Reconstruction of palaeoprecipitation values for the Chinese loess plateau from proxy magnetic data

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INTRODUCTION

In N.C. China, the spatial and temporal coverage of windblown dust (loess) deposits, and their interbedded buried soils (palaeosols), renders them the most complete terrestrial record of climate change for the Quaternary. The loess was formed by aeolian transport from extensive adjacent dust sources (eg the Gobi desert, the Tibetan plateau), and subsequent deposition over arid/semi-arid regions within an area trending W-E, between lats. 33° - 47°N and longs. 127° - 75°E (nearly 0.5 million km^2). Loess formation was at a maximum during cool, dry climatic periods. During warmer, wetter stages, dust transport was greatly reduced, vegetation colonised the loess surface, and in situ weathering and soil development were initiated. In summary, undisturbed horizontal accretion of the loess, and its periodic *in situ* weathering to soil horizons, produced the horizontal 'stripes' of pale loess and reddened palaeosol, traceable over hundreds of kilometers.

The thickest sequences of loess, in the western and central parts of the Loess Plateau, exceed 300m. In the eastern and southern areas, they are thinner and finer- grained. These variations span a contemporary climatic gradient, from relatively dry in the west (330mm rainfall p.a.) to increasingly humid in the south and east (eg. 580mm in Xi'an, 650mm in Baoji).

MAGNETIC PROPERTIES OF THE CHINESE LOESS/SOIL SEQUENCES

In *directional* terms, the loess sequences contain a detailed palaeomagnetic record. Matching of their reversal magnetostratigraphy with the geomagnetic polarity timescale shows that loess deposition began about 2.5 million years BP (Heller *et al.*, 1984). The *non- directional* magnetic properties of the loess reflect the mineralogy, concentration and grain size of magnetic iron species present. Kukla *et al.*, (1988) followed the earlier work of Heller & Liu (1984) by showing that field measurements of magnetic susceptibility (MS) provide precise differentiation between loess layers and palaeosol layers, even where the latter are very weakly developed. MS values are higher (by a factor between 2 - 5) in the soils than in the loess. They also noted the striking degree of correlation between the loess/soil MS record and the oxygen-isotope record of the deep-sea (Figure 1).

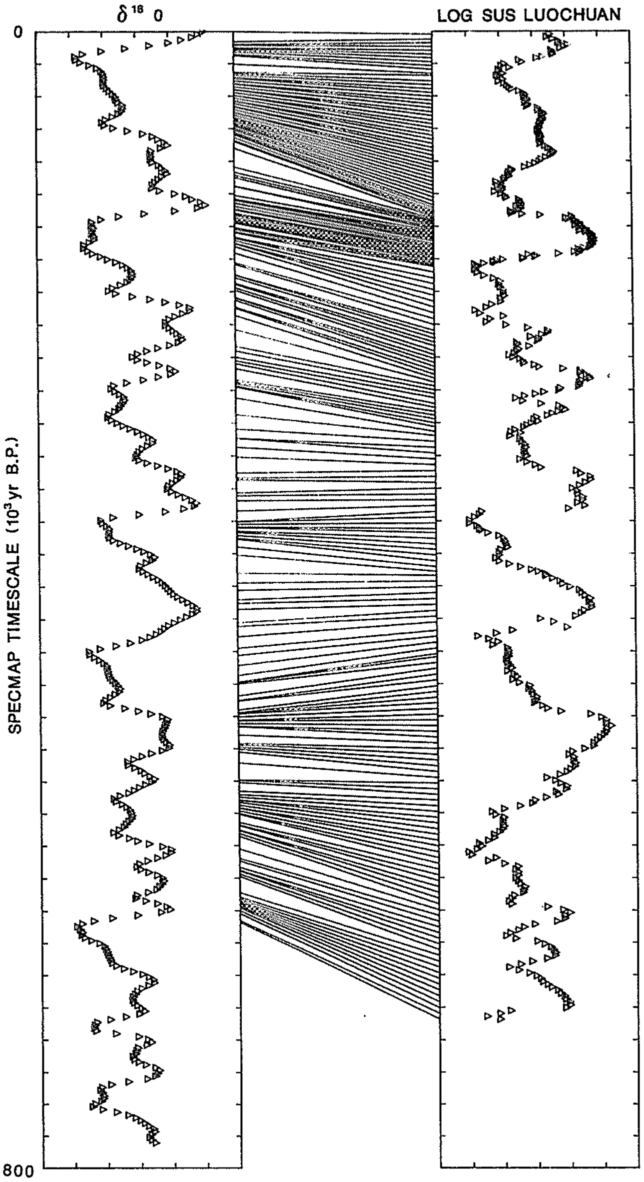

Figure 1. Loess-soil MS record from Luochuan compared with deep-sea stable isotope (after Kukla et al. 1988).

