The Loess-Paleosol Sequence in China and Climatic History

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The classic loess deposits of China have been intensively studied in recent years, especially from the standpoint of paleoclimate. A sequence up to 200 m thick of interlayered loesses and paleosols has been firmly established dating back to 2.4 Ma. The authors suggest that the base of this sequence may indeed be a useful marker for the start of the Quaternary. The stratigraphy, magnetostratigraphy, petrography, chemistry and fossil content of the layers and their close correlation with results from deep-sea cores permit reconstruction of varying paleoenvironments and paleoclimates. The chronology of these changes indicates major oscillations with periods of 80,000, 40,000 and 20,000 years, with a possible return to glacial climates in another 5,000 years. (Ed.)

Title Photo: Aerial view of loess tablelands ("yuan"), Heshui, Gansu Province, China. From Wang and Zhang (1980).

Introduction

Loess deposits, ranging up to several hundred metres in thickness and covering an area of 440,000 km², are widespread in China between latitudes 33° and 47°N, and longitudes 75° and 125°E (Fig. 1; for a somewhat different version see Figure 2 of Liu, Dong and An, 1984 - Ed.). The main body of loess in China mantles hills and plateaus in the semi-arid steppes east of 100°E, and particularly around the famous Loess Plateau of the middle reaches of the Huanghe (Yellow

Figure 1: Distribution of loess in China - after Wang and Song (1983). Dashed line indicates southern limit of loess.

Figure 2: Geological section through loess deposits of Heimugou, near Luochuan, Shaanxi Province. Q_1 , Q_2 , Q_3 - Lower, Middle, Upper Pleistocene; N_2 - Late Pliocene. L - loess, S - paleosol. 1 - surface soil and underlying black soil, 2 - cinnamon paleosols, 3 - other paleosols, 4 - Malan Loess, 5 - Lishi Loess, 6 - Wucheng Loess, 7 - calcareous concretions, 8 - red clay. J - Jaramillo subchron, O - Olduvai subchron.

Figure 3: General view of Heimugou gully near Luochuan, looking downstream.

River) Valley (see title photo). Thick Quaternary loess and fluvial deposits are intercalated with each other in the eastern part of the Loess Plateau. Farther eastwards there are sporadic loess deposits on the North China Plain, the middle and lower reaches of Changjiang (Yangtze River) Valley and the islands along China's east coast.

Many workers have argued the origin of loess deposits, and in some regions debate continues. In China, however, there is general agreement that loess represents an accumulation of wind-borne dust and silt derived by deflation of surficial rocks in desert and arid areas to the north and west. Indeed, loess and desert areas together cover about 20% of the total area of China (approximately 1,900,000 km²), forming a closely connected "Desert-Loess Belt" (Liu, Dong and An, 1984). From west to east this belt crosses different environments, with deposits ranging from glacial to saline lake, fluvial-lacustrine and marine. In general, there is a northwest to southeast progression within this belt from rock desert and Gobi (gravel desert) to desert to loess, with desert and loess usually interfingering with each other along mutual boundaries (Wang and Song, 1983).

The constituent materials of loess deposits in China are similar to those in other parts of the world (Wang and Song, 1983). The grains are mainly silt size and average 0.005 mm to 0.05 mm, with none greater than 0.25 mm. Grains less than 0.005 mm generally make up 10-25% of loess, with older deposits tending to be more fine grained. More than 90% of the minerals contained are quartz, feldspar and muscovite, and over 20 heavy mineral species are commonly recognized. Illite, montmorillonite and kaolinite are the main clay minerals, and $CaCO_3$ is the most common soluble salt, making up 10-20% of the total volume, though other salts also occur. Surface markings on quartz grains, as observed under the SEM, are typical of wind abrasion, and broken shapes indicate mechanical disintegration following deposition.

General Stratigraphy

Extensive studies of the fossil content of loess deposits, and more recently of their geochemistry and paleomagnetism, have led to the recognition of four major units with many interlayered paleosols (Fig. 2). The lowest is an Early Pleistocene, reddish to light-brown, well-cemented and relatively fine-grained loess with fossils of Nihewan fauna (e.g. *Proboscoidipparian sinensis*). This Wucheng Loess reaches up to 100 m thick and rests conformably on reddish clays of Late Pliocene age. The boundary between the two coincides with the Gauss-Matuyama magnetic transition at 2.4 Ma ago (Heller and Liu, 1984). Indeed, as shown below, this is a good candidate for the Pliocene-Pleistocene boundary, for there were many biological and climatic changes at this level (Liu, Yuan and Lu, 1984; An, 1984).

