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A detailed record of normal–reversed-polarity transition obtained from a thick loess sequence at Jiuzhoutai, near Lanzhou, China

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SUMMARY

A record of normal–reversed-polarity transition has been obtained from a 4 m thickness of loess exposed at a section near Lanzhou, China. Magnetostratigraphic studies suggest it may represent a reversal bounding the onset of a reversed-polarity zone within the Jaramillo Normal Subchron. The natural remanent magnetization consists of two components: a low-coercivity (≤ 20 mT), low-unblocking-temperature ($\leq 300\,^{\circ}$C) component of viscous origin and a high-coercivity (> 20 mT), high-unblocking-temperature (250–700 °C) component carrying the characteristic remanence. Mineral magnetic analyses confirmed the presence of magnetite, its low-temperature oxidation products and haematite, each contributing to the remanence properties. Grain size and concentration showed limited variations and there was little evidence for the presence of the ultrafine magnetic phase commonly associated with palaeosol formation. Pedogenic processes appeared negligible and their effects unimportant, with detrital processes dominating the mineralogy and most probably the acquisition of the characteristic remanence. The reversal record was characterized by the decay and recovery of the geocentric axial dipole term with large directional swings occurring during periods of reduced relative palaeofield intensity. The virtual geomagnetic poles traced a complex path exhibiting no particular geographical confinement. Relative palaeofield intensity determinations were insensitive to the choice of normalization parameter and showed a distinctive asymmetry. Striking similarities were observed with the Matuyama–Jaramillo reversal record, obtained from the same section (Rolph 1993), and the Steens Mountain reversal record (Prévot *et al.* 1985), lending further support for the existence of unusually high post-transitional field intensities

Key words: China, loess, magnetic polarity, palaeomagnetism.

INTRODUCTION

Data compilations of single (Clement 1991) and multiple (Tric *et al.* 1991; Laj *et al.* 1991) sedimentary records of geomagnetic polarity reversals suggest the retention of a simple field geometry that persists over several reversals. This is expressed by confined paths of sequential virtual geomagnetic poles (VGPs), as they move between stable polarity positions, which appear as two preferred antipodal bands situated over the Americas and Eastern Asia. Using a separate data set Valet *et al.* (1992) questioned the significance of these preferred longitudinal bands, a position supported by Prévot & Camps (1993), whose data set of volcanic records did not show any evidence for confinement of VGPs.

It has been suggested that the preferential distribution of VGPs in sedimentary records may be an artefact of the remanence acquisition process (e.g. Rochette 1990; Langereis, van Hoof & Rochette 1992), although this has been questioned by Weeks *et al.* (1992). Additionally, the statistical analysis of Valet *et al.* (1992) was shown to be suspect by McFadden, Barton & Merrill (1993), who devised a different method for testing the hypothesis of preferred VGP paths. Their conclusion was that the preference is unlikely to have arisen from a uniform random distribution, although there is a strong bias in the site distribution of reversal records that may be responsible for the observed confinement. Quidelleur & Valet (1994) suggested that inclination shallowing in sedimentary records during periods of weak magnetic field might give rise to VGPs $\pm 90^{\circ}$ from the site longitude, and that the site distribution is such that the majority of VGP paths thus obtained would fall over the Americas and its antipode. Egbert (1992), on the other hand, pointed out that the VGP transformation may be responsible for the observed bias.

Further meaningful analyses require a more uniform global

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distribution of observation sites. The study presented here describes a reversal record obtained from the loess deposits of northern central China, an area relatively under-represented in current reversal databases.

GEOLOGICAL SETTING AND SAMPLING

Chinese loess is an aeolian silt deposit, the main body of which is found in a broad belt extending over northern central China known as the Loess Plateau (LP, Fig. 1). The deposits consist of alternating loess and palaeosol horizons representing accumulation during cold, arid (loess) and warm, humid (palaeosol) conditions. Most palaeosol horizons can be correlated across the whole of the LP, becoming more reddish and heavily weathered from west to east, a characteristic shared by the loess horizons. This reflects the superposition of local climate regimes upon regional glacial/interglacial fluctuations.

