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Spatial and temporal reconstructions of changes in the Asian palaeomonsoon: A new mineral magnetic approach

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Abstract

A new quantitative approach is proposed for estimating palaeoprecipitation across the Chinese Loess Plateau. At present, there is a strong rainfall gradient across the plateau from ~ 300 mm/yr in the near-desert conditions in the northwest to over ~ 750 mm/yr in the southeast, just 700 km distant. We find that the concentration of ferrimagnetic iron oxide minerals in nine *modern* soil types (represented by 37 individual soil profiles) is strongly correlated with this contemporary rainfall gradient. The ferrimagnetic concentration rises along this gradient, from 0.01% in the northwest to over 0.2% in the southeast. The nine modern soil types have been used in the construction of a rainfall vs. magnetic susceptibility (least squares regression) climofunction. Past variations of loess-soil iron oxide content are easily established through magnetic susceptibility measurements and so can be used to reconstruct the rainfall of former interglacial and glacial periods. The physical and pedological basis of the rainfall vs. susceptibility relationship is discussed and potential limitations of our rainfall reconstruction method are explored.

Our palaeoclimate reconstructions indicate dramatic changes in rainfall due to variations in the structure of the Asian monsoon. The rainfall variations are about four times greater than has been suggested for this region by atmospheric general circulation modelling. Our data indicate increased rainfall throughout central China both in interglacial periods and in the early Holocene. The increases in monsoonal rain were particularly pronounced at our westernmost sites, adjacent to the northeastern edge of the Tibetan plateau. In contrast, for glacial periods a reduction in rainfall is found across the whole loess area, with the greatest decreases in the southeast.

1. Introduction

In north-central 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 (e.g., the Gobi desert, the Tibetan plateau), and subsequent deposition over arid/semi-arid regions within an area trending W–E, between 33°–47°N and 127°–75°E (nearly 0.5 million km^2). Loess formation was at a maximum during cool, dry climatic periods. During

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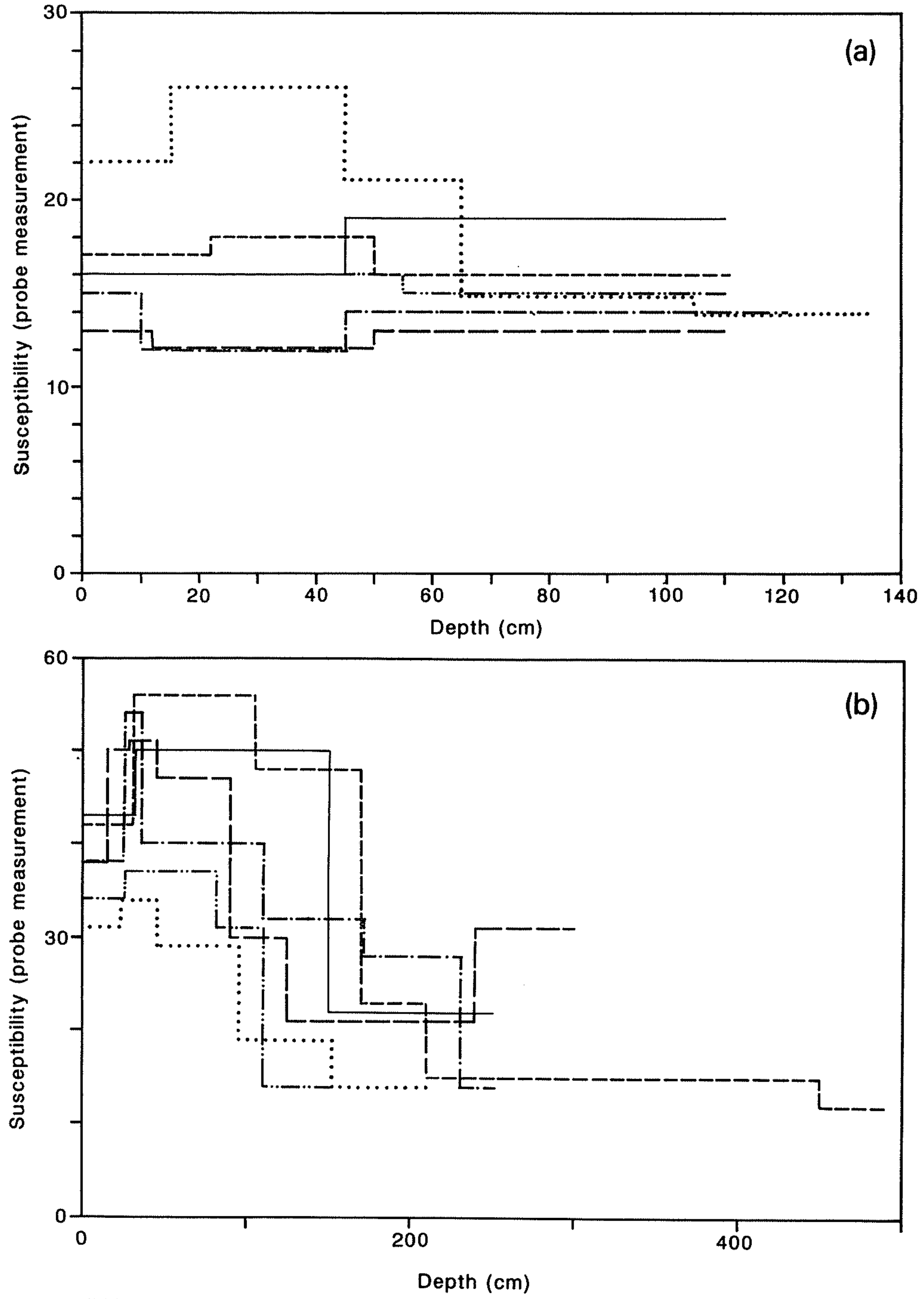

