

## A record of the Blake Event during the last interglacial paleosol in the western Loess Plateau of China

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### Abstract

A high-resolution record of the Blake Event has been obtained from a 40 m well dug in a loess section at Jiuzhoutai in the City of Lanzhou in the western Loess Plateau of China. The paleomagnetic signal is principally carried by magnetite both in loess and paleosols. The Blake Event is located at the boundary between paleosol S1-c of the last interglacial (equivalent to MIS 5e in deep-sea records) and loess L2-2 (MIS 5d), and is characterized by a triple feature consisting of two short reversed intervals separated by a short normal interval. The directional changes are abrupt, as previously revealed in other records, and suggest geocentric dipole field behavior before, after and during the event, but not necessarily during N–R or R–N transitions. The age and duration of the event are estimated as between 119.97 and 114.47 kyr BP and 5.5 kyr, respectively, from thermoluminescence dating and astronomically tuned climate stratigraphy based on high-resolution magnetic susceptibility.

*Keywords:* paleomagnetism; Brunhes Epoch; Loess Plateau

### 1. Introduction

During the last two decades, intervals with apparently reversed or anomalous directions have been revealed during the upper Brunhes Chron in the loess–paleosol sequences of the Loess Plateau of China [1–9] and in lacustrine sediments in surrounding areas [10–14]. Most of these directional anomalies have been claimed to reflect the Blake Event [1–14]. However, many of these records were based

on only one or a few reversed samples whose positions in relation to the loess–paleosol sequences in the sections are ambiguous. Because the loess–paleosol sequences have become one of the most important climatic indicators in terms of monsoonal and global climate changes [15–19], and given that some uncertainties remain regarding the age of the Blake Event as well as its geomagnetic field behavior [9,20–27], a better characterization of the Blake Event in loess sequences is urgently needed.

The Lanzhou loess of the western Loess Plateau appears to be one of the more ideal recorders for this

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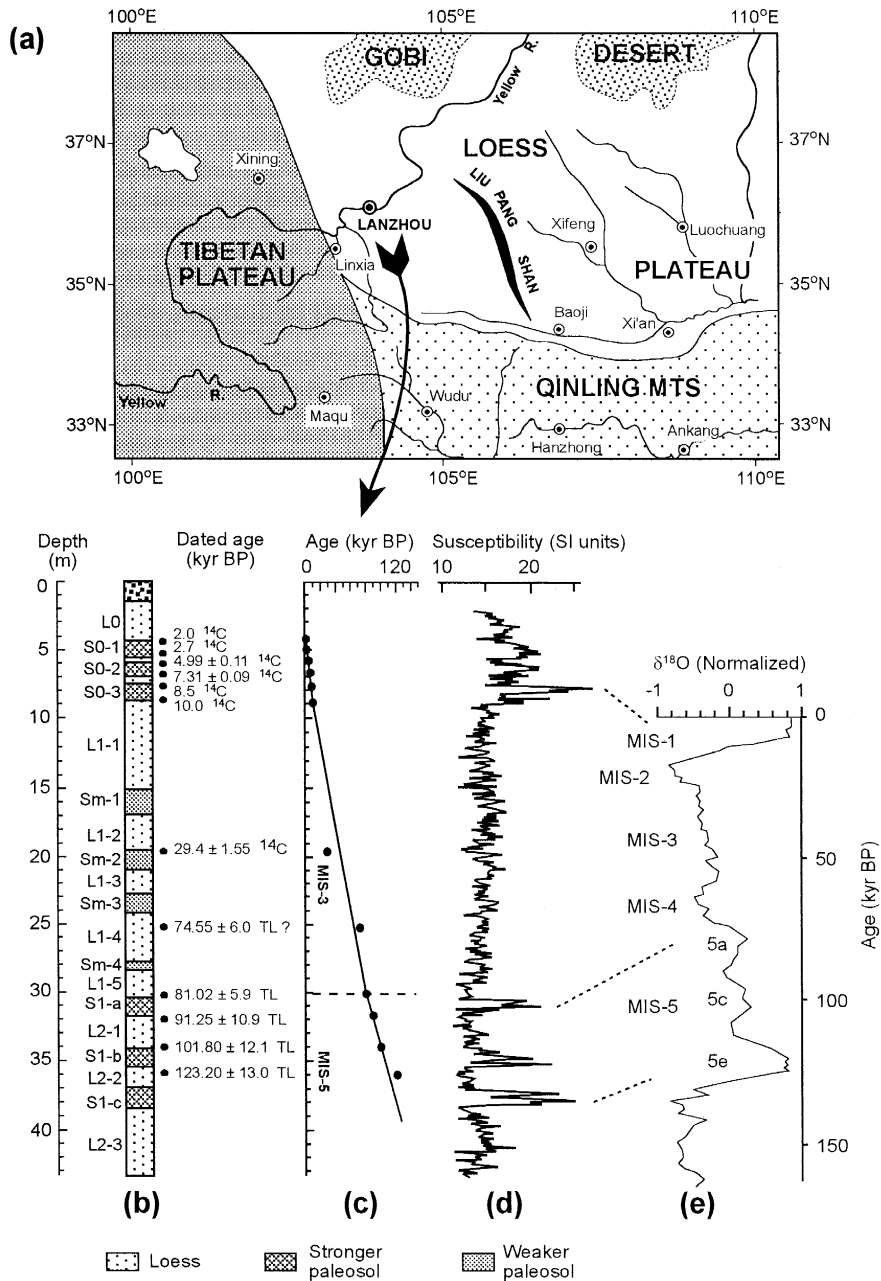