This correlation indicates linkage between the N. hemisphere atmospheric processes driving mid-latitude continental glaciation and those controlling Asian dust transport and soil development. To reconstruct past climatic data from the proxy magnetic data requires understanding of the source of the magnetic variations, and how it responds to climatic forcing. Heller & Liu (1986) suggested the higher MS of the palaeosols resulted from accumulation of detrital (aeolian) magnetic minerals due to leaching of calcium carbonate and soil compaction processes. Kukla *et al.*, (1988) proposed the MS signal came from atmospheric input, from high-level transport of sub-micron particles of magnetite. They infer dilution of the magnetite concentration during cold, dry periods, when local, low-MS dust was deposited, and non-dilution during interglacials, with low rates of loess deposition.

These models rely on two assumptions which we show are invalid (Maher & Thompson, 1991). First, Kukla *et al.*, assume a constant rate of magnetite accumulation across the Loess Plateau. We have measured samples from correlated palaeosol horizons from 6 sites across the Plateau, which show consistently lower magnetic content in the west than in the south and east (Figure 2).

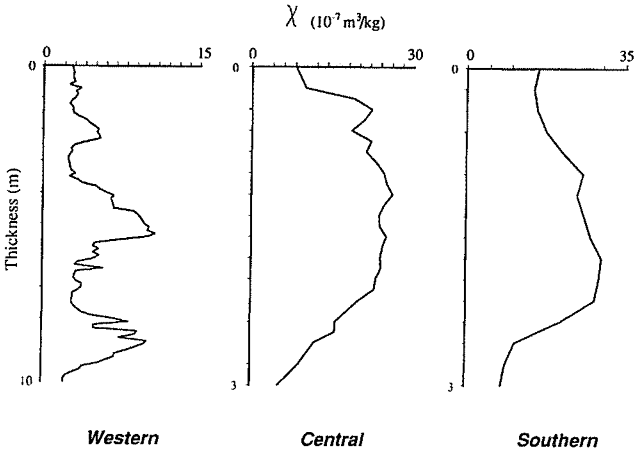

Figure 2. Magnetic contents v. depth for western, central and southern sites.

Second, both the Kukla and Heller & Liu models assume there are no differences in the grain size of the magnetic minerals in the loess and soils. Applying detailed rock magnetic analyses to soil and loess samples from our 6 Plateau sites, we find the soils contain not just higher magnetic concen-trations, but also distinctively ultrafine (nannometer-scale) magnetic grain sizes. Importantly, neither the Kukla nor the Heller model allows for *in situ* formation of magnetite during soil development, a phenomenon reported for a range of contemporary soils in the humid temperate zone (eg. Maher & Taylor, 1988; Fassbinder *et al.*, 1990).

PEDOGENIC FORMATION OF MAGNETITE - THE CLIMATIC LINK

We have used scanning and transmission electron microscopy (SEM, TEM) to examine magnetic grains extracted from loess and palaeosol samples by high-gradient magnetic extraction. A strongly bimodal grain size distribution is present in both sample types. Using SEM, large (> 2mm) geometric crystals are observable, with variable amounts of titanium-substitution, and variable degrees of weathering and surface damage (Figure 3, a and b).