Fig. 1. Volume susceptibility measurements for the modern soils from three regions of the Loess Plateau. Note that susceptibility values in the topsoil appear to decrease as a result of decreasing soil density.

Soil type	Rainfall (mm)	Latitude (N)	Longitude (E)
(a) Xerosol (semi-desert)	321	37.10	104.06
(b) Cambisol	560	35.08	109.56
(c) Chernozem	630	35.45	109.26

Note the increase in susceptibility up each profile and the trend of higher susceptibility enhancement with greater annual rainfall.

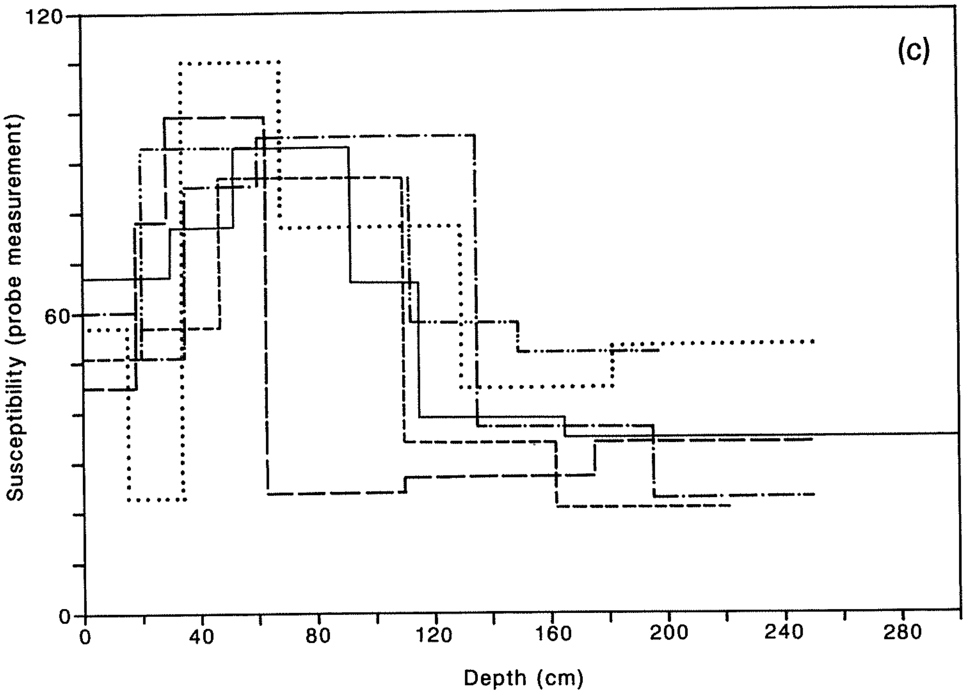

Fig. 1 (continued).

warmer, wetter stages dust transport was greatly reduced, vegetation colonised the loess surface more permanently, and in-situ weathering and soil development were promoted. The thickest sequences of loess, in the western and central parts of the Loess Plateau, exceed 300 m. In the east and south they are thinner and finer grained. These variations span a contemporary climatic gradient, from relatively dry in the west (330 mm rainfall/yr) to increasingly humid in the south and east (up to 650 mm/yr).

The rock magnetic properties of the loess and soils reflect the mineralogy, concentration and grain size of their constituent magnetic iron oxides. Measurements of magnetic susceptibility provide precise differentiation between relatively unweathered loess layers and palaeosol layers, even where the latter are weakly developed. Susceptibility values are higher (by a factor of between 2 and 5) in the soils than in the loess. Following the important work of Liu et al. [1] and Heller et al. [2], we aim to retrieve Quaternary palaeoclimatic (rainfall) data for past interglacial and glacial periods in the Quaternary from the proxy record held by the loess/soil susceptibility record. Heller et al. [2] used paired measurements of ^{10}Be concentration and magnetic susceptibility to attempt rainfall reconstructions. Here, we take a simpler approach and use magnetic susceptibility alone, rather than any other property, because it is sufficiently sensitive to reflect weathering and soil formation [3], it is easily and quickly measured, and susceptibility data are available for sixteen loess/palaeosol sequences distributed across the Loess Plateau.