Fig. 1. (a) Location map illustrating the position of Lanzhou with respect to the Tibetan Plateau and the Loess Plateau. (b) The Loess-paleosol sequence of the Jiuzhoutai well section. (c) The age-depth relationship. (d) Volume magnetic susceptibility measured in the field using a Bartington MS2 susceptibility meter. (e) Comparison with the standard marine isotope climate record [29]. The nickpoint between the two linear patterns in (c) marks the change from a low dust input regime during the last interglacial to a high dust input regime during the last glacial. The depth in (b) is the sum of the well depth (40 m) and the natural outcrop height (4.3 m) above the well.

purpose, because the Lanzhou region has had very high dust input rates, producing the thickest known loess section in the world [3], yet with relatively weak pedogenesis. Previous work has shown the existence of the Blake Event in the Jiuzhoutai loess section in Lanzhou [3,5,6]. In this paper we present detailed results from the Jiuzhoutai well loess section.

## 2. Stratigraphy and sampling

The Jiuzhoutai loess section is located on the northern sixth terrace of Huang He (Yellow River) in Lanzhou City (36°N and 103°50'E; Fig. 1a) and has a maximum thickness of 318 m [1,3,19]. It consists of 18 pairs of paleosol and intervening loess layers with deposition starting at about 1.4 Ma [1,3,19]. The sequence in the Jiuzhoutai section is one of the most representative for the western Loess Plateau. A 40 m deep well with a diameter of c. 1.8 m was dug at the top of the Jiuzhoutai section in order to get fresh samples, and was complemented by a 6 m additional well, dug especially for a detailed parallel study of the last interglacial paleosols in a gully. The top of the 40 m well starts below a 4.3 m outcrop of loess L0 (Fig. 1b). So the total depth of the section in this study is 44.3 m. The well section consists of a distinctive dark paleosol S0 series at the top, Malan loesses (L1-1 to L1-5) and their embedded weak paleosols of the Sm series (Sm-1 to Sm-4) at the middle, and Lishi loesses (L2-1 to L2-3) and their embedded yellowish brown paleosols of the S1 series (S1-a to S1-c) at the bottom (at total depths 30.4–38.5 m). Previous organic carbon and thermoluminescence (TL) data [18,19] show that loess L0 and paleosol series S0 are Holocene in age, whereas loess series L1 and paleosols Sm were deposited during the last glacial, and L2 and S1 during the last Pleistocene interglacial. These assignments are broadly in accord with those for the sequence from the central part of the Loess Plateau [15–17], and correlate well with the isotope record from an Antarctic ice core [28] and with standard marine isotope (MIS) records [29], so that S0, Sm and S1 correlate with warm stages of MIS-1, 3 and 5, respectively [18] (Fig. 1). These correlations are further supported by measurements of magnetic sus-