The section investigated lies on the flanks of Jiuzhoutai mountain, located *ca.* 5 km NW of the city of Lanzhou, NW China (36°N, 103.8°E, Fig. 1). Here 318 m of loess deposits lie above imbricate gravels of the highest local terrace of the Huang He (Yellow River), which in turn lie unconformably on Cretaceous red desert sandstones. In this region the climate is arid/semi-arid, the palaeosols are poorly developed and in the field they are visually indistinct.

Magnetostratigraphic studies (Burbank & Li 1985; Rolph *et al.* 1989; Chen, Li & Zhang 1991) locate the Jaramillo Normal Subchron (JNS) between 76 and 95 m above the loess/gravel contact (Figs 2a,b,c). All stratigraphic levels are given as heights above this contact. Rolph *et al.* (1989) detected three polarity boundaries in the interval 87–95 m (Fig. 2c), and their presence was confirmed by a more detailed sampling of this interval (Fig. 2d). The wider sampling space employed by Burbank & Li (1985) and Chen *et al.* (1991) might explain their apparent absence in these studies. There is no field evidence to suggest extensive local slumping and/or shear block movement at this particular point in the section. As will be shown below, the change from normal (N) to reversed (R) polarity directions does not occur suddenly, as one might expect for a tectonically controlled boundary.

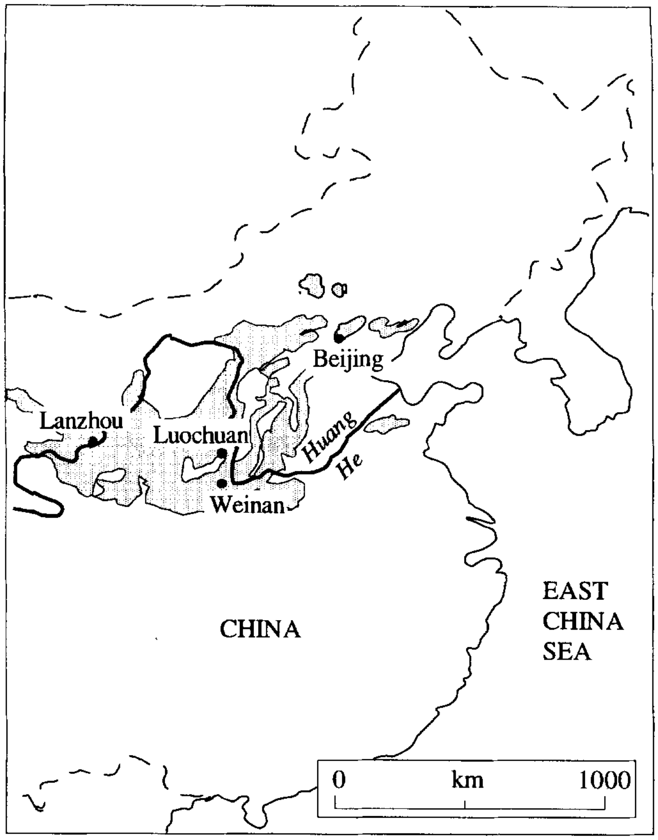

Figure 1. Map of the Loess Plateau of central China (shaded) showing the locations of the sections mentioned in the text.

Recently published magnetostratigraphies for the Quaternary (e.g. Cande & Kent 1992) do not show such a complicated structure for the JNS. However, the high accumulation rates exhibited by the loess deposits in this part of the LP means that they might be able to resolve geomagnetic behaviour in much finer detail. At Jiuzhoutai the apparent accumulation rate has remained fairly constant at 22.6 cm kyr^{-1} since the onset of the JNS. This makes the period of R polarity between 90 and 94 m some 18 kyr in length and the N polarity zone between 94 and 97m 13 kyr in length. Such short-term features may be filtered in lower-resolution records. In a study of rapidly deposited marine sediments (Pillans *et al.* 1994) there was some indication of a short period of R polarity within the JNS. This is consistant with the Jiuzhoutai results, although further magnetostratigraphic investigations of parallel sections are necessary to test this interpretation fully.