2. Magnetic susceptibility and soil development

The processes that have resulted in the susceptibility variations of the loess/palaeosol sequences have been much debated [3–7]. Briefly, Kukla et al. [8] and Kukla and An [9] favoured a constant atmospheric input of iron oxides which has been diluted by weakly magnetic dust at times of rapid loess accumulation. Heller and Liu [23] have identified decalcification of topsoil (with down-profile reprecipitation of carbonate) as a means of iron oxide concentration (and down-profile dilution). Zhou et al. [10] and Maher and Thompson [3] favoured pedogenic processes as the overriding factor. We envisage pedogenic enhancement of the Chinese loess susceptibility as largely following the soil processes set out by Le Borgne [11] based on his studies of French soils. As the organic content of the loess soils builds up, particularly at times of warm and wetter climates, successive oxidation and reduction cycles increase the concentration of authigenic fine-grained (submicrometre) magnetite. The Fe^{2+} required for precipitation of this mixed Fe^{2+}/Fe^{3+} compound is probably produced by bacterial reduction of iron oxides in moist zones of the soil microenvironment. Formation of magnetite by this pathway is, sensu stricto, inorganic, as the Fe-reducing bacteria play no role in the precipitation product [12].

To attempt palaeoclimatic reconstructions, we first need to establish the relationship between the magnetic susceptibility of the Chinese soils and the major factors of soil formation.

Jenny [13] identified five major soil-forming factors—climate (cl), vegetation (o), topography (r), parent material (p) and time (t)—and established the soil system equation

$$S = \text{function}(cl,o,r,p,t) \qquad (1)$$

where S denotes the soil or any soil property.

To isolate any single factor (e.g., climate) and to discover how it controls a particular soil property, all the remaining factors must be eliminated from Eq. (1).

The Chinese Loess Plateau is an ideal region in which to attempt to solve this equation for the factor of climate. First, the parent material (p) across the plateau (wind-blown dust) is exceptionally uniform. Second, topography (r) similarly varies little across the Chinese Loess Plateau, with loess units stretching horizontally for kilometre after kilometre. These two factors can therefore be taken as constants in Eq. (1). Third, vegetation (o) can be assumed to be intimately interrelated (i.e., to co-vary) with climate. Therefore, Eq. (1) can be reduced to a function of climate and time.

3. Climofunctions

Climate can be expected to be a particularly dominant factor in Eq. (1) as the climate of the Loess Plateau has varied significantly during the Quaternary. A steep gradient in rainfall exists at the present day from west to south and east.

To determine the contemporary climatic influence on soil magnetic susceptibility in this region, 39 modern soils were sampled from nine localities across the Loess Plateau (Fig. 3d). The soils, developed on recent geomorphic surfaces within the plateau area, were carefully selected to avoid, as far as possible, disturbance by erosion, industrial pollution and farming. Most of the soils show increased magnetic susceptibility towards the top of the profile. The susceptibility enhancement is much more pronounced in the soils from

Table 1
Correlation coefficients

		Susceptibility	Log(Susceptibility)
Precipitation	Annual	0.83	0.95
Precipitation	Winter	0.76	0.79
Precipitation	Summer	0.62	0.64
Temperature	Winter	0.72	0.77
Temperature	Summer	0.85	0.74

the southern and eastern areas, whereas soils from the western areas show only modest enhancement (Fig. 1). Significantly, the susceptibility values of these modern soils fall within the range of those from the palaeosols. Two profiles from the 39 sampled were discarded, one having an anomalously high susceptibility (attributed to colluvial input of topsoil), the other an anomalously low susceptibility (attributed to truncation by erosion).

To identify the pedogenic component of the susceptibility, we simply calculate the difference in susceptibility of the B (subsoil) and C (parent material) horizons, as given in Eq. (2):

$$\chi_{B-C} = \chi_B - \chi_C \tag{2}$$

The susceptibility of the B horizon was used, rather than the A (topsoil), for two reasons: first, to avoid the possibility of surface magnetic contamination, and second, to make reasonable comparison with the mostly truncated palaeosol profiles. This pedogenic enhancement of magnetic susceptibility ($\chi_{\mathrm{B-C}}$) has been compared with 30 yr averages (1951–1980 AD) of the present-day climate. The main climatic factors considered were annual and seasonal rainfall and air temperature. Linear and polynomial relationships between pedogenic enhancement and the climate parameters were investigated. The strongest relationship, with a correlation coefficient of $+0.95$ (Table 1), was found for the logarithm of susceptibility against annual rainfall.

As climate parameters naturally exhibit collinearity, other factors (e.g., summer (June, July, August) rain) also show good relationships with pedogenic susceptibility (Table 1). Step-up–step-down regression analysis [14], using a partial F-test, was used to identify how many of the climate parameters are needed to provide a parsimonious fit to the susceptibility data. The analysis showed that annual rainfall (P_{A}) alone provided an excellent fit with the logarithm of contemporary pedogenic susceptibility $\chi_{\mathrm{B-C}}$.

Finally, the time factor t (i.e., the time the soil remains in the weathering zone) must be considered.