ceptibility, carried out at 5 cm intervals in the well using a Bartington MS2 susceptibility meter. Four prominent peaks in the susceptibility record are found in the better developed soil horizons, which in turn correlate with the warmer intervals (MIS-1, MIS-5a, c and e) of the isotope record (Fig. 1d and e).

In accordance with the previous reports of the Blake Event in the Jiuzhoutai loess section [3–6], we anticipated that the event would occur in our section between S1-b and S1-c, around 34–39 m in total depth. Paleomagnetic sites were sampled at 2.5 cm intervals for the interval of 35.3–39.3 m in total depth. This sample spacing corresponds to an average interval of about 180 years between successive sites, but it must be realized that sedimentation rates can be variable in loess–paleosol sequences. Three oriented cubic samples of 2 × 2 × 2 cm were taken at each site level, yielding a total of more than 400 samples.

## 3. Laboratory measurements and paleomagnetic results

The NRM of a first set of samples (one per site) was measured using an older version of the DIGICO magnetometer at Lanzhou University and was demagnetized with alternating fields (AF), mainly at 35 mT. These measurements provided an ambiguous record that hinted at the existence of the Blake Event, in agreement with other previous work in which AF demagnetization could not successfully isolate the characteristic remanence of many samples [3]. Therefore, the remaining two sets of samples were measured with a 2G cryogenic magnetometer in a magnetically shielded room at the University of Michigan. Prior to demagnetization, anisotropy of magnetic susceptibility (AMS) measurements were carried out using a KLY-2 susceptibility bridge. A pilot set of 130 samples was then thermally demagnetized from 100°C to 700°C in fifteen steps varying between 10 and 50°C. As we will show later, little useful information could be extracted from demagnetization steps above 580°C and therefore the remaining samples were treated up to 580°C using similar temperature intervals. The magnetization of the sample holders was measured separately and was subtracted from the total magnetization of samples in

their holders after each thermal demagnetization step. In order to monitor possible mineralogical changes during thermal demagnetization mass magnetic susceptibility was measured with a KLY-2 susceptibility bridge at room temperature after each demagnetization step.

Progressive thermal demagnetization of loess and paleosol shows the removal of a randomly oriented, laboratory induced magnetization by 100°C, followed by a continued and relatively large decrease in remanence intensity between 100°C and 250°C (Fig. 2). In the corresponding Zijderveld diagrams, we can see that a component of magnetization is being removed in this interval with northerly and down directions. At temperatures above 250°C the characteristic remanent magnetization (ChRM) is clearly isolated: this component of magnetization is either also northerly and down (Fig. 2a,b) or antipodal to it (southerly and up) (Fig. 2c). Above temperatures of about 580°C, directions begin to change randomly in many samples, although in a few samples (e.g., Fig. 2c,f), the magnetization persists without change in

direction up to 680°C, indicating a minor contribution of hematite to the remanence.

We interpret the lower unblocking temperature component as a viscous remanent magnetization acquired during recent times, on the basis of its low coercivity and unblocking temperatures (< 250°C), and its persistently northerly and down direction that conforms to the present-day geomagnetic field. The characteristic remanence isolated above 250°C, on the other hand, is clearly ancient, especially given that reversals are preserved.

A slight increase in susceptibility after treatments above 400°C and a rapid decay in magnetic susceptibility after treatments above 580°C was observed in all loess and soil samples (Fig. 3), indicating mineralogical changes that may involve, in part, oxidation of magnetite or maghemite.