The present study looks in detail at the N–R transition that marks the onset of the short R polarity interval within the JNS (Fig. 2d). This occurs within the stratigraphic interval 87–91 m, which is exposed on the subvertical faces of a naturally occurring gully, close to a cave near the top of the gully. It is referred to throughout this text as the JZT(cave) reversal. The loess here is hard, compacted and well-cemented. A soft skin between 1 and 3 cm thick covered parts of the exposed surfaces and probably formed as a product of surface run-off during rainfall/snow melt. It was readily discernible from *in-situ* material by its softness and texture and was scraped off using a hand knife. An overlapping sequence of fully oriented block samples (approximate dimensions 10 × 10 × 20 cm) was then collected. Subsampling in the laboratory involved taking 2 cm cubes from vertical columns prepared from cross-sectioned block samples. For an accumulation rate of 22.6 cm kyr^{-1} this provided a sampling frequency of approximately 11 samples kyr^{-1}. Pairs of specimens were taken from adjacent columns to give two parallel specimen sets spanning the vertical length of the section. Specimens were subjected to either stepwise thermal (TH) or alternating-field (AF) demagnetization of their natural remanent magnetization. Specimens subjected to AF demagnetization were used in mineral magnetic analysis and relative palaeofield intensity determination.

NATURAL REMANENT MAGNETIZATION (NRM)

Stepwise TH demagnetization was carried out using a Magnetic Measurements thermal demagnetizer (MMTD1). The NRM of specimens thus demagnetized was measured using a Cryogenic Consultants Ltd three-axis cryogenic magnetometer (GM400 series). Both demagnetizer and magnetometer were situated in a Magnetic Measurements low-field-

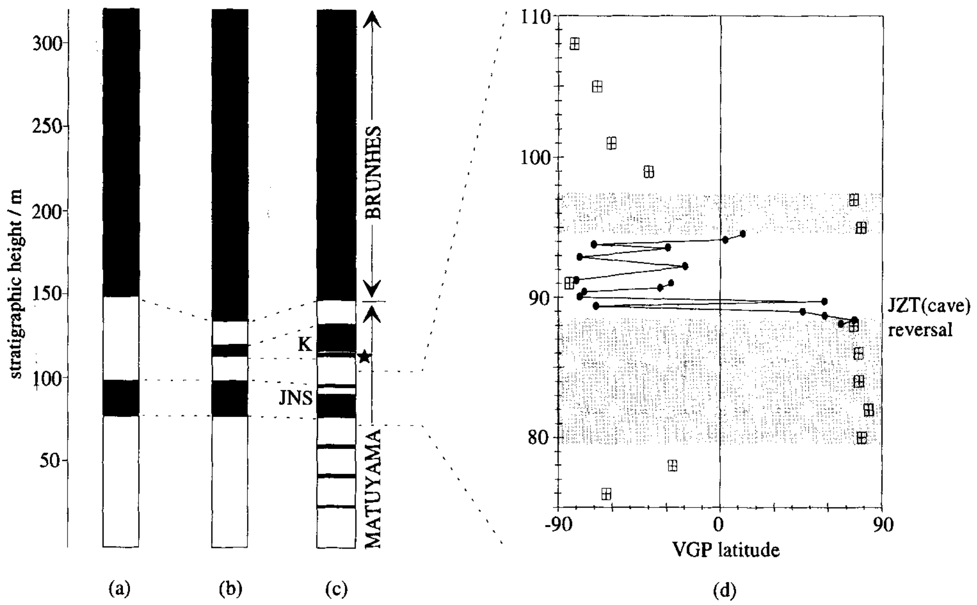

Figure 2. Magnetostratigraphy of the Jiuzhoutai section as defined by (a) Burbank & Li (1985), (b) Chen *et al.* (1991) and (c) Rolph *et al.* (1989), where K is the Kamikatsura Normal Subchron and JNS is the Jaramillo Normal Subchron. The star indicates the polarity boundary described in Fig. 12. (d) shows the VGP latitudes for the data points in the stratigraphic interval 85–110 m. The open symbols denote the points defined by Rolph *et al.* (1989) and the closed symbols those of the more detailed sampling undertaken in the present study.