4. Chronofunctions

The two main types of chronofunction found in soil science and in the earth sciences generally are (i) linear growth and (ii) exponential approach to steady state. Linear growth corresponds to the situation in which one process dominates. The approach to steady state corresponds to the case in which two or more processes, acting at different rates, compete and eventually give rise to a dynamic balance.

Some soil properties, such as topsoil pH and build-up of organic matter, have been found to develop over a few centuries or millenia [13]. We suggest a similar rate of organic matter accumulation in the Chinese palaeosols, and an accompanying rate of enhancement of magnetic susceptibility. The similarity of the magnetic enhancement of modern Chinese soils to that of the palaeosols in the loess sequences supports the idea that the modern soils are close to steady state. Further evidence in support of this view comes from the Chinese palaeosols themselves. These have taken several times longer than the modern soils to develop, but their pedogenic susceptibility values remain comparable with those of the modern soils.

In contrast, Singer al. [15], in a study of Californian soils, interpret their soil magnetic data as a slow, linear enhancement of magnetic susceptibility, over periods up to 1 m.y. Soils on different parent materials presumably evolve at different rates. The Chinese loess soils may be expected to mature rapidly; the parent material is highly ‘weatherable’, being fine grained, carbonate-rich, unconsolidated, and permeable.

Our palaeorainfall reconstructions are based on the key assumption that the modern Chinese soils have matured to, or close to, a magnetic steady state, in a few thousand years of active pedogenesis. We thus assume that as the Chinese loess and soils have been exposed to weathering for at least this time period, and so have had the time to approach magnetic steady state; the time factor of Eq. (1) is unimportant and can be discounted. On this basis, we have established a formal climofunction that can be used to reconstruct past climate change directly from magnetic susceptibility measurements.

We use the relationship between annual precipitation (P_A) and pedogenic susceptibility (χ_{B-C}) obtained from our modern soils:

$$P_A \mathrm{mm/yr} = 222 + 199 \log 10(\chi_{B-C} 10^{-8} \mathrm{m}^3 \mathrm{kg}^{-1}) \qquad (3)$$

as the basis for estimating palaeoprecipitation on the Chinese Loess Plateau from magnetic susceptibility measurements. The modern soil data for our nine regions and this logarithmic regression relationship are plotted in Fig. 2.

5. Rainfall reconstructions

We have applied our method to magnetic susceptibility measurements (our own and published data of others) from three periods: the most recent palaeosol (S0, ~ 9 kyr BP), the first loess layer (Ll, ~ 18 kyr BP), and the last interglacial palaeosol (S1, ~ 126 kyr BP).

The following steps were used in our reconstructions:

(1) All volume susceptibility measurements obtained with a Bartington Instruments field probe were scaled to mass-specific susceptibility (in the unit 10^{-8} m^3 kg^{-1}).

(2) The parent loess at each site was assigned the susceptibility value of the L9 loess (one of the most rapidly accumulated, least weathered loess units). Where the L9 layer was not present, the susceptibility of L9 at a neighbouring site was used. The median L9 value is 24.10^{-8} m^3 kg^{-1}, not dissimilar to the values obtained by Verosub et al. [16] after chemical extraction of the pedogenic ferrites.

(3) Susceptibility differences (e.g., $\chi_{S0} - \chi_{L9}$) were found for each time period. The maxi-

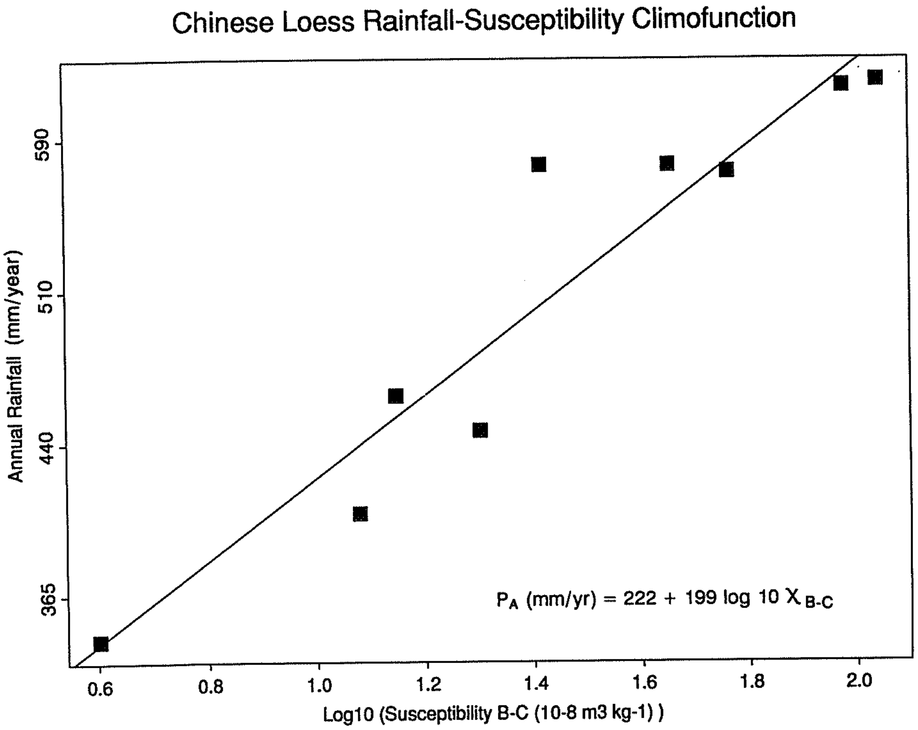

Fig. 2. Least squares regression of annual rainfall vs. susceptibility, based on pedogenic susceptibility ($\chi_B - \chi_C$) in modern soils and 30 yr (1951–1980 AD) rainfall averages.