Paleomagnetic directions were obtained from principal component analysis of the thermal demagnetization patterns in each sample, and mean directions for each horizon obtained by averaging the two sample directions at each level; AF results were not

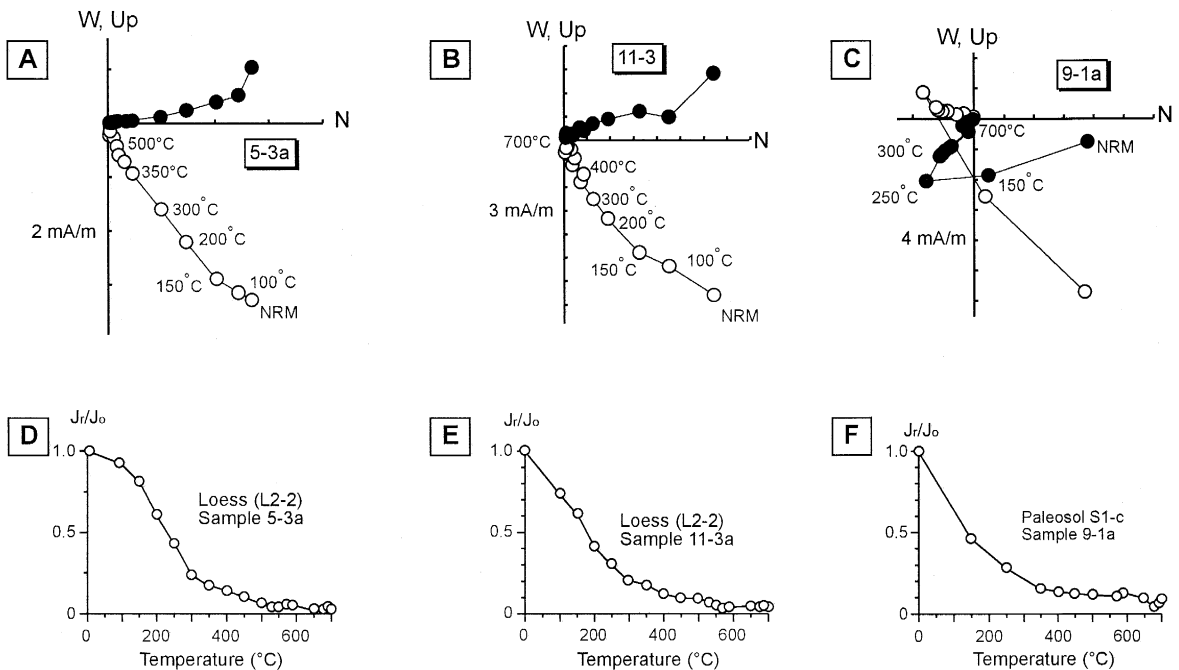


Fig. 2. Example orthogonal projections of progressive demagnetization for samples of loess (a) and (b) and paleosol (c) from the Jiuzhoutai well section, along with their respective decay curves (d)–(f). ● = projections onto the horizontal plane; ○ = projections onto the vertical plane. Sample locations are marked by asterisks in Fig. 4.

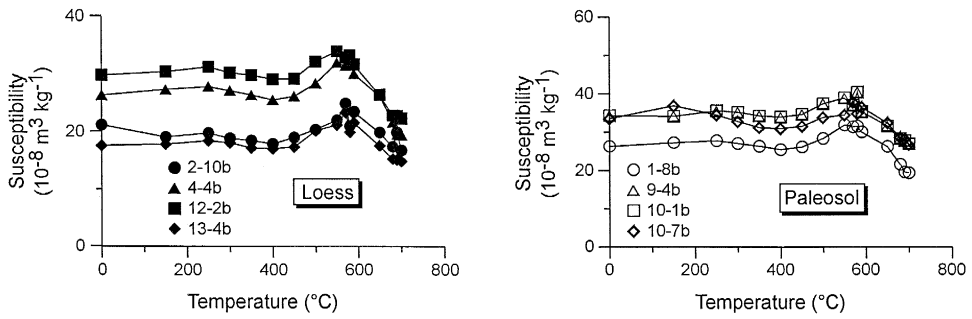


Fig. 3. Variation in the magnetic susceptibility of representative loess and paleosol samples during thermal demagnetization.