environment cage (MMLFC). A majority of specimens were initially demagnetized at 200–300 °C, then at 50 °C steps up to 600–700 °C, or until remanence measurements became unstable. Selected specimens were demagnetized in more detail at lower temperatures. AF demagnetization was conducted using a two-axis tumbling system with a maximum AF of 170 mT, remanence measurements being made using a Molspin spinner magnetometer. Specimens were demagnetized in 10 mT steps up to 40–60 mT, then at irregular steps up to 100–170 mT.

Initial NRM directions exhibited both positive and negative inclinations with concentrations close to the present-day field direction and its antipode. Recent (i.e. Brunhes age) viscous overprints were not sufficient to fully obscure R polarity directions, in contrast with palaeomagnetic results obtained from loess deposits from the (more strongly weathered) eastern parts of the LP (Heller & Liu 1984). Intensities ranged from 0.025 to 1.324×10^{-5} Am^2 kg^{-1}, with specimens having R polarity directions tending to have relatively high intensities.

Both TH and AF demagnetization yielded similar results (Fig. 3). A low-unblocking-temperature (≤ 300 °C), low-coercivity (≤ 20 mT) component with predominantly northerly, positively inclined directions probably represents a Brunhes age viscous overprint. Characteristic directions were revealed at 200–300 °C or 20 mT, beyond which the remanence vector decayed linearly towards the origin of the demagnetization plots. Up to 20 per cent of NRM remained at 170 mT or 600 °C. TH demagnetization was more successful than AF in defining characteristic directions. The characteristic remanence showed distinct unblocking between 250–300 °C and 650–700 °C, suggesting it was being carried by several mineral phases.

Close agreement was observed between the directions obtained through principal component analysis and single-step TH cleaning at 300 °C (Table 1). The largest discrepancies were found in those specimens having relatively low partially demagnetized NRM intensities, for which the best-fit direction was poorly constrained (i.e. there was a large maximum angular deviation about the fitted direction, Fig. 3h). Measurements of low-field magnetic susceptibility after each heating step indicated that considerable alteration was occurring beyond 350 °C. This, along with the modest changes in the remanence vector of the weaker specimens beyond this temperature, introduced uncertainties in the determination of the best-fit direction. Therefore, the directions after TH cleaning at 300 °C were taken as representative of the characteristic directions, effectively maximizing the NRM/noise ratio by using information obtained prior to significant thermally induced alteration.

The asymmetry of the mean N and R polarity directions (Table 1) probably indicates that the record does not extend into significant periods of fully N or R polarity. This is supported by the results of the magnetostratigraphic study of Rolph *et al.* (1989), which yielded mean N and R polarity directions that were almost exactly antiparallel (declination/inclination/α_{95} = 1.5°/51.1°/3.1° and 177.7°/−52.6°/5.4°, respectively) and close to the present-day field direction and its antipode. Thus the characteristic remanence seems unaffected by inclination shallowing and post-formational tectonic rotation.

MAGNETIC MINERALOGY

Magnetite, maghemite and haematite of varying grain sizes have all been identified in Chinese loess in previous studies (e.g. Heller & Liu 1984; Kukla *et al.* 1988; Zhou *et al.* 1990; Maher & Thompson 1991; Liu *et al.* 1992). In weathered loess and palaeosol horizons there is a relative increase in the amount of fine-grained [superparamagnetic (SP)/stable single domain (SSD)] magnetite/maghemite compared to unaltered loess, giving rise to an increase in low-field magnetic susceptibility (χ)