mum susceptibility value for each palaeosol was used in this calculation.

(4) Palaeorainfall was calculated from the climofunction of Eq. (3).

(5) Present-day rainfall was estimated by a cubic polynomial interpolation procedure from the 30 yr average rainfall grid [Hulme, pers. commun.]. Differences in annual precipitation (e.g., $P_{\mathrm{A9\ kyr}} - P_{\mathrm{A0\ kyr}}$) were then calculated, and plotted in Fig. 3.

6. Sensitivity analysis

We have studied the sensitivity of our approach to any errors in magnetic susceptibility estimates and measurements. In our rainfall reconstruction procedure, we make the two assumptions that (i) the susceptibility enhancement $\chi_{\mathrm{B-C}}$ of modern-day soils has reached a magnetic steady state, and (ii) the susceptibility of the parent material χ_{C} at each loess/palaeosol site

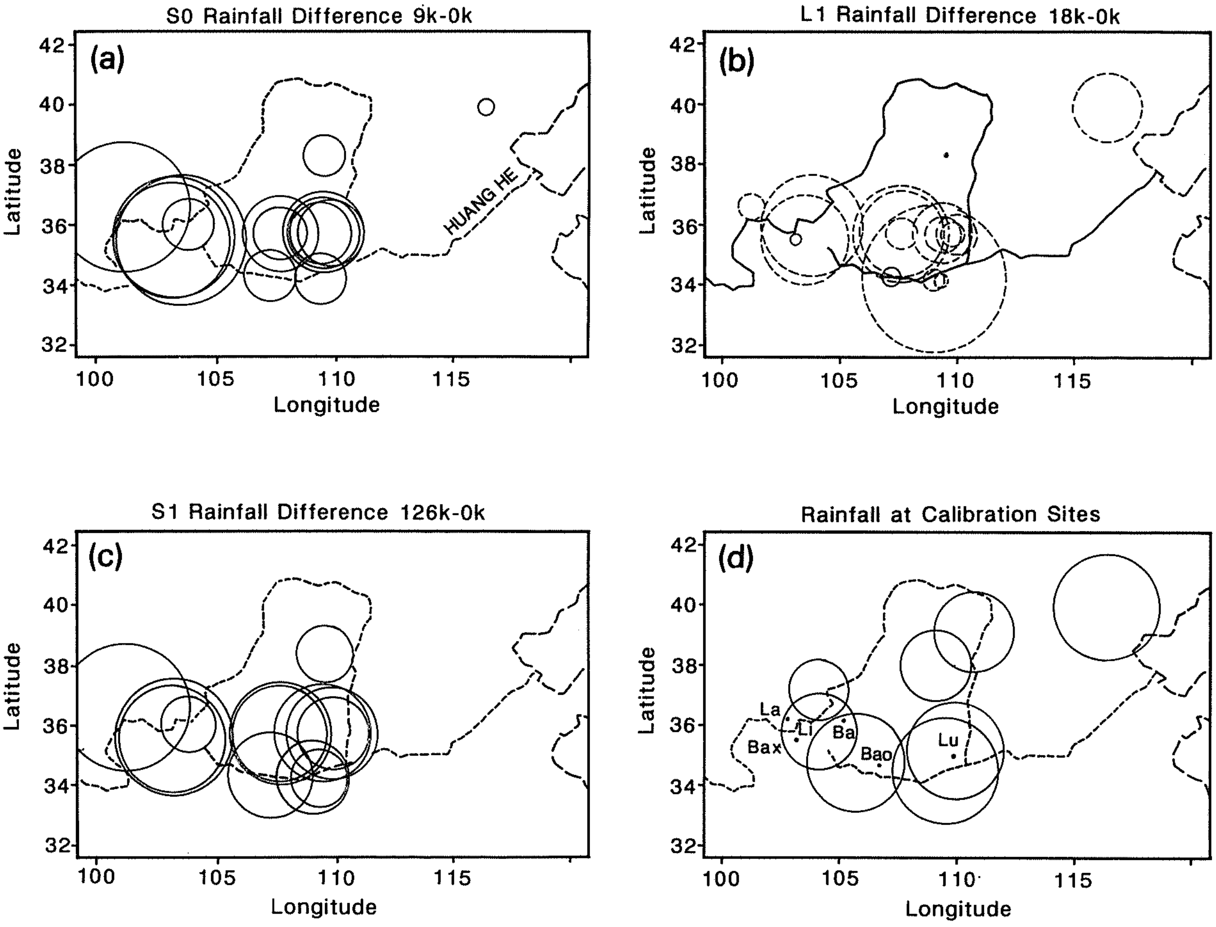

Fig. 3. Rainfall reconstructions for three time slices. The radius of the circles is proportional to the difference in rainfall compared to the present day. (a) Rainfall differences at 9 kyr BP. The largest circle indicates an increase in rainfall of +215 mm/yr (b) Rainfall differences at 18 kyr BP. The largest dashed circle indicates a decrease in rainfall of −266 mm/yr. (c) Rainfall differences at 126 kyr BP. The largest circle indicates an increase in rainfall of +220 mm/yr. The reconstructions of (a) to (c) are all based directly on the climofunction of Eq. (3). (d) Location of modern soil profiles used in the construction of Fig. 2. *La* = Lanzhou; *Bax* = Baxie; *Li* = Linxia; *Ba* = Baicaoyuan; *Bao* = Baoji; *Lu* = Luochuan. The radius of the circles is proportional to the 30 yr annual rainfall averages (1951–1980 AD) at the soil sites.

is equal to the susceptibility of the local loess unit L9. Table 2 summarises the results of our sensitivity calculations for discrepancies of 10 and 25% in each of these two assumptions. The resulting errors in the rainfall reconstructions are dependent on the logarithmic form of our calibration equation.

Typically, a discrepancy of 10% in either assumption propagates in the logarithmic relationship of Eq. (3) to cause an error of about 2% in our rainfall estimates. If the modern soils are 'under-enhanced' by 25%, this would produce an overestimate of rainfall of typically 5%. However, notice how the absolute errors in our rainfall reconstruction, caused by under-enhancement, are exactly the same at all sites and are reasonably small (note 'b' in Table 2). Given a 25% discrepancy in estimates of parent material susceptibility (for *both* the loess/palaeosols and the modern-day soils), an error in rainfall reconstruction of about 3% results. The greatest percentage errors are naturally found for loess/palaeosol sites which display little magnetic enhancement (far right-hand column of Table 2).