included. Two short intervals of reversed directions, separated by a short normal interval, are observed at total depths between 3732.5 and 3775 cm (Fig. 4). The lower reversed interval starts with a shift in inclination from ca. +60° to +40°, followed by a rapid shift from +40° to -25°, and reaches a reversed inclination minimum of about -45°. The

lower interval ends in the opposite fashion with a quick return to normal inclinations of +40° to +60° (Fig. 4). The accompanying declinations track the shifts at the start but return to northerly before the inclination changes sign back to positive (Fig. 4). The upper reversed interval reveals a similar behavior and appears longer than the lower one (Fig. 4).

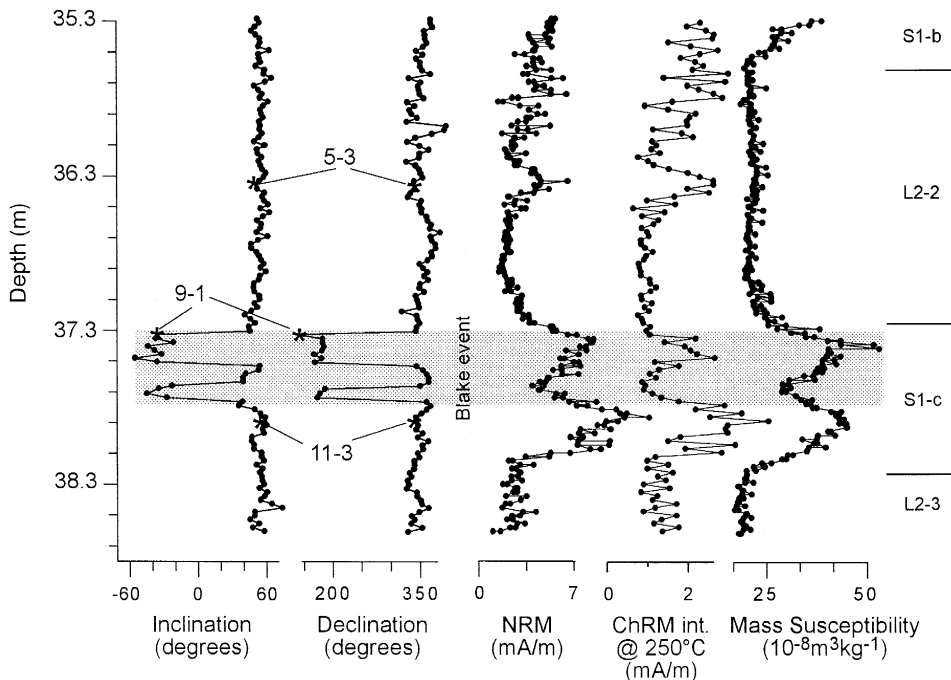


Fig. 4. Inclinations, declinations, NRM and ChRM (at 250°C) magnetic intensities, and mass susceptibility versus depth in a portion of the Jiuzhoutai well loess section, showing the record of the Blake Event. The mass susceptibility was calculated from measurements of bulk susceptibility on a KLY-2 susceptibility bridge corrected for the weight of the sample. For locations marked by asterisks, demagnetization diagrams are shown in Fig. 2. Soil and loess horizons on the right are as in Fig. 1.

Intensities of the total NRM and the characteristic remanence (taken after treatment of 250°C) are also plotted in Fig. 4, and parallel the changes in the susceptibility, which tells us that they do not necessarily relate to the strength of the ancient geomagnetic field but likely reflect the content of magnetic minerals, which, in turn, may be influenced by climatic variations.