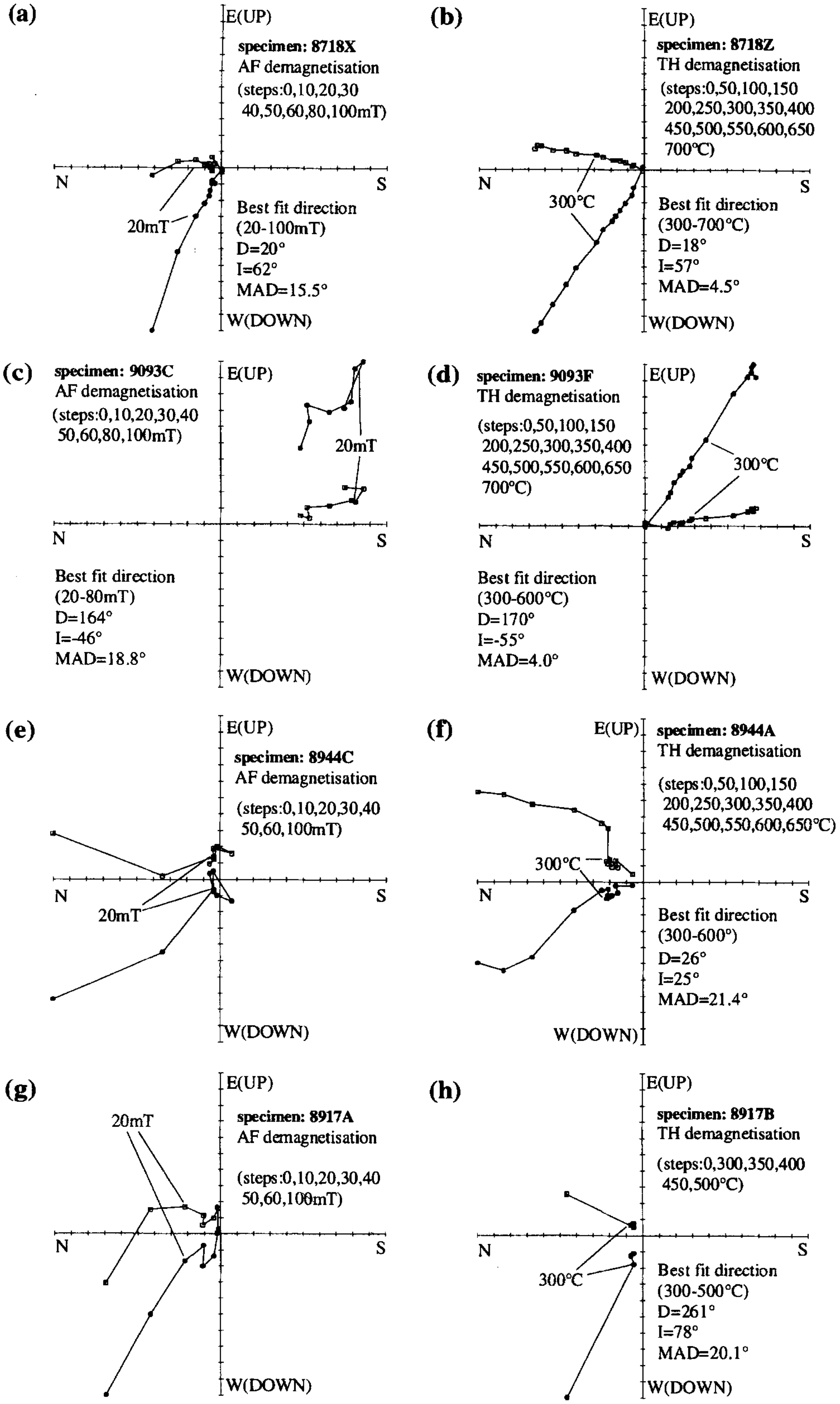

Figure 3. Orthogonal vector projections of stepwise demagnetization of NRM. Plots on the left (right) represent specimens that have been subjected to AF (TH) demagnetization. Sample codes reflect their stratigraphic height within the section. The horizontal (vertical) projection is marked with a square (circle).