Discrepancies in the measurement of the susceptibility of the loess/palaeosols can also produce errors in rainfall reconstruction. A mistake of 10% in susceptibility at any one site, as might for example be produced by a difference in inter-laboratory calibration, results in an error in rainfall reconstruction of just 3% (Table 2).

In summary, the sensitivity analyses show that our approach is pleasingly robust with respect to our assumptions concerning χ_{B-C} and χ_{C}. Discrepancies in these assumptions of around 5–10% lead to errors of only 1–2% in our rainfall reconstructions. Any systematic measurement errors of the loess/palaeosol susceptibilities similarly have a reduced effect on rainfall reconstructions following our differencing and transformation procedure. The sensitivity analyses indicate, then, that the more critical part of our procedure concerns the overall accuracy and form of the rainfall–susceptibility regression relationship of Eq. (3). The relationship is testable through further magnetic studies of modern-day soils. Work on soils from both the main area of loess deposition and from around the main Loess Plateau will

Table 2
Sensitivity of rainfall reconstructions to errors in magnetic susceptibilities

Susceptibility	**Rainfall reconstruction**		
Modern soils, χ_{B-C}	Rainfall	Mean error	Worst error[a]
At steady-state, fully enhanced (100%)	No difference	0%	0%
90% of steady-state	0.023 mm/day[b]	2% too high	4% too high
75% of steady-state	0.068 mm/day[b]	5% too high	12% too high
χ_{C} (Of *both* the loess/palaeosols and modern-day soils)			
$\chi_{C} = \chi L9$ exactly	No difference	0%	0%
10% error in χ_{C}	0.002 mm/day[c]	2%	32%
25% error in χ_{C}	0.003 mm/day[c]	3%	47%
χ_{B-C} (Of loess/palaeosols)			
10% error in χ_{B-C}	0.0024 mm/day[b]	3%	4%
25% error in χ_{B-C}	0.0061 mm/day[b]	5%	10%

[a] Dry loess/palaeosol site with particularly low susceptibilities. [b] Exactly the same rainfall difference at each site. [c] Average rainfall difference of all 22 loess/palaeosol sites.

provide a greater coverage of climate regimes and hence a further check on the overall form of the rainfall–susceptibility calibration function in China. The rainfall reconstructions obtained from magnetic susceptibility measurements can be directly compared with palaeorainfall results from GCM modelling. These can be subjected to further independent validation through estimation of palaeorainfall using changes in lake level and observations of the migration of flora and fauna.