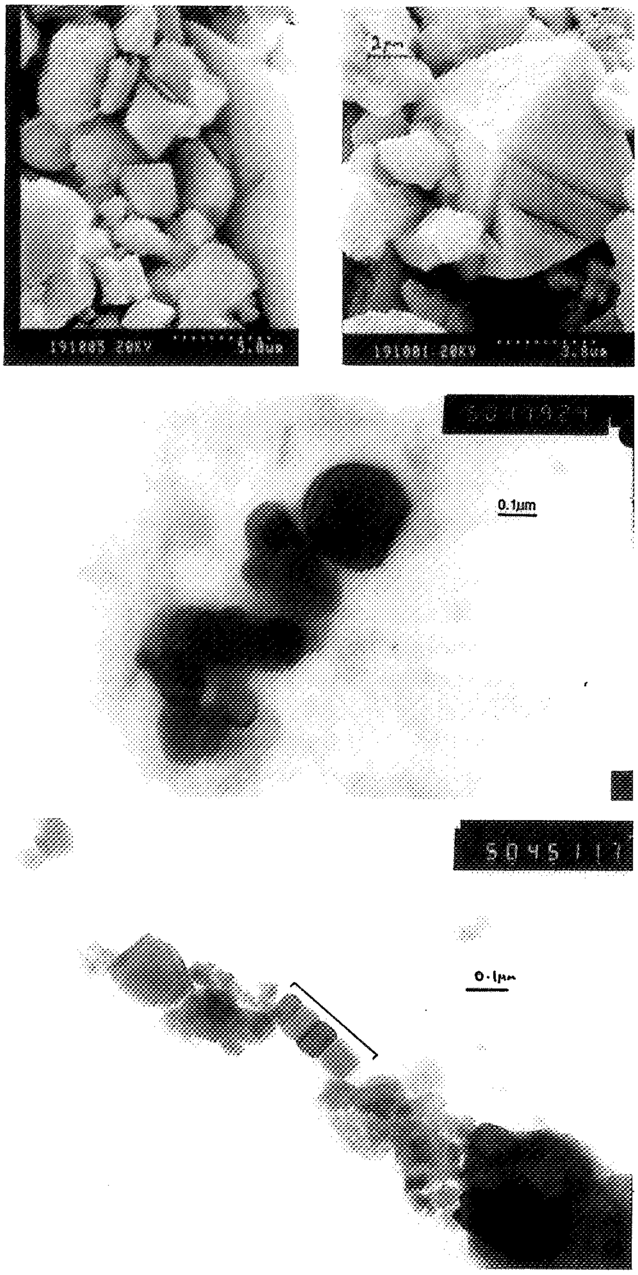

Figure 3. TEM images f magnetic grains from loess and palaeosoil. (a) top left; (b) top right; (c) centre; (d) bottom.

These are detrital, lithogenic magnetic grains, brought to these sediments by aeolian transport. Using TEM, the sub-micron part of the magnetic assemblage can be resolved. Two distinct types of ultrafine grain are present: Type A grains occur as a mixture of grain sizes (10nm - 200nm); Type B grains occupy a very narrow grain size (~50nm), and are occasionally seen in intact chains (Figure 3, c and d).

Quantitative analysis is difficult, but Type A grains appear to be dominant. These 2 groups of sub-micron grains are authigenic in origin, and occur in much higher concentrations in the palaeosols than in the unweathered loess. Type A grains are formed by uncontrolled, inorganic precipitation of magnetite within the soil micro-environment. The link to climate, and rainfall in particular, is that this process requires formation of Fe^{2+}, either by Fe-reducing bacteria in locally wet, anoxic zones, or by the action of organic phenols. As the soil dries and oxidation proceeds, the Fe^{2+} can react with Fe^{3+} oxides to form the mixed Fe^{2+}/Fe^{3+} compound, magnetite (Taylor *et al.*, 1988; Tamaura *et al.*, 1983). Type B grains are formed by controlled, organic precipitation within the cells of magnetotactic bacteria (Blakemore, 1982). One Fe-reducing bacterium supplies the Fe^{2+} for inorganic precipitation of hundreds of magnetite crystals (of uncontrolled but ultrafine grain size), whilst one magnetotactic bacterium makes tens of crystals, of intracellularly- controlled dimensions. The inorganic process produces many ultrafine, superparamagnetic (SP) grains, which contribute disproportionately to measurements of MS (Maher, 1988). Statistical analysis suggests that 90% of the loess MS record is contributed by SP grains (Maher & Thompson,1992). Because of their large surface area, these crystals are prone to oxidation to maghemite, another strongly magnetic iron oxide.

