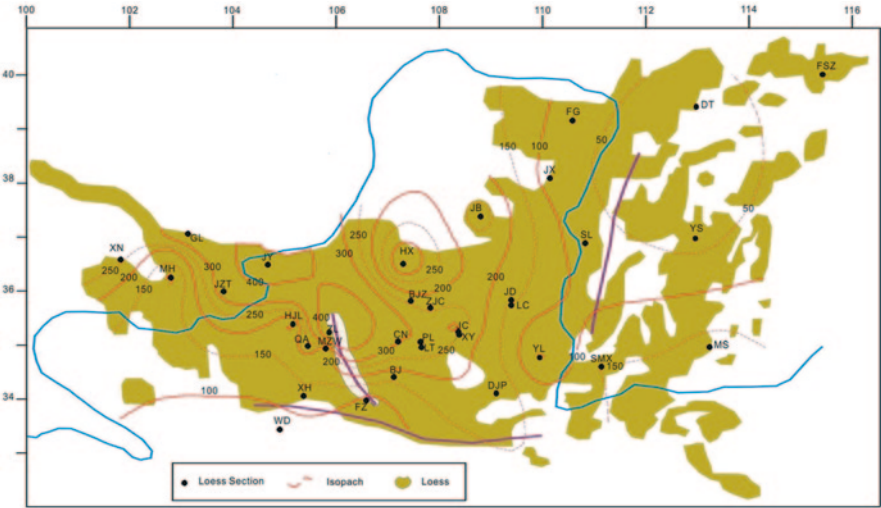


Fig. 2.2 Spatial variability of thickness of loess deposits on the Chinese Loess Plateau

(Fig. 2.1c). This spatial distribution of the loess is clearly related to the anticyclonic winter monsoon formed in the stable high-pressure cells centred in Lake Baikal and Mongolia. Outside this zone, the dust flux has been lower but loess nevertheless is dispersed over Nanjing, Jiujiang, Wuhan, Sanxia, Sichuan Basin, Chuanxi Basin, Qaidam Basin, and eastern Tibet. Elevations at which the loess is found vary greatly depending on the locality. In the Turpan Basin of Xinjiang, loess is found on the surface at an elevation of 150 m below sea level. On the continental shelf of the East China Sea and the Yellow Sea, loess is located in seawater at depths of 50–60 m during the global glacial maxima. Loess deposits are 4500 m above sea level the Pamir Plateau, 5340 m in the western Kunlun mountains, and 4300 m on the Chuanxi Plateau (Liu et al. 1985; Sun 2005b). On the central Loess Plateau, elevations of the loess tablelands are 1000–1800 m, whereas in the western Loess Plateau the loess deposits accumulated around 2000–2500 m above sea level.

Spatial distribution of the red clay is not identical to that of the later Quaternary loess-paleosol sequences (Fig. 2.1). Miocene red clay is mainly located in Tianshui–Qin’an area, to the west of the Liupan Mountains (Guo et al. 2002; Qiang et al. 2011). Red clay is found only sporadically in the Xining Basin (Lu et al. 2004b) and on the eastern Loess Plateau near Shilou in Shanxi (Xu et al. 2009). Late Miocene to Pliocene red clay sequences, however, are extensively distributed on the central Loess Plateau (e.g. Zheng et al. 1992; Sun et al. 1998a; 1998b; Ding et al. 1999b; Ding et al. 2001b). Early Pleistocene Wucheng loess is situated north of 35°N and east of 110°E, including the northern slope of the western Kunlun mountains. Middle Pleistocene Lishi loess extends to southeastern China, having a larger distribution area than the Wucheng loess. For example, Xiashu loess in the mid-low reaches of the Yangtze River is the counterpart of the Lishi and Malan loess.

Late Pleistocene Malan loess covering different geomorphologic units is even more widely distributed, extending to the Miaodao Islands in the east, and to the middle and low reaches of Yangtze River in the south. The zonal expansion of loess since the Pleistocene suggests gradually increasing aridity at the dust sources throughout the Quaternary.

The thickness of loess deposits on the Loess Plateau decreases gradually from northwest to southeast (Fig. 2.2). Loess deposits in the northwestern Loess Plateau (e.g., Lanzhou and Jingyuan sections) are obviously thicker than the loess sequences in the central and southeastern Loess Plateau (e.g., Xifeng, Luochuan and Weinan sections). The thickness of the Quaternary loess sequence on the central Loess Plateau is 100–180 m, but reaches 450 m on the western Loess Plateau (Fig. 2.2). Southeastward thinning of the loess deposits indicates that the dust deposited on the Loess Plateau has mainly been transported by the northwesterly winter monsoon (Liu 1985; An et al. 1991b; Xiao et al. 1992). Loess sections from the central Loess Plateau are fairly complete, and usually encompass the whole of the Quaternary (Liu et al. 1985). More recently, a 670-m loess core was retrieved from the western Kunlun by drilling, includes loess from the Quaternary and late Pliocene (Fang Xiaomin, personal communication 2010).