7. Limitations of the rainfall vs. susceptibility climofunction

The limited range of annual rainfall at our contemporary calibration sites compared to the range of rainfall in our predictions requires consideration. We find that our calibration climofunction is reasonable in comparison with susceptibility enhancement from other warm temperate zone localities in the northern hemisphere. Desert and semi-arid soils from Morocco, Sudan and western North America typically have modest enhancement of around 5×10^{-8} m^3 kg^{-1} [Dearing, pers. commun., 1993; Maher, 24]. European brown earth soils (cambisols) and central Asian chernozems have medium enhancements of $\sim 50 \times 10^{-8}$ m^3 kg^{-1} [17], whereas the highest enhancement (500×10^{-8} m^3 kg^{-1}) has been found in the wetter parts of Morocco [Dearing, pers. commun., 1993] and California [15]. Although exceptions can be found to this general pattern, due to local factors such as soil burning, or parent material (e.g., sands) resistant to enhancement, the hemispheric pattern is in good agreement with the Chinese climofunction.

8. Climate change

Our reconstructions of palaeorainfall over the Loess Plateau indicate much higher rainfall in the early Holocene (9–5 kyr BP) and the last interglacial (126 kyr BP) in those areas that are presently semi-arid. These include the western locations of Lanzhou, Linxia, Baxie and, particularly, Baicaoyuan. Only slightly wetter conditions are indicated for Baoji and Luochuan, in the south and east, where there is the highest contemporary rainfall. The marked increase in rainfall inferred for the western plateau area suggests intensification of the summer monsoon at these times. At present, summer rainfall in China is dominated by the east Asian monsoon. This is well illustrated by Baicaoyuan, which currently lies in a rain shadow to the west of the Liupan Shan range and has a rainfall of only 350 mm/yr compared to Xifeng to the east of the mountains with 550 mm /yr. It is tempting to ascribe the enhanced early Holocene and interglacial rainfall in the western areas to strengthening of the Indian monsoon, with concurrent northward penetration of moisture-bearing winds, despite the significant topographic obstacle of the Himalayas and the Tibetan plateau (altitude of ~ 9000m). However, it is equally possible that intensification of the east Asian monsoon could overcome the rain shadow effect presently exerted by the Liupan Shan (altitude of ~ 3000 m).

Independent indications of increased rainfall and monsoon intensity during the early Holocene come from soil particle size analysis [18], pollen evidence [19], lake levels [20] and GCM results [21]. The GCM data suggest significant intensification of the Indian monsoon in the early Holocene, and also during the last interglacial, when the monsoon may have been twice as intense as at present. In comparison with the GCM estimates, our rainfall data suggest variations about four times larger over the Loess Plateau area. However, it may be inappropriate at present to make detailed comparisons between our reconstructed rainfall data and the GCM rainfall estimates, given the crude spatial resolution of the latter. The GCM data identify levels of enhanced precipitation in line with our reconstructions for the area to the west of the Loess Plateau.

In contrast, the greatest decreases in rainfall in central China occurred during glacial periods. Our reconstructions identify greatest desiccation in the presently wet areas of the southeast plateau. The magnitude of change identified by us for the last glacial (18 kyr BP) closely matches that suggested by the GCM data.

Beer et al. [22] and Heller et al. [2] suggested that ^{10}Be concentrations in the Chinese loess could be used, in conjunction with magnetic susceptibility, to calculate palaeorainfall. Their rainfall reconstructions are at variance with our data. For example, Heller et al. [2] deduce high rainfall values (twice the contemporary average) for short periods around 25 ky and 55 ky BP. Similarly, they estimate *reduced* rainfall for the last interglacial (530 mm/yr compared with 630 mm at present) for one of the southern sites.

In contrast to Heller et al. [2] we ascribe both magnetic susceptibility enhancement and ^{10}Be retention in the Chinese loess sequences primarily to pedogenic development. We speculate that the Beer et al. [22] approach depends critically on (i) their assumption of a constant atmospheric background flux of ^{10}Be, and (ii) difficulties involved in determining the very accurate estimates of loess accumulation rates required by their method. In addition, if a correlation between *modern* rainfall and the Holocene palaeosol S0 ($\sim$ 10 kyr old) is used to reconstruct palaeorainfall, the resulting calibration will be invalid given any significant climate change *within* the Holocene.

9. Conclusions

(1) Modern soils in north-central China show a high degree of correlation between their pedogenic magnetic susceptibility (χ_{B-C}) and contemporary annual rainfall ($r = 0.95$). The susceptibility is dominated by in-situ formation of fine-grained ferrimagnets.

(2) We can use this correlation to reconstruct rainfall for interglacial and glacial episodes spanning the entire Quaternary across the Loess Plateau. Climate change, rather than soil-forming duration, is the key factor in controlling pedogenic susceptibility.

(3) We identify large variations in palaeorainfall across the Loess Plateau. For the last interglacial, the presently dry western sites received up to 60% more rainfall per year (compared to present), and the presently humid south and east sites up to 30% more. For glacial episodes, we identify reduced rainfall across the region.

(4) We also identify higher rainfall across the Loess Plateau in the early Holocene ($\sim$ 9 kyr BP), in accordance with independent local evidence including lake level and vegetational change. Climate reconstructions based on the correlation of susceptibility values from the Holocene palaeosol S0 against contemporary rainfall are therefore invalid.