Table 1. Fisher mean directions of the component of NRM removed between 300 and 600 °C [NRM(300–600 °C)], and that remaining after TH cleaning at 300 °C [NRM(300 °C)] for those specimens demagnetized at 600 °C or beyond.

	Declination	Inclination	α_{95}	n
positive inclination				
NRM(300-600°C)	344.2°	40.7°	7.3°	48
NRM(300°C)	346.5°	40.0°	6.0°	48
negative inclination				
NRM(300-600°C)	173.0°	-62.3°	7.3°	59
NRM(300°C)	176.5°	-61.8°	6.3°	59

and its frequency dependence (χ_{fd}), along with increases in both anhysteretic remanence (ARM) and isothermal remanence (IRM). This takes place against a fairly constant high-coercivity 'background' consisting of magnetite, its low-temperature oxidation products and haematite (Evans & Heller 1994; Eyre & Shaw 1994).

In the present study χ has been measured at low (0.47 kHz, χ_l) and high (4.7 kHz, χ_h) frequencies using a Bartington dual frequency susceptibility meter (MS1B) and is mass-normalized. The parameter χ_{fd} is the difference between the low- and high-frequency susceptibilities, here expressed as a percentage ($\chi_{fd} = 100(\chi_l - \chi_h)/\chi_l$). χ_l varied between 15.3 and 18.1×10^{-8} m^{3}kg^{-1} with a mean of 16.6×10^{-8} m^{3}kg^{-1}, typical for relatively unaltered loess and close to the 'background' values established by Heller *et al.* (1991). The low values of χ_{fd} (mean 1.7 per cent, with only two specimens exceeding 5 per cent) indicate that the role of SP material is less important than elsewhere across the LP.

Stepwise IRM acquisition up to 4 T (termed saturation IRM, SIRM) was conducted using Molspin (0–0.3 T) and Trilec (0.4–4.0 T) pulse magnetizers with subsequent remanence measurements made using a Molspin spinner magnetometer. The normalized IRM acquisition curves for eight representative specimens are shown in Fig. 4(a). Each has the same shape, with 81–82 per cent of SIRM acquired at 300 mT, the maximum theoretical coercivity of magnetite (McElhinny 1973). Beyond 300 mT the curves flatten but do not reach saturation, indicating the presence of high-coercivity minerals.

By looking at the gradient of the acquisition curves some comment can be made on the mineral phases contributing to the IRM. This was achieved by fitting the IRM gradient with a number of log-Gaussian distributions that are taken as representative of the coercivity distributions of the constituent mineral components (Robertson & France 1994; Eyre 1994). The modelled curves were fitted iteratively by adjusting three parameters for each of the chosen log-Gaussian distributions: the centre field (equivalent to the mean acquisition coercivity, MAC), the standard deviation and the relative height. The area under each distribution curve gives its relative contribution to the total remanence. A good fit for each of the curves was obtained by using three distributions or components (Fig. 4b,c). Component 1 had a MAC of 35 mT, close to that expected for SD magnetite (Thompson & Oldfield 1986), and