The overlying Middle Pleistocene Lishi Loess is greyish brown with poorly cemented upper portions and mammalian fossils of Choukoutien fauna (e.g. *Megaloceras pachyosteus*). Spores and pollen remains indicate that woody plants, which dominate the lower layers, decreased in time in favour of shrubs and herbs. The thickness generally ranges between 40 and 70 m, rarely as high as 200 m.

The Late Pleistocene Malan Loess is greyish yellow, loosely cemented, coarse grained and contains substantial amounts of unstable minerals. Mammalian fossils (e.g. *Equus przewalskyi*) have been found, and palynological studies indicate that herbs predominated over bushes. The total thickness is generally 10-30 m. The Malan, like the Upper Lishi, is of Brunhes normal polarity.

At the top of the section is a thin (2-3 m) loess of Holocene age. This is a greyish yellow in colour, very loose, and with several black loams. The latter contain many Neolithic artifacts dating back to 5,000-9,000 yBP (Zheng, 1984).

Recent studies of Quaternary deposits in China show that since the Early Pleistocene there have been numerous periods of desertification, loess deposition and paleosol formation. These can be used to reconstruct paleoclimates, with eolian sand and loess indicating cold and dry climates and paleosols

Figure 5: Loess exposure at Heimugou, Luochuan. S5 is a clearly marked polygenetic cinnamon brown soil.

Figure 4: Loess profile on the wall of the Heimugou gully. The thickest paleosol (S5) stands out clearly.

formed on sand and loess indicating relatively warm periods with higher humidity. Thus, the occurrence of repeated sand-paleosol and loess-paleosol sequences in the geological record show that there have been alternating climatic changes from dry and cold to wet and warm.

For example, a profile at Yulin (north Shaanxi Province), where desert and loess deposits interfinger, consists of repetitions of eolian sand, representing periods of sand encroachment, and paleosol, representing periods of stabilization. Altogether more than ten periods of Pleistocene desertification are recorded here. However, the existence of multiple climatic fluctuations during the Quaternary can best be demonstrated in the 140 metre-thick loess profile at Luochuan (central Shaanxi Province) in the Loess Plateau. The more than 20 stages recorded here are described in the following.

The Luochuan Sequence

At Heimugou near Luochuan, the Loess Plateau is cut by numerous gullies on the walls of which the entire loess-paleosol series is well exposed (Figs. 3, 4 and 5). Here the sequence can be subdivided into two parts. The upper part extends downwards to 76 m beneath the surface and includes layers 1.1 Ma old and younger, belonging to the Upper Malan Loess and the Lishi Loess. There are 14 loess beds in all, numbered from L14 (oldest) to L1 (youngest), each overlain by a well-developed paleosol (S14 to S0).

The lower part, extending downwards from 76 m to 130 m, dates from 1.1 to 2.4 Ma and constitutes the lowest part of the Lishi Loess and the whole of the Wucheng Loess. Thick loess layers here (L15 to WL3) are interlayered with three closely grouped paleosol series (WS1, WS2 and WS3), which contain 4 to 5 soils intercalated with thin loess layers. At

Heimugou, the base of the loess rests on about 20 m of Upper Pliocene red clay deposited on an eroded surface of Jurassic sandstone.

Within the Luochuan section, there are 11 loess layers over two metres in thickness, each indicating a long dry and cold period. Among these, L1 (Malan Loess), L9 (the upper sandy loess) and L15 (the lower sandy loess) are the thickest, and most spectacular in the profile. Both L9 and L15 are important aquifers here, and even when exposed in gullies they are usually moist and covered by vegetation. Paleosols S1, S5 and WS2 are well developed cinnamon soils, with S5 a polygenetic complex of three superimposed cinnamon brown soils (Fig. 5). The latter is easily recognized in the field because of its clear stratigraphic position, greater thickness and redder colour.

Studies of the magnetostratigraphy of the Luochuan profile reveal that the Brunhes-Matuyama boundary, well established at 730,000 yBP (Mankinen and Darlymple, 1979), is situated in the middle to upper part of L8 (Fig. 2; Heller and Liu, 1982, 1984; Torii et al., 1983). The Jaramillo subchron (0.9 to 0.97 Ma) is located between L10 and L11, the Olduvai subchron (1.67 to 1.87 Ma) at the WS2 paleosol group, and the boundary between Matuyama and Gauss (2.48 Ma) is situated in the uppermost part of the Upper Pliocene red clay underneath the loess.