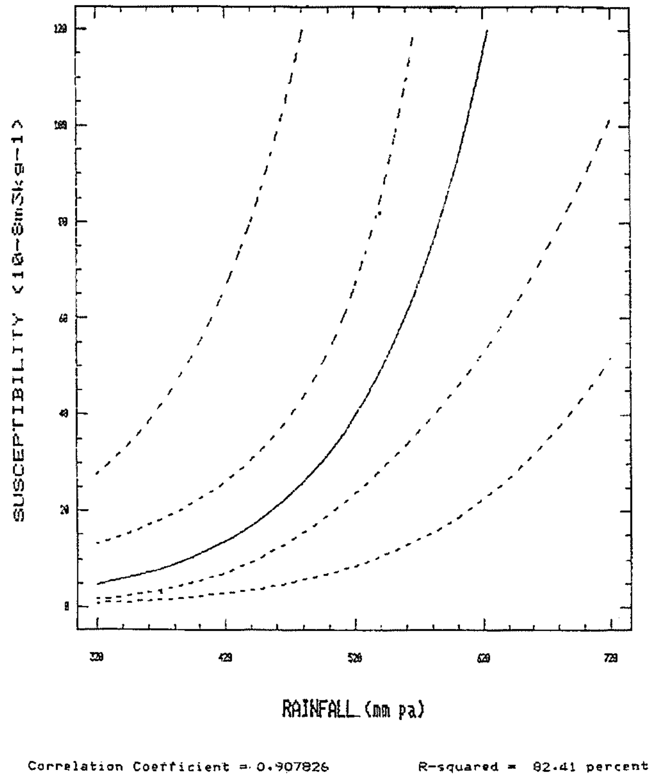

Figure 5. Regression of susceptibility on rainfall for young soils of the Loess Plateau.

Field and laboratory observations show that optimum conditions for pedogenic formation of magnetite occur in warm, seasonally wet areas in well-drained, near-neutral pH soils. Deserts (hot or cold) are too dry to make magnetite. Poorly-drained soils cause its dissolution.

If loess deposition in China had proceeded without intermittent weathering and soil formation, the magnetic signal would vary little, the detrital magnetites of the loess contributing a very low MS of $\sim 20.10^{-8} m^3 kg^{-1}$. But with periods of reduced dust input and prolonged soil formation, low concentrations (<1%) of magnetically- distinctive ultrafine magnetite (variably oxidised to maghemite) developed in response to seasonal rainfall and resultant reduction/ oxidation conditions within the soil. This is the specific link between the MS record of the Chinese loess/soils and climate change.

RECONSTRUCTION OF RAINFALL FROM MAGNETIC SUSCEPTIBILITY

The soil-forming relationship, S (Soil) or s (a soil property) = function{climate, relief, parent material, organisms and time} can be converted into a climofunction for the Chinese palaeosols, as all of the factors other than climate can reasonably be assigned as constants. Such a climofunction can be established directly as we find a strong relationship between present rainfall (the 1958-88 mean) and the MS of young (<5kyrs) soils in the Loess Plateau (Figure 5). This MS-rainfall climofunction allows us to calculate past rainfall values for the early Holocene and the last interglacial from magnetic measurements. The results (Table 1) indicate much higher rainfall for both these times in the presently semi-arid western area around Lanzhou, Linxia, Baxie and, particularly, Baicaoyuan.

Table 1: Reconstructed Rainfall Values

	SO	S1	Now	SO-Now	S1-Now
Luochuan	656	696	630	+26	+66
Xifeng	636	693	550	+86	+143
Linxia	616	598	500	+116	+98
Yulin	522	479	400	+122	+79
Liujiapo	676	711	580	+96	+131
Baoji	654	704	650	+4	+54
Lanzhou	450	457	330	+120	+127
Jixian	-	646	550	-	+96
B'caoyuan	608	644	350	+258	+294
Baxie	637	-	460	+177	-

NB 2SE = +/- 20-100mm rain p.a.

Only slightly wetter conditions are indicated for Baoji and Luochuan, which have the highest contemporary rainfall. The marked increase in rainfall inferred for the western plateau area suggests intensification and northward penetration of the Indian summmer monsoon. At present, the eastern monsoon is dominant (eg Baicaoyuan, currently in a rainshadow to the west of the Liupan Shan range, has 350mm rain p.a.; Xifeng, to the east, has 550mm p.a.). The Indian monsoon would strengthen if the zone of maximum summer heating shifted from N. Pakistan to a more central Asian position. We find good agreement between these reconstructed rainfall values and General Circulation Model data for these time slices (9 and 126 ka).

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