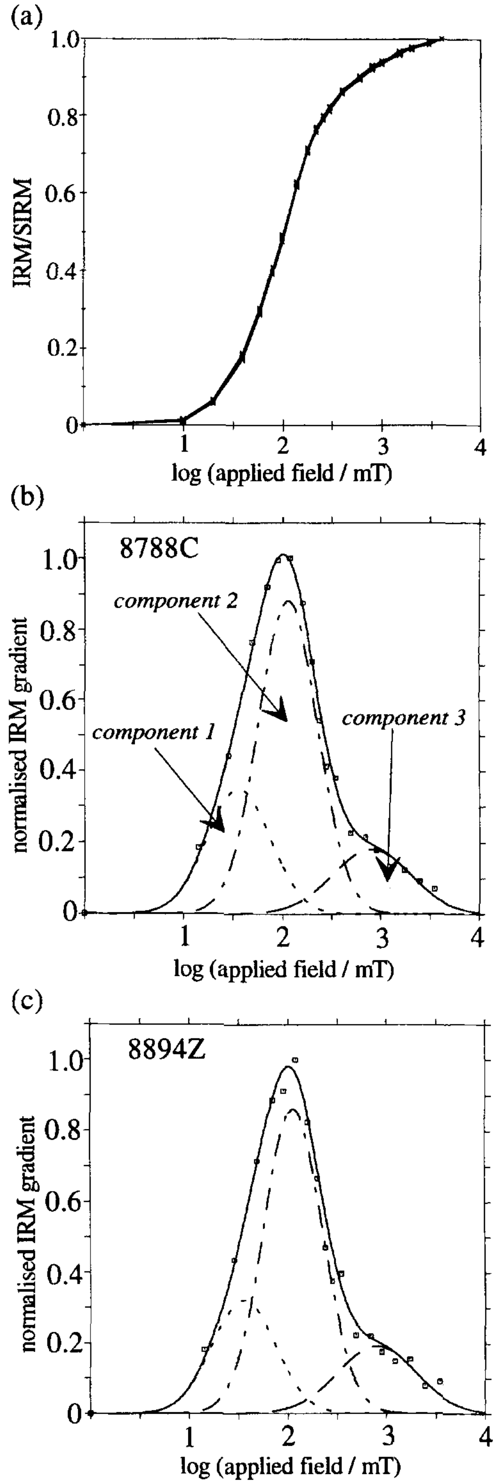

Figure 4. IRM acquisition. (a) stepwise acquisition of IRM (eight specimens are displayed), (b) and (c) IRM coercivity spectra (open symbols) and fitted Gaussian approximation (solid line). Dashed lines denote each of the fitted Gaussian distributions.

comprised 20.7–25.0 per cent of the total remanence. Component 2 was the largest of the components, constituting 58.9–63.1 per cent of the total remanence. It had a MAC of 112 mT and represents a high-coercivity ferrimagnetic phase or a low-coercivity haematite phase. Component 3 had a MAC of 794 mT, comparable with the value of 0.7 T quoted by Thompson & Oldfield (1986) for fine-grained haematite. Between 16.3 and 17.4 per cent of the total remanence was carried by this component.

Magnetic hysteresis was investigated using a Molyneux vibrating sample magnetometer. The peak applied field (± 1 T) was not sufficient to saturate any haematite present in the specimens. A pair of typical loops are shown in Fig. 5. At high fields (>400 mT) the ascending and descending branches were indistinguishable and dominated by paramagnetic behaviour. Hysteresis parameters were calculated after the removal of the paramagnetic contribution, which was determined from the slope between 0.6 and 1.0 T. The ratio of saturation remanence to saturation magnetization (M_{rs}/M_s) varied between 0.254 and 0.182 with a mean of 0.212, intermediate between the values expected for SSD (0.5) and multidomain (MD, 0.02) material. The mean coercivity of 1.35×10^4 Am^{-1} was higher than the value of 0.8×10^4 Am^{-1} expected for single-domain magnetite (Thompson & Oldfield 1986).

Thermomagnetic behaviour was measured using a horizontal translation force balance with a heating time of 20 min. between room temperature and 700 °C. Heating and cooling were carried out in air in an applied field of 550 mT. All specimens exhibited similar behaviour, with Curie temperatures of 600–610 °C exceeding that of pure magnetite. A change in slope on heating at *ca.* 280–300 °C and a loss in magnetization on cooling indicated the presence of maghemite. A significant part of the characteristic magnetization of the specimens was removed in this temperature range. The applied field was insufficient to saturate any haematite present in the specimens.

The high values for the mean coercivity and Curie temperature can be explained by the predominance of partially oxidized magnetite. Cation-deficient and maghemized rims can form on magnetite as a consequence of low-temperature weathering processes (e.g. O'Reilly 1984), raising the coercivity of the grains above that of pure magnetite (van Velzen & Zijderveld 1992) and elevating the Curie temperature. The high MAC of IRM component