(5) The changes in rainfall are caused by changes in the intensity of the Indian and east Asian monsoons, as modelled by GCMs. When GCMs of higher spatial resolution become available, it may be possible to make detailed comparisons between our reconstructed rainfall data and the GCM rainfall estimates.

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References

[1] T.S. Liu, Z.S. An, B.Y. Yuan and J.M. Han, The loess–paleosol sequence in China and climate history, Episodes 8, 21–28, 1985.

[2] F. Heller, C.D. Shen, J. Beer, X.M. Liu, T.S. Liu, A. Bronger, M. Suter, G. Bonani, Quantitative estimates of pedogenic ferromagnetic mineral formation in Chinese loess and palaeoclimatic implications, Earth Planet. Sci. Lett. 114, 385–390, 1993.

[3] B.A. Maher and R. Thompson, Paleoclimatic significance of the mineral magnetic record of the Chinese loess and paleosols, Quat. Res. 37, 155–170, 1992.

[4] B.A. Maher and R. Thompson, Mineral magnetic record of the Chinese loess and palaeosol, Geology 19, 3–6, 1991.

[5] J.J. Hus and J. Han, The contribution of loess magnetism

in China to the retrieval of past global changes—some problems, Phys. Earth Planet. Inter. 70, 154–168, 1992.

[6] J. Han et al., The rock magnetic properties of the Malan and Lishi formations on the Loess Plateau of China, in: Loess, Environment and Global Change, T. Liu, ed., pp. 30–47, Science Press, Beijing, 1991.

[7] M.E. Evans and F. Heller, Magnetic enhancement and palaeoclimate: study of a loess/palaeosol couplet across the Loess Plateau of China, Geophys. J. Int. 117, 257–264, 1994.

[8] G. Kukla, F. Heller, X.M. Liu, T.C. Xu, T.S. Liu and Z.A. An, Pleistocene climates in China dated by magnetic susceptibility, Geology 16, 811–814, 1988.

[9] G. Kukla and Z. An, Loess stratigraphy in Central China, Palaeogeogr., Palaeoclimatol., Palaeoecol. 72, 203–225, 1989.

[10] L.P. Zhou, F. Oldfield, A.G. Wintle, S.G. Robinson and J.T. Wang, Partly pedogenic origin of magnetic variations in Chinese loess, Nature 346, 737–739, 1990.

[11] E. Le Borgne, Susceptibilite magnetique anormale du sol superficiel, Ann. Geophys. 11, 399–419, 1955.

[12] B.A. Maher, Inorganic formation of ultrafine-grained magnetite, in: Iron Biominerals, R.B. Frankel and R.P. Blakemore, eds., pp. 179–191, Plenum, 1991.

[13] H. Jenny, Factors of Soil Formation, McGraw-Hill, 1941.

[14] D.G. Kleinbaum, L.L. Kupper and K.E. Muller, Applied Regression Analysis and other Multivariate Methods, 2nd Ed., PWS–Kent, Boston, 1988.

[15] M.J. Singer, P. Fine, K.L. Verosub and O.A. Chadwick, Time dependence of magnetic susceptibility of soil chronosequences on the California coast, Quat. Res. 37, 323–332, 1992.

[16] K.L. Verosub, P. Fine, M.J. Singer and J. TenPas, Pedogenesis and paleoclimate: interpretation of the magnetic susceptibility record of Chinese loess–paleosol sequences, Geology 21, 1011–1014, 1993.

[17] A.A. Lukshin, T.I. Rumyantseva and V.P. Kovrigo, Magnetic susceptibility of the principal soil types of the Udmuit Assr, Sov. Soil Sci. 3, 88–93, 1968.

[18] S.K. Banerjee, C.P. Hunt and X.M. Liu, Separation of local signals from the regional paleomonsoon record of the Chinese loess plateau: a rock magnetic approach, Geophys. Res. Lett. 20, 843–846, 1993.

[19] D.I. Jarvis, Pollen evidence of changing Holocene monsoon climate in Sichuan Province, China, Quat. Res. 39, 325–337, 1993.

[20] Q.-M. Wang, Extension and retraction of Beiyangdian Lake in the past 10,000 years, Geogr. Res. 2, 15–20, 1983.

[21] J.E. Kutzbach and P.J. Guetter, The influence of changing orbital parameters and surface boundary conditions on climate simulations for the past 18,OOO years, J. Atmos. Sci. 43, 1726–1759, 1988.

[22] J. Beer, C.D. Shen, F. Heller, T.S. Liu, G. Bonani, B. Dittrich, M. Suter and P.W. Kubik, Be-10 and magnetic susceptibility in Chinese loess, Geophys. Res. Lett. 20, 57–60, 1993.

[23] F. Heller, X.M. Liu, T.S. Liu and T.C. Xu, Magnetic susceptibility of loess in China, Earth Planet. Sci. Lett. 103, 301–310, 1991.

[24] B.A. Maher, Origins and transformations of magnetic minerals in soils, Ph.D. Thesis, Univ. Liverpool, 1984.