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Holocene loess accumulation and soil development at the western edge of the Chinese Loess Plateau: implications for magnetic proxies of palaeorainfall

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Abstract

A high-resolution Holocene sequence of loess, palaeosols and incipient soils at the western edge of the Chinese Loess Plateau, dated using optically stimulated luminescence techniques, is used to identify the respective influence of dust accumulation rate, time and climate on soil magnetic properties. Dust deposition and soil formation have both been quasi-continuous through the Holocene at this site; the soils are thus accretionary in nature. The degree of soil development (as indicated both by geochemical and magnetic properties, which correlate strongly) varied through the Holocene. Compared with the less-weathered loess units, each palaeosol is enriched in nitrogen and organic carbon, depleted of carbonate due to leaching, and displays higher values of pedogenic magnetic susceptibility, frequency-dependent susceptibility (%), remanences and magnetisation. Magnetic grain size indicators show that the pedogenic ferrimagnets are ultrafine, of single domain and superparamagnetic dimensions. Sediment accumulation rates were lowest from ~12 to 2.5 ka, providing ample time (100 s of years) for weathering and soil formation to proceed, yet pedogenesis through this interval was relatively weak. Conversely, soil development was stronger during later intervals—when loess accumulation rates were higher, and soil-forming intervals were correspondingly shorter. In terms of Jenny's (1941) soil-forming equation, accumulation rate (and thus time), sediment source (parent material) and topography show no systematic variation between the loess and the palaeosols. Therefore, climate seems to be the key soil-forming factor which has controlled the geochemical and magnetic properties of these Holocene palaeosols.

1. Introduction

The magnetic properties of the loess and interbedded palaeosols of the Chinese Loess Plateau have been identified as a quantitative proxy of palaeorainfall, through the Quaternary period (Heller et al., 1993; Maher et al., 1994; Liu et al., 1995; Han et al., 1996). Magnetic, geochemical and microscopy data from modern soils across the Loess Plateau, and also from an increasing number of northern hemisphere temperate zone sites (Maher et al., 2002), indicate that the basis of the observed magnetic/climatic couple is the pedogenic formation of ultrafine (<0.1 μm), superparamagnetic (SP) and single domain (SD) grains of the strongly magnetic iron oxide, magnetite. The link with climate, and especially rainfall, rests on the premise that magnetite is a mixed Fe^{2+}/Fe^{3+} iron oxide and so its in situ formation, in the trace amounts responsible for the observed magnetic enhancement in soils, requires the initial presence in the soil matrix of some Fe^{2+}:

$$2OH^{-}+Fe^{2}+2Fe(OH)_3 \rightarrow Fe_3O_4 + 4H_2O.$$

Reduction of Fe^{3+} can occur even in generally oxidizing, well-drained soils in response to wetting of the soil matrix. Physiologically diverse, Fe-reducing bacteria (Bell et al., 1987) can 'switch on' in temporarily anoxic soil micro-sites (Maher, 1986). Soils show increased magnetic susceptibility when drying follows short periods of wetness (Le Borgne, 1955), suggesting that upon re-oxidation of these micro-environments, extra-cellular precipitation of ultrafine-grained magnetite can

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result (Tamaura et al., 1983; Lovley et al., 1987; Maher and Taylor, 1988). Due to their large surface/volume ratio, these grains can subsequently oxidise to maghemite. The distinctive magnetic grains found in the Chinese palaeosols match those found in similarly buffered, well-drained modern soils, free from the effects of burning or pollution (Maher, 1998), and those synthesised under laboratory conditions realistic in terms of the soil environment (Taylor et al., 1987).