#### 4. Age of the Blake Event

The event found in our section covers at least 17 sites (42.5 cm) and is located just at the top of paleosol S1-c, as indicated both by the soil horizon itself and by its magnetic susceptibility (Figs. 1 and 4). Thermoluminescence (TL) dating has suggested that the formation of a paleosol probably takes twice as long as it takes to deposit the same thickness of loess [15–19]. For example, the duration to form paleosol S1-a with a thickness of 125 cm is estimated as 10.23 kyr (Fig. 1). In contrast, loess L2-1, thought to have taken about the same time (10.55 kyr) to form, is 230 cm thick (Fig. 1). The intervals to deposit equivalent sedimentary thicknesses in soil and loess have been calculated from the TL ages of S1-a and L2-1 in the Jiuzhoutai section as 81.84 yr/cm and 45.44 yr/cm, respectively. Using these

rates and the TL ages in Fig. 1, it can be argued that the event started at about 121.5 kyr BP and lasted for about 3.5 kyr. However, TL ages of loess older than 100 kyr have generally been regarded as being biased from their true ages [30]. We also note that a large error range (5.9–13 kyr) is associated with our TL ages for the S1 series (Fig. 1). Therefore, an astronomical tuning method [29,31] was used to constrain the age of the event. Following the procedures introduced in [29,31], we tuned our magnetic susceptibility climate record (Fig. 1d), which has been extended to the bottom of the Jiuzhoutai section (data and initial age points after [3,19]), to the orbital forcing variations [32], using the following assumptions: (1) the Asian monsoons have responded linearly to the orbital forcing variations with phase lags as in the Baoji loess section on the central Loess Plateau [31] and marine records [29]; and (2) formation of a soil will take twice as long as the same thickness of loess [31]. The results show that the event started at ca. 119.97 kyr BP and ended at ca. 114.47 kyr BP with a duration of 5.5 kyr, enabling us to define this interval of reversed polarity as the Blake Event [15–18,23–27]. Durations of the lower and upper reversed intervals and the intermediate short normal interval within the event are estimated as 2.58, 1.61 and 1.31 kyr BP, respectively.

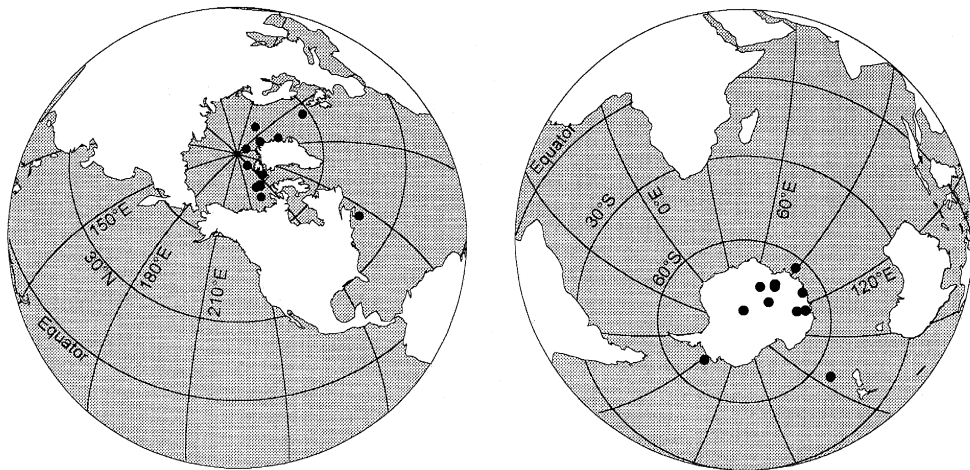


Fig. 5. Virtual Geomagnetic Poles (VGPs) for the depth interval (37.25–37.80 m) that contains the Blake Event in the Jiuzhoutai well section.

## 5. Discussion

Our results support the existence of a triple feature of the Blake Event; that is, two short reversed intervals separated by a short normal interval, with an age for the event of 115–120 kyr BP and a duration of about 5,500 years. In the Zoige Basin, ca. 300 km south of Lanzhou, a paleomagnetic study of a lacustrine sediment core (RM), with high sediment input rates, has also revealed a triple feature, in agreement with our characterization of the Blake Event [12].