The loess sedimentation rate is normally ~200 m/Ma near Lanzhou in the western Loess Plateau, decreasing to 50–100 m/Ma in the central Loess Plateau. Loess sedimentation rates in Xinjiang and the Kunlun are all >100 m/Ma. Spatial variations in the thickness and sedimentation rate of loess deposits over northern China indicate that the loess deposits originated from inland Asia and were transported dominantly by the winter monsoon.

2.2.1 *Quaternary Loess-paleosol Sequences*

Before the 1990s, numerous studies on loess grain size, mineral components and dust-transport mechanisms had solidified the understanding that on the Loess Plateau, loess thickness and grain size both decrease gradually from northwest to southeast, whereas the degree of soil development increases (Liu et al. 1985). In contrast, because of the limited exposure and evident confinement of the underlying red clay deposits in localized depressions in the paleo-topographic surface, the scientific understanding of their thickness, spatial distribution, origin and chronology of the red clay was greatly hampered. In the past two decades, dozens of typical loess/red-clay sections have been analyzed (Fig. 2.3). Of these, the Luochuan, Xifeng, Duanjiapo, Jingbian, Weinan, Lingtai, Fugu, Shilou, Jiaxian, and Jingchuan sections in the central Loess Plateau (east of the Luipian Mountains and west of Lvliang Mountains) all share the same time duration for the loess (2.6 Ma), and basal ages ranging from 5 to 11 Ma for the red clay. The Lanzhou, Jingyuan loess, Qin'an, and Zhuanglang sections in the western Loess Plateau (west of the Liupan Mountains) have basal ages for ranging from 1.4 to 1.8 Ma for the Quaternary loess,

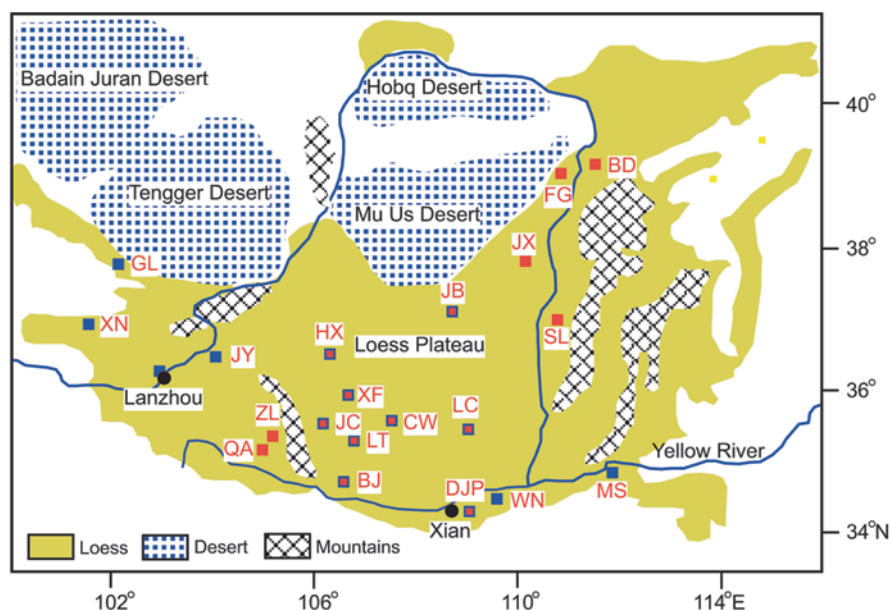


Fig. 2.3 Typical loess and red clay sections on the Chinese Loess Plateau. Sections are located at Baoji (BJ), Baode (BD), Changwu (CW), Duanjiapo (DJP), Fugu (FG), Gulang (GL), Huanxian (HX), Jiaxian (JX), Jingbian (JB), Jingchuan (JC), Jingyuan (JY), Lantian (LT), Lanzhou, Lingtai (LT), Luochuan (LC), Mangshan (MS), Qin'an (QA), Shilou (SL), Weinan (WN), Xifeng (XF), Xining(XN) and Zhuanglang (ZL)

and 22 to 25 Ma for the red clay, respectively (Burbank and Li 1985; Liu 1985; Yue et al. 1991; Guo et al. 2002; Qiang et al. 2011).