The model of a dominantly pedogenic magnetite source predicts a testable and direct causal correlation between rainfall and soil magnetic properties, in well-drained, near-neutral soils. For a range of alkaline or near-neutral, temperate, well-drained soils, strong correlation is found (Maher and Thompson, 1995; Maher et al., 2002) between annual rainfall and pedogenic magnetic susceptibility (i.e. susceptibility$_{\text{A or B horizon}}$ $-$susceptibility$_{\text{C horizon}}$), up to a maximum of around 1500 mm rain/yr (when soils become too leached and acidic to support magnetite formation). In contrast, however, Kukla et al. (1988) proposed that the major process responsible for the Chinese loess/soil magnetic contrasts is magnetic 'dilution', controlled by a constant 'rain-out' of fine-grained magnetite from the atmosphere and a varying rate of accumulation of weakly magnetic windblown dust. According to this model, soils have higher magnetic concentrations due to reduced sedimentation rates and loess units have lower magnetic concentrations due to increased sedimentation rates. Indeed, Porter et al. (2001) claim that 84% of the magnetic susceptibility variance of modern soils across the Chinese Loess Plateau can be accounted for by 'dust dilution' effects.

Given the scarcity of proxies for robust and quantitative reconstruction of palaeoclimate, essential for testing of climate model postdictions and predictions, and the significance of Asian monsoon variations in this highly populated region, it is important to test the validity of these two contrasting interpretations and hence the reliability of the proposed magnetism/rainfall link. Tests have so far been made on a spatial scale, examining soil magnetism/climate relationships in different geographic regions (Maher et al., 2002; Maher and Thompson, 1995). Here, we examine the temporal dimension, through detailed analysis of dust accumulation and soil formation rates in a high-resolution Holocene sequence of loess and palaeosols, to identify the respective roles of accumulation rate, time and climate for soil magnetic properties.

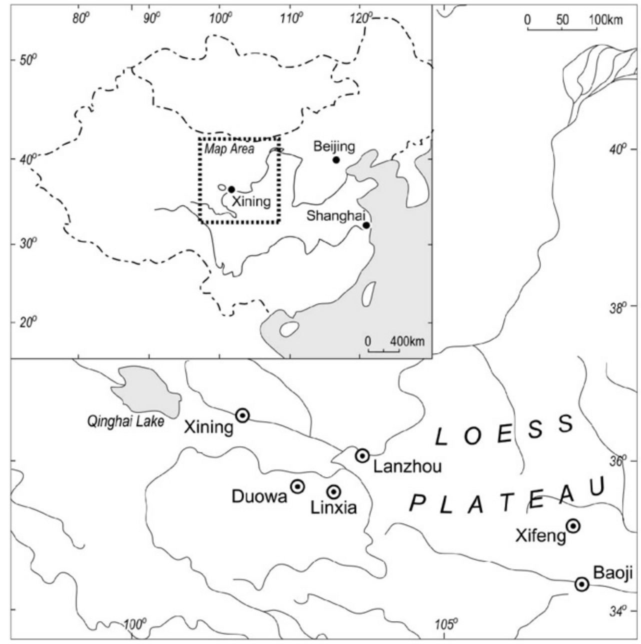

Fig. 1. Location map showing the Duowa site. The loess/soil sequence is exposed in a terrace of the Linwusu river (a tributary of the Huang He), to the west of the Chinese Loess Plateau, Qinghai Province (N35°39′; E102°38′), at approximately 2000 m altitude.

Fig. 2. The loess/soil sequence at Duowa (photo: Zhou, L.P).

2. Site and methods

A 4.6 m thick Holocene loess/palaeosol sequence, located at Duowa, Qinghai Province (Figs. 1 and 2) at the semi-arid western edge of the Loess Plateau, exhibits at its surface a modern, agricultural soil and below this, multiple palaeosols interbedded with less-weathered loess. Three of the palaeosols are visually obvious as darker layers in the otherwise light-coloured loess (Fig. 2); all, including incipient soils, can be detected by field measurements of magnetic susceptibility. We sampled this section at 5 cm intervals for magnetic, geochemical and particle size analyses. Additionally, 19 samples were taken for dating by optically stimulated luminescence (OSL), to provide the most detailed record yet obtained of Holocene dust accumulation and soil formation rates. The OSL methods and results are discussed in detail by Roberts and Wintle (2001) and Roberts et al. (2001).