However, our results differ in structure from those derived from the Xining loess section by Zhu et al. [9], in which the Blake Event has three short reversed intervals separated by two short normal inter-

vals and is reportedly located at depths of 1675–1731 cm in the last interglacial soil series. Because the Blake Event at Xining is located in loess, whereas our placement is in a paleosol, and given the lack of details about the stratigraphy at Xining, it is difficult at present to make a direct comparison between our results and those of Zhu et al. [9].

Virtual Geomagnetic Poles (VGPs) are shown in Fig. 5 for the interval of 37.25–37.80 m that contains the Blake Event. The VGP groupings are antipodal, albeit not exactly coaxial with the rotation axis, illustrating that the geomagnetic field during the fully normal and reversed stages of the Event was that of a geocentric dipole. Because of a scarcity of transitional directions in our record, no details can be provided about transitional VGP paths.

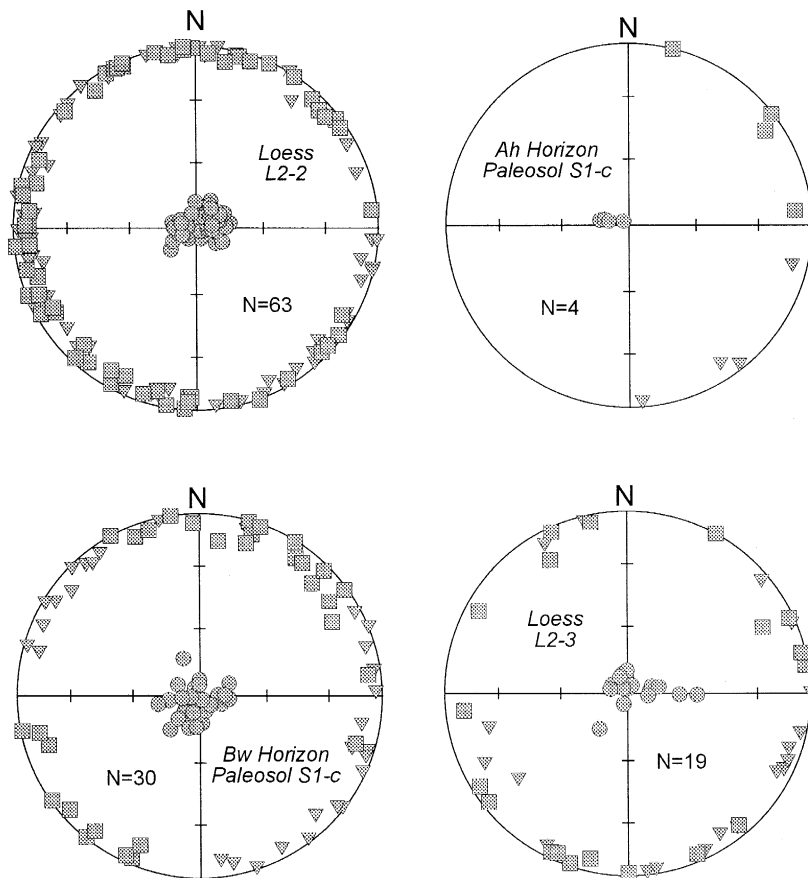


Fig. 6. Lower hemisphere equal area projections of the AMS data from loess horizon L2-2, the Ah horizon of Paleosol S1-c, the Bw horizon of Paleosol S1-c and the L2-3 loess horizon. Squares = the maximum axes; triangles = the intermediate axes; circles = the minimum axes. Note that a similar pattern is observed in all four horizons.