Using these levels as markers, the rate of loess deposition can be determined (An, Geng and Zheng, in press). The initial age of each pair of the paleosol and loess layers can be calculated from the ratio of each paleosol-loess to the total amount of sedimentation (g/cm^2) within a certain time period. Extrapolating the depositional rate for the period 0.97 to 1.67 Ma, the start of deposition of the Luochuan loess-paleosol sequence is estimated at 2.4 Ma ago.

Paleoenvironments of the Luochuan Sequence

Valuable information on the paleoclimates and paleoenvironments of the Pleistocene can be obtained from a comparative study of the sediments. The genetic types of loess and paleosol, their pollen and micromammalian fossils, differences in grain size distribution, magnetic susceptibility, CaCO_3 content, and other geochemical indicators are all tools for understanding the past. Particularly useful in this respect has been a comparative study of the geographical distribution and climatic zonation of paleosols, fossil snail assemblages (Chen, Lu and An, 1982) and the pollen content (Zhou, Liang and Liu, 1982) of the different loesses and paleosols with those of recent loesses and soils.

On the basis of granulometric, geochemical and micromorphological studies of the upper part of the Luochuan sequence, it is possible to differentiate the loess into

Figure 6: Climatic fluctuation curves as shown by various textural, chemical and magnetic parameters. For legend see Figure 2.

weakly weathered, medium weathered, and strongly weathered loess (Fig. 7). This division is also assisted by determination of the clay and CaCO_3 contents and the $\text{Fe}_2\text{O}_3/\text{FeO}$ ratio, which indicates the degree of weathering and maturity of the loess (Fig. 6).

Under the microscope, the paleosols can be distinguished on the basis of structure and texture. Black, calc-cinnamon, cinnamon (leached), luvic cinnamon and brown cinnamon soils can be identified (Fig. 7). Comparisons with their present-day analogs indicate (Lu and An, 1979) that these paleosols formed in environments ranging from drier, cold desert steppe (black soil) to warmer, more humid forest steppe (brown cinnamon soil).

For example, similar soils to the S5 cinnamon brown group at the top of the Lower Lishi Loess at Luochuan now exist in eastern China (Shandong Peninsula) where the mean annual temperature is $12^\circ\text{--}14^\circ\text{C}$ and average annual precipitation is 700–1,000 mm. The present day counterparts at Luochuan are 10°C and 500 mm. Thus 0.56 to 0.46 Ma ago the mean annual temperature at Luochuan was $2\text{--}4^\circ\text{C}$ higher and the average yearly precipitation 200–500 mm greater than today.

Similar studies have also established that the weakly weathered loess at Luochuan developed in a relatively arid environment with a mean annual temperature of about 0°C and a mean annual precipitation of about 200 mm. The variations in the mean precipitation and temperature at Luochuan since 1.1 Ma can also be reconstructed from modern synoptic data on this region (Fig. 7). The maximum fluctuation of the mean annual temperature is estimated to be from 0°C to 14°C , and that of mean annual precipitation from 200 mm to 800 mm (Liu et al., in press).

For the last 2.4 Ma, climatic fluctuations can also be reconstructed (Fig. 6) from the vertical distribution of the average grain size ($M\Phi$), the ratio of coarse silt to clay (K_d/C_l), the CaCO_3 content, and the $\text{Fe}_2\text{O}_3/\text{FeO}$ ratio (weight percentage), as well as the magnetic susceptibility (S1). In general, the coarser the average grain size the stronger the velocity of the transport agent (wind) and the drier the climate, as compared to finer average grain size deposits. A higher content of CaCO_3 is also characteristic of soil and loess in dry and cold environments as compared with those of humid and warm environments where the soluble CaCO_3 is usually removed by the percolating water.

As regards the $\text{Fe}_2\text{O}_3/\text{FeO}$ ratio, in a dry and cold environment iron usually exists as FeO, but in a humid and warm climate Fe_2O_3 is the prevalent state. Lower ratios of Fe_2O_3 to FeO, and coarser average grain sizes, higher CaCO_3 contents, and lower susceptibilities thus indicate dry, cold climate environments (desert steppe) whereas the converse indicates warmer humid conditions (forest steppe).