The following is a brief comparison of typical loess/red-clay sequences on the Loess Plateau. Quaternary loess-paleosol sequences on the Chinese Loess Plateau share many similarities (Fig. 2.4), with typical profiles exposed at Luochuan (Liu et al. 1985), Xifeng (Kukla 1987), Baoji (Rutter et al. 1991; Ding et al. 1993), Lingtai (Sun et al. 1998b; Ding et al. 1999b), and Lanzhou (Burbank and Li 1985). It is clear that the thickness of the loess exceeds 300 m in the Lanzhou section, near the dust sources, but decreases to 170 m in the Xifeng and Lingtai sections of the middle Loess Plateau, and is only 130–140 m in the Baoji and Luochuan sections. The pedogenic intensity of paleosol layers is significantly lower in the northerly Luochuan and Xifeng sections than in the more southerly Lingtai and Baoji sections. Paleosol development in the Wucheng Loess best shows this spatial discrepancy. In the Luochuan and Xifeng sections, the Wucheng Loess can be divided into three paleosol complex (WS 1–3) interbedded with three loess complexes (WL1–3). In Baoji and Weinan sections, however, Wucheng Loess can be further subdivided into 17 paleosol layers (S15–32) intercalated by 18 loess layers (L15–L33), suggesting that in the southern Loess Plateau paleosol units were well-developed resulting from the stronger influence of the the East Asian summer monsoon. The depth of

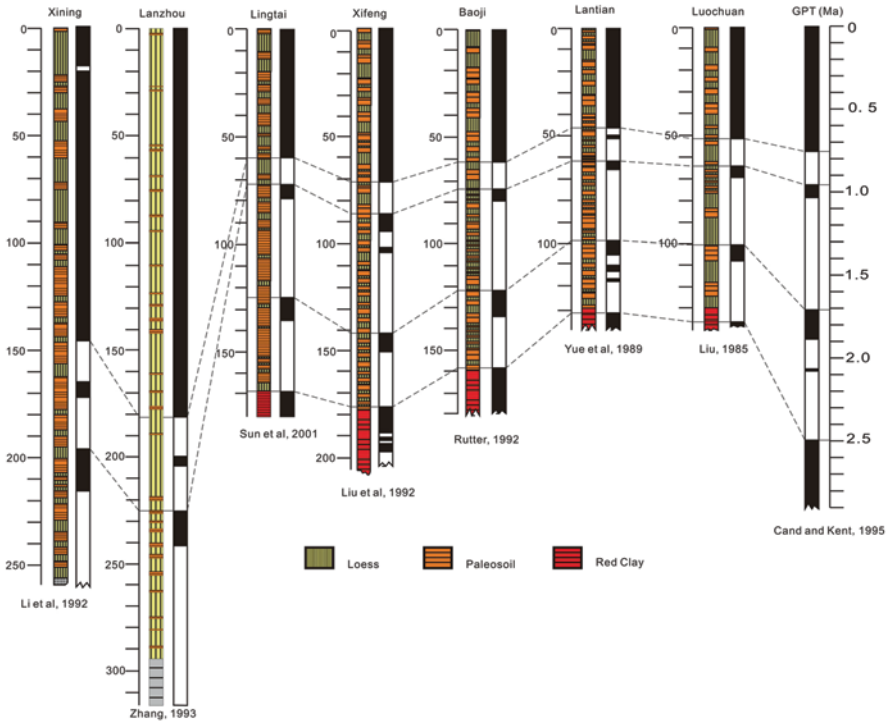


Fig. 2.4 Comparison of Quaternary loess-paleosol sequences on the Chinese Loess Plateau. For locations of sections, see [fig. 2.3](#) GPTS—Geomagnetic Polarity Time Scale *black* sections have normal polarity, *white* sections show reversed

the typical marker layers (S1, S5, L9, L15, etc.) in different sections shows that loess strata are normally thicker in the northwestern Loess Plateau, while paleosol strata are commonly compacted in the southeastern Loess Plateau. As described above, this is interpreted to result from the alternating dominance of the winter and summer monsoons over the past 2.5 Ma.

2.2.2 Red Clay Deposits on the Central CLP

In the past two decades, investigation of the dominantly Tertiary red clay sequence has become a hot topic in Chinese paleoclimate research. There have been two motivations: to determine the onset and evolution of Asian aridification and cast light on the paleoclimatic history. Through systematic field geological surveys, many late Cenozoic eolian sequences including the Tertiary red clay on the central Loess Plateau were studied intensively to conduct stratigraphy and paleomagnetism studies. These sections include the Lingtai, Xifeng and Bajiuzui sections on the middle

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