Magnetic analyses (susceptibility, frequency-dependent susceptibility, anhysteretic remanence, isothermal remanence, saturation magnetisation, coercive force, and high-field susceptibility) were applied to all samples collected. Carbonate was determined using gasometric methods, and total nitrogen and organic carbon by CHN analyzer. Particle size was determined by laser analysis using a Coulter Counter LS 130.

3. Results

The OSL dating shows that the sequence spans the entire period of the Holocene; the data indicate that dust deposition has been quasi-continuous from ~12 ka to the present day (Fig. 3). There is no evidence of any significant hiatus in dust deposition through the entire sequence. The dust accumulation rate was lowest from ~12 to ~2.5 ka (~20 cm/kyr). It increased from ~2.5 ka to ~34 cm/kyr and increased again (to ~80 cm/kyr) from 0.68 ka to the present day (Fig. 3). For the upper ~1.3 m of the section, the OSL, magnetic and particle size data (Figs. 3–5) all indicate major human agricultural impact (Roberts et al., 2001); this part of the sequence will thus be excluded from subsequent discussion. An earlier but more minor episode of disturbance is indicated by two unexpectedly high OSL ages at 2.2 and 2.3 m depth. However, sedimentation was continuous from 2.2 to 1.3 m depth, no extraneous material appears to have been artificially added in this interval, and loess and soil units alternate, apparently unaffected by the subsequent episode of disturbance at the site.

Two of the visible palaeosols (PS3 and 5) and one of the less-developed soils (PS4) are bracketed by OSL dates. Although only a limited number (⩽3) of OSL ages relate to each palaeosol, it appears (Figs. 3 and 5) that there is little difference in the sedimentation rate for each palaeosol and for the loess immediately over- or underlying it. If anything, the rate of dust deposition during the time of strongest palaeosol formation is slightly higher than that during loess formation. For this site, therefore, soil formation has operated contemporaneously with the continuous accumulation of dust—a phenomenon observed previously for older palaeosols elsewhere in the Chinese Loess Plateau (e.g. An et al., 1990; Kemp et al., 1996). The palaeosols are thus accretionary; hence, the duration of the soil-forming period can be calculated for each palaeosol. For the visible soils, the OSL ages suggest that PS3 (~25 cm thick) formed in <300 yr and PS5 (~35 cm thick) in <1800 yr.The remaining weakly developed soils do not have bracketing dates but soil-forming intervals can reasonably be estimated based upon their thickness and the calculated sedimentation rate. PS2 (~20 cm thick) formed in <450 yr, PS4 (~15 cm thick) in <200 yr, PS6 (~25 cm thick) in ~1250 yr, and PS7 (~15 cm thick) in ~750 yr.Given the number of soils formed within just a few thousand years (e.g. from 1–2.5 m depth, four palaeosols formed within 2000 yr), any delay between dust deposition and onset of weathering appears to have been minimal. Hence, these are likely to be realistic estimates of the soil-forming durations.