To be able to locate the Blake Event in loess–paleosol sequences is of enormous importance, because it can aid in detailed loess–paleosol sequence correlation, which is needed for high-resolution studies of climate change. Soil sequences and magnetic susceptibility show that the Blake Event in our section is located just below the boundary of soil S1-c and loess L2-2 (Fig. 4). At this level of the section a bioturbated soil horizon, Ah, is developed, with a high organic content and loose structure. In areas with high precipitation, for example, the central and eastern Loess Plateau, most Ah horizons of paleosols in loess have been seriously bioturbated [15] and many have been eroded during the sharp climatic change near the end of paleosol formation [15–19]. This may, in part, explain why it has been so difficult to detect the short Blake Event elsewhere on the central Loess Plateau. The dry climate and high dust input rate in the Lanzhou area minimize the possibilities of these disturbances in our section. Soil micro-morphology has confirmed that bioturbation was weak and that erosion in our paleosols and loess was minimal [33]. Our AMS measurements further support this conclusion, in that there is a very similar pattern (oblate) throughout loess L2-3, the lower (Bw horizon) and the upper part (Ah horizon) of paleosol S1-c, which includes the Blake Event, and loess L2-2 (Fig. 6). Because the location of the Blake Event in our section is clearly indicated by magnetostratigraphy in a section defined by excellent soil horizon stratigraphy as well as by magnetic susceptibility, the event is of great value in stratigraphic correlation on the Loess Plateau.

Our estimate of the age as about 114.5–120 ka for the Blake Event is in agreement with several previous estimates published in the last decade [9,24,26]. Other age determinations for the event are either significantly younger [34] or older [35–38], so that a wide age range between 105 and 138 ka, or even 161 ka, exists in the literature (e.g., [37,38]). The accuracy of many of these age determinations, however, is dependent on correlations with isotope stratigraphy, while assuming that magnetization acquisition has been instantaneous. If a lag occurs between (a) the earlier time of deposition and (b) a later time at which the magnetization was acquired, the age estimate of the event would be too old if based on (a); that is, older rocks that have been remagnetized

during the Blake Event. This could explain some of the older age estimates. Most studies have concluded, however, that the Blake Event occurred at the end of the Eemian Interglacial [24], and this is also what we have found.

Of greater complexity is the issue of the duration of the event, as well as its apparently abrupt transitions in our record. Estimates of the duration of the Blake Event have ranged from a low of 4–6 ka [9,24,26,34], to a longer interval of about 10 ka [25,37], or even up to a very long 50 ka [23], with our estimate falling near the lower end. Estimates of event duration in sedimentary records rely directly on a knowledge of sedimentation rate, which, at best, is known as an average of what may well have been rather variable rates of short duration. Corrections for such variation may differ for different studies. Abruptness in the reversal record (i.e., the absence of transitional directions) may also be indicative of highly variable rates on short time scales. It is, of course, possible that this may have played a role in the Lanzhou record described here. Conventional estimates for the duration of transitions have been of the order of several thousand years [39], whereas our sample spacing appears to require a duration of a few hundred years or less. However, transitions as short as some 50 years have now also been proposed [40,41]. A higher temporal resolution and denser sampling is needed, however, before the Lanzhou loess–paleosol record can be used to contribute substantially to this issue.

## 6. Conclusions

On the basis of the results above, the following conclusions are presented:

(1) The high resolution Lanzhou loess–paleosol record has great potential for more detailed study of the Blake Event.

(2) The Blake Event has been found just below the boundary between the last interglacial paleosol S1-c and loess L2-2, and is characterized by a triple feature consisting of two short reversed intervals separated by a short normal interval. The directional changes are abrupt rather than gradual.

(3) Thermoluminescence dating and astronomical tuning constrain the age of the Blake Event between

119.97 kyr BP and 114.47 kyr BP with a duration of 5.5 kyr.

(4) The geomagnetic field appears to have been largely that of a geocentric dipole during the fully reversed and normal polarity states before, during and after the Blake Event.

(5) The Blake Event is of global significance, and its age near the end of the Eemian Interglacial may aid in stratigraphic correlations related to climate changes at that time (e.g., [42]).

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