The climatic curve for the loess-paleosol series of Luochuan during the past 2.4 Ma can also be correlated (Figs. 6 and 7) with the results of Pacific Ocean deep-sea cores studied by Shackleton and Opdyke (1973, 1976; see also Kukla, 1970). Here loess L1 correlates with stages 2, 3, and 4 of the oxygen isotope curve, and paleosol S1 correlates with stage 5. Other

earlier loess layers correlate with even numbered stages and paleosols with odd numbered stages of the oxygen isotopic curve. The polygenetic soil S5 is tentatively correlated with stages 13, 14, and 15. This correlation from land to sea shows that the Quaternary climatic fluctuations revealed by the Luochuan sequence are synchronous with those in the deep sea and hence of worldwide significance. This is the most important conclusion reached from the study of Chinese loess.

Major Events Recorded in the Loess-Paleosol Sequence

The characteristics of the climatic fluctuation revealed by the Luochuan profile show that prior to the Matuyama chron, and especially before the Jaramillo subchron, there were more fluctuations with smaller amplitude, and the climate was comparatively warm and humid. In contrast, the later Brunhes chron had fewer fluctuation cycles but larger amplitude oscillations and was cooler and drier.

Several other important geological events are clearly recorded in the loess-paleosol sequence. The red clay, together with its abundant elephant, rhinoceros and other animal fossils, is well known as the product of a warm and humid climate, and the appearance of the loess at 2.4 Ma records an abrupt climatic deterioration to cold and dry. At the same time, paleontological evidence demonstrates a change (at the base of the Wucheng Loess and the top of the underlying red clay) in the ancestral form of the mole-rat *Prosiphneus intermedius* to its modern counterpart *Myospalax omogodon* (Teilhard de Chardin and Young, 1931; Liu et al., 1982). These burrowing mole-rats adapted ecologically to

Figure 7: Different loess-paleosol types in upper part of Luochuan sequence. Paleoenvironmental parameters based largely on comparison with present-day soils. 1 - weakly weathered loess, 2 - medium weathered loess, 3 - strongly weathered loess, 4 - black loessial soil, 5 - calc-cinnamon soil, 6 - leached cinnamon soil, 7 - luvic cinnamon soil, 8 - brown cinnamon soil.

underground living and flourished in the soft loess during cold periods. Could this sudden climatic change indicate the beginning of the continental Pleistocene?

In northern China, other Pliocene-Pleistocene deposits also record this geological event. At Nihewan, the type locality of the Chinese Villafranchian, the Chengqiang profile at the 2.4 Ma level records the first appearance of the true horse (*Equus sanmenniensis*; Tang and Ji, 1983). In the Dongyaozitou profile here, the Pliocene/Pleistocene boundary as indicated by the early and middle Villafranchian fauna occurs near the 2.5 Ma level in the magnetostratigraphic record (Li and Wang, 1982).

A climatic deterioration at this time is indicated by foraminifera and nannofossils characteristic of cold water and a subarctic environment. Near Beijing, in the suburban district of Shunyi, at about 428 m below the surface a bore hole reached marine bed in fluvial loess deposits yielding typical Early Pleistocene forams including *Hyalinea balthica* (An et al., 1979) and the nannofossils *Coccolithus pelagicus* and *Emiliania huxleyi* (Wang and He, 1982). Paleomagnetic data indicate that the age of this marine layer is 2.3 Ma.

In northern China there are a series of intermontane basins such as the Yushe, Yangyuan and Huailai, which are filled with Quaternary fluvio-lacustrine deposits. Recent paleomagnetic work shows that the Matuyama-Gauss boundary here coincides with a shift from fine-grained, green clayey lacustrine deposits to coarse-grained, yellowish calcareous fluvial-lacustrine sediments (Li and Wang, 1982). All this evidence indicates a widespread deterioration in the climate of northern China about 2.3-2.4 Ma ago.

Figure 8: A - Variational sequence of indirect climatic indices for the Luochuan loess-paleosols. B - Autospectral characteristics of the Luochuan sequence. See text for explanation

Table 1		
The time sequence (in thousand years before present) of loess-paleosol sequence in Luochuan since 1 Ma ago. See text for explanation.		
Sequence	Model I	Model II
S0	10	10
L1	95	70
S1	140	140
L2	200	200
S2	250	250
L3	300	290
S3	330	330
L4	375	350
S4	410	410
L5	460	446
S5	555	555
L6	642	630
S6	660	660
L7	700	705
S7	720	720
L8	742	740
S8	770	770
L9	870	822
S9	900	900
L10	920	920
S10	940	940
L11	960	957
S11	970	970
L12		

A climatic change from warm to cold around 2.2 to 2.3 Ma ago has also been detected in other important continental and marine profiles, such as at Osaka (Itihara and Kemei, 1982). In Australia, at Lake George, the Matuyama/Gauss boundary marks the change of the lake from a dry phase to a deep water phase (Singh, Opdyke and Bowler, 1981). Shackleton and Opdyke (1977) have reported evidence from deep-sea core V28-179 of a great expansion in ice cover about 2.5 Ma ago. A pronounced climatic change around 2.5 Ma ago from warm to cold has also been detected in the Black Sea (Hsu and Giovanoli, 1979). Thus, it seems that at around 2.3-2.4 Ma ago, at the beginning of the Matuyama chron, there occurred a geological-climatological-biological event of such magnitude that it should be regarded as the beginning of the Quaternary.

A second major event detected in the Chinese loess-paleosol sequence is the climatic optimum event of the Olduvai subchron, 1.72 to 1.88 Ma ago. Recent palynological studies show that the WS2 paleosols in the Wucheng Loess dating from this interval consist of a group of dull brownish red soils with pollen of broad leafy trees, such as *Betula*, *Quercus*, *Rhus*, and *Alnus* (Zhou et al., in press). These indicate a climatic optimum.

Following a period of steppe vegetation, two cold dry episodes are indicated on the Loess Plateau by two well-developed and easily recognized sandy loesses, of which the upper (L9) was deposited 0.8 Ma ago and the lower (L15) at 1.15 Ma ago. These layers might represent repeated southward advances of the dune sand from the Ordos Desert in the north (K. Hsu, personal communication), and also the development of a desert-steppe vegetation. The 0.8 Ma episode may be correlated with oxygen isotopic stage 22 of deep-sea core V28-238 (Fig. 6).

From 0.56 to 0.46 Ma ago, there was a climatic optimum and soil forming event, represented by the development of the S5 group of cinnamon brown soils. This climatic optimum may be correlated with layer 10 of Locality 1 at Choukoutien, the cave of Peking Man (*Homo erectus pekingensis*) near Beijing, where the human fossil-bearing travertine and fine-grained deposits represent a warm climate, suitable for hominoid occupation (Liu, 1982). This climatic event was also of worldwide significance.

Environment of Early Man in North China

The geological age of Peking Man at Choukoutien cave is 0.46-0.23 Ma, according to various dating methods (Zhao, Liu and Ma, 1982). This time span for the occupation of the cave is rather long. A related subspecies, the Lantien Man (*Homo erectus lantienensis*) was discovered in the loess-paleosol sequence at Chenjiawo and Gongwangling near Lantien south of Xian (Woo, 1964, 1966). At the Chenjiawo locality, the stratigraphical position of fossil man was found to be equivalent to S6 (0.66 Ma) on the Luochuan scale, whereas at the Gongwangling locality, the fossil hominoid layer was assigned either to L9 (0.8 Ma) or to L15 (1.15 Ma) of the Luochuan profile. In North China therefore, ancient man might have appeared as early as 1.15 Ma ago, living at the southern part of the Loess Plateau near the Qingling Mountains for at least 300,000 years. Later, around 0.46 Ma, Peking Man migrated to the north, occupying Choukoutien caves for another 230,000 years.

Spectral Analysis of the Loess-Paleosol Series

For a further understanding of the characteristics of the time framework of the loess-paleosol series, the variation of different elements down the profile was studied. The coarse silt/clay ratio (Kd/cl), the CaCO_3 content, the $\text{Fe}_2\text{O}_3/\text{FeO}$ ratios, and the susceptibility (K) were chosen for a multispectral analysis (Lu and An, in press). Two time models were designed (Fig. 8). In model I, one loess-paleosol pair was selected as a calibration unit, and its absolute age determined by interpolation from the magnetostratigraphic

time scale. Table 1 shows the time span of each loess and paleosol as calculated from the depositional rate and the magnetostratigraphy.

Using the initial age of each loess-paleosol pair calculated from model I and the ratios of cold and warm stages within each climatic cycle as recorded by the oxygen isotopes in cores V28-238 and V28-239, the ages of the loesses and paleosols have been calculated for the last one million years to establish model II (Table 1).

The results of this analysis show that there were major oscillations in geological-climatological events at Luochuan with periods of about eighty, forty, and twenty thousand years. The prevailing period of oscillation of about 80,000 years generally indicates the mean duration of the paleosol-loess cycles. If 15,000 years before the present is taken as the beginning of the present maximum cold episode, a periodicity about 20,000 years raises the possibility that a dry and cold glacial climate might reoccur in only another 5,000 years!

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Photo not available!

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