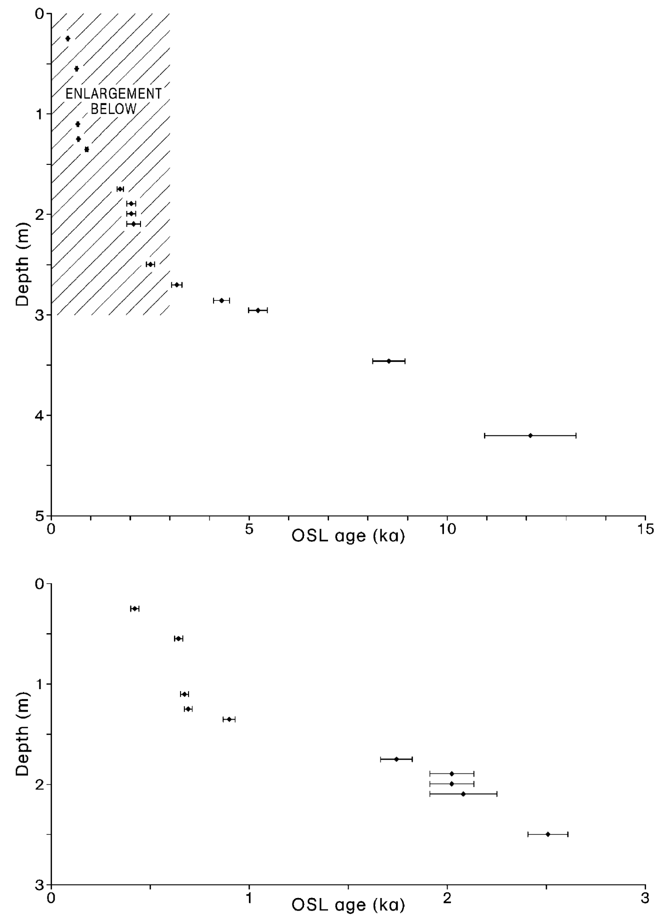

Fig. 3. OSL chronology, with the OSL data for the upper 2.5 m also being shown on an expanded scale for clarity. For the OSL ages, errors are typically ⩽ 5% (see Roberts et al., 2001).

Having established the timing and duration of soil formation, the degree of development of each of the Duowa palaeosols can be assessed from the geochemical and magnetic data (Fig. 5). The geochemical data vary with the stratigraphy and also correlate with the magnetic data (Figs. 5 and 6). Organic carbon values range from ~0.1% in the least-weathered loess, to ~0.5–1% in the least developed palaeosols and ~1.5% in the more developed soils. Total nitrogen values follow a similar pattern, being higher in the soils and varying

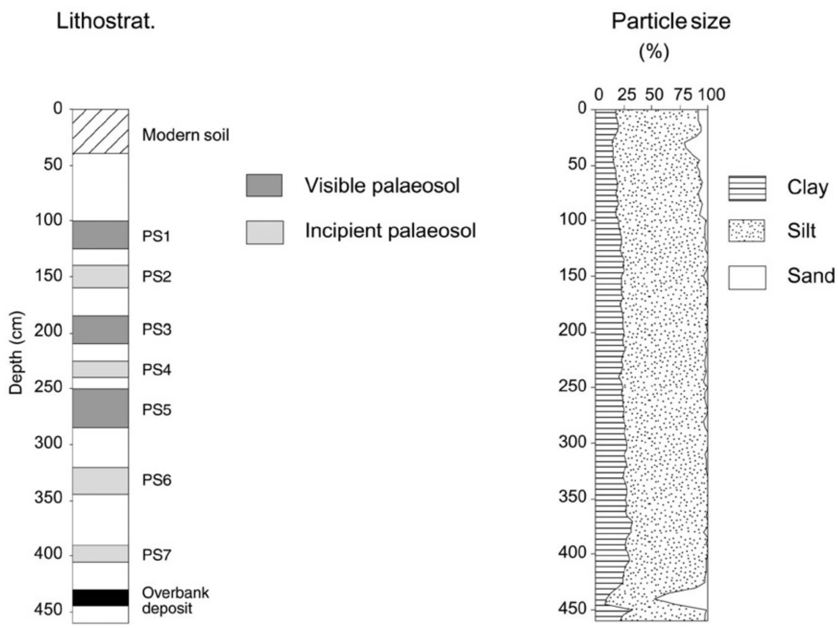

Fig. 4. Stratigraphy and particle size data for the Duowa section. 'Soils' are distinguished from 'loess' based on their concentration of organic C, total N, $CaCO_3$ and magnetic properties, their upper and lower boundaries drawn at the mid-points of the data peaks or troughs (see Fig. 5).

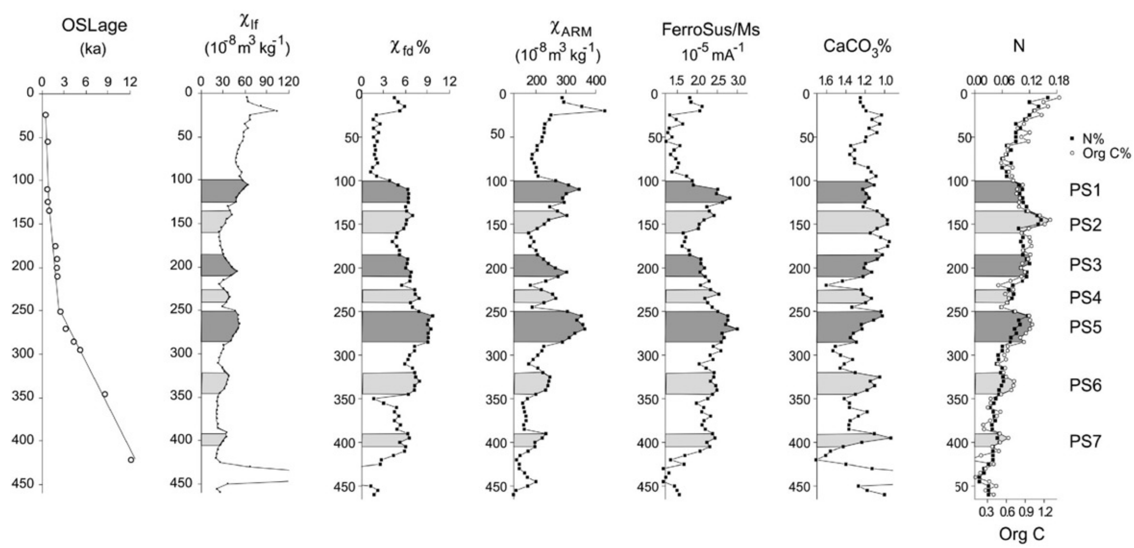

Fig. 5. OSL, magnetic and geochemical data (organic C%, total N% and $CaCO_3$%). Note the reversed scale for the $CaCO_3$ data.

from 0.01% to 0.05%, within the range reported by Zhu et al. (1983) for loess-derived kastanozems (light chestnut brown soils) and sierozems (greyish brown, calcareous soils). Conversely, carbonate values are negatively correlated with the organic C and N data, being depleted, due to leaching, from a maximum of $\sim$1.7% in the least-weathered loess to $\sim$0.9% in the palaeosols (Figs. 5 and 6). In terms of magnetic properties, the least-weathered loess has low magnetic susceptibility values ($\sim 20 \times 10^{-8}\,m^3\,kg^{-1}$), and moderately high values of both frequency-dependent susceptibility ($\sim$5–6%) and the ratio of anhysteretic remanence to saturation remanence ($\sim 0.8 \times 10^{-3}\,mA^{-1}$). These magnetic data indicate the presence within the Duowa loess of a low concentration of magnetite or maghemite of single domain/superparamagnetic dimensions. Compared with the Chinese Loess Plateau sensu stricto, a localised and distinctive dust source is indicated for the marginal Duowa site (Fig. 7). In contrast to the parent loess, magnetic susceptibility is enhanced in every palaeosol (rising from $\sim$20 to $\sim 60 \times 10^{-8}\,m^3\,kg^{-1}$), as are anhysteretic and saturation remanence. Each soil is further characterised by elevated values of various magnetic grain size proxies, including: the ratio of the

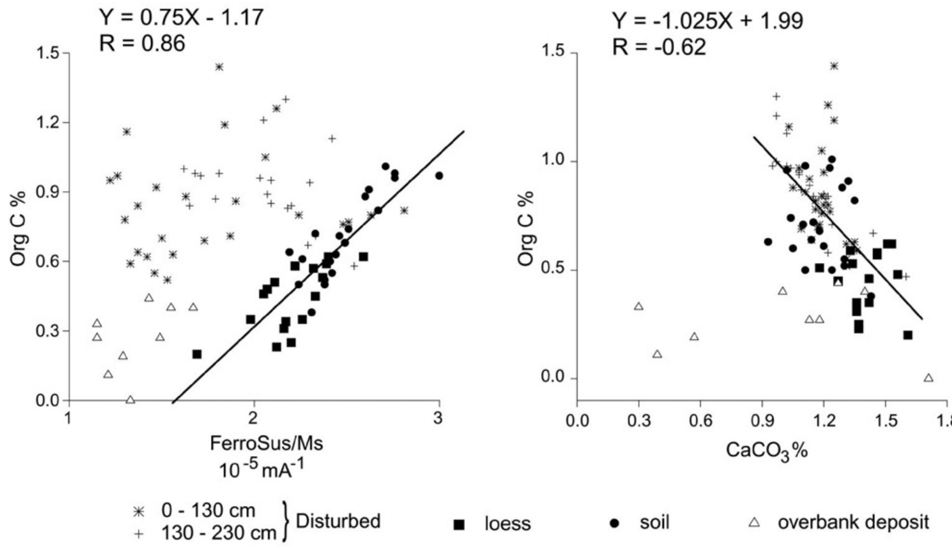

Fig. 6. Inter-relationships between the ratio of ferrimagnetic susceptibility and saturation magnetisation (a magnetic grain size indicator, with higher values indicating increased concentrations of ultrafine magnetite), organic C % and calcium carbonate %.

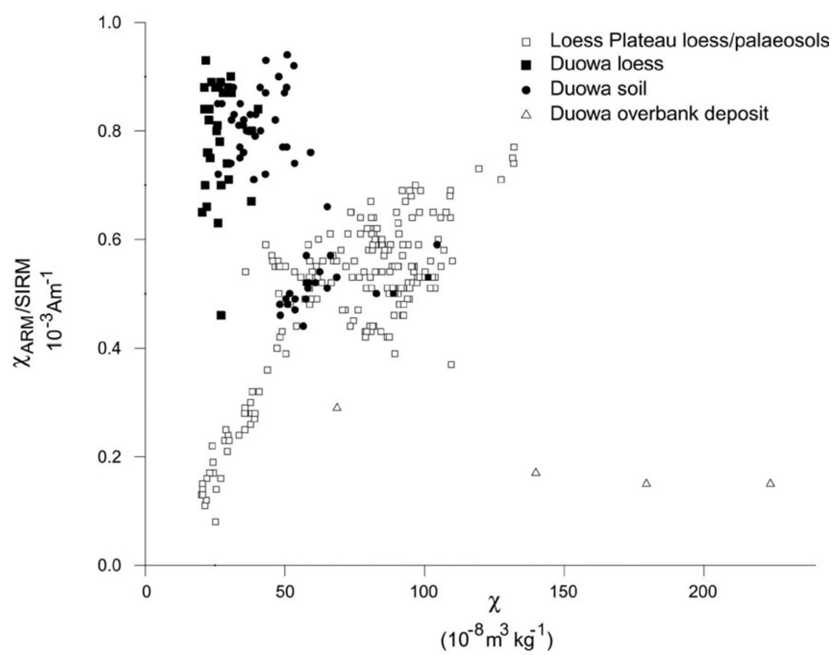

Fig. 7. The ratio of anhysteretic remanence to saturation remanence versus magnetic susceptibility for the Duowa loess and palaeosols, compared with sites from the Loess Plateau sensu stricto.

saturation remanence and the saturation magnetisation; frequency-dependent susceptibility (normalised as a % of the low-frequency susceptibility); and the ferrimagnetic susceptibility (normalised for magnetic concentration by dividing by the saturation magnetisation) (Fig. 5). These data indicate increased concentrations of ferrimagnets, of sub-micrometre, single domain and superparamagnetic dimensions, within even the most weakly developed palaeosols. Finally, in terms of particle size, most of the sequence (from ~1.3–4.3 m depth) is uniformly dominated by silt (~75%) and clay (~25%), with minimal amounts of sand (Fig. 4).

In summary, compared with the less-weathered loess units, each palaeosol and incipient palaeosol is enriched in organic C and total N, leached of carbonate, and displays magnetic properties indicating increased concentrations of sub-micrometre, SD and SP ferrimagnets.

4. Discussion

For this loess/palaeosol sequence, OSL dating has shown that supply and accumulation of sediment has occurred quasi-continuously through the Holocene. The uniformity of particle size distribution through most of the sequence suggests there has been no significant change in the local, magnetically distinctive dust source through this interval. Critically, the degree of soil development (as indicated by the geochemical and magnetic properties, which are strongly correlated) seems to bear no relationship to the rate of dust accumulation and thus the soil-forming duration. Accumulation rates were lowest from ~12 to 2.5 ka, providing ample time for weathering and soil formation to proceed yet pedogenesis through this interval was both episodic and relatively weak. 'Loess' is readily altered to 'soil' upon vegetation growth, which leads to incorporation of organic C and N (Jenny, 1941), leaching of carbonate, and pedogenic formation of iron oxides, including magnetite (which may oxidise towards maghemite), haematite and goethite. Vegetation growth in turn depends in this presently semi-arid region upon the availability of moisture. That soil-forming processes act rapidly in loess is shown, for example, by Hallberg et al.'s (1978) study of soil development on an artificial loess surface in the US. Within just 100 yr, unaltered loess spoil was weathered to form a 31-cm thick A horizon, with organic carbon values of up to 2.6%, and significant translocation of clay. Despite continuous accretion of dust, every one of the Duowa palaeosols has had soil-forming durations several times longer than this (i.e. ranging from 100 s to 1000 s of years). The weak degree of soil development for the lower palaeosols at this site thus indicates that the climate from ~12–5 ka provided conditions inimical to soil formation (i.e. too dry to support vegetation growth). Conversely, soil development was stronger during later intervals—when dust accumulation rates were either the same or higher, and soil-forming intervals were correspondingly shorter. More intense pedogenesis during these intervals thus appears to reflect more suitable (i.e. wetter) climatic conditions. Thus, for this presently semi-arid area, the measured soil properties (including magnetic properties) developed within such short timescales that changes in sedimentation rate appear to have played no role in controlling the degree of pedogenesis.

5. Conclusions

1. For a Holocene sequence of multiple palaeosols and interbedded loess units, at the presently semi-arid western edge of the Chinese Loess Plateau, dust has accumulated quasi-continuously through the last 12 kyr, mostly at a rate of ~20 cm/kyr. Hence, dust was accumulating during each soil-forming interval.
2. The degree of soil development, as indicated by geochemical and magnetic parameters, appears to bear no relationship to the dust accumulation rate or the soil-forming duration, as determined by the OSL dates. Contrary to expectation, the weakest soils formed when dust accumulation rates were lowest and available soil-forming durations were longest.
3. The data presented counter previous assumptions of palaeosol formation being associated with landscape stability and reduced sediment fluxes. Rather, these palaeosols are accretionary; soil formation has operated contemporaneously with the continuous accumulation of dust.
4. Accumulation rate (and thus time) and sediment source (parent material) show no systematic variation between the loess and the palaeosols at this site. There is also no topographic variation through time. Therefore, another soil-forming factor must have controlled the geochemical and magnetic properties of these Holocene palaeosols. By elimination, the controlling factor seems to be climate (and its co-variant, organic activity), and, in this semi-arid region, particularly rainfall.
5. This may be a critical finding with regard to quantitative rainfall reconstructions from the adjacent Chinese Loess Plateau sequences based on palaeosol magnetic properties, as it identifies the key role of climate in controlling the magnetic properties of these sediments and eliminates both dust 'dilution' and soil-forming duration as significant magnetic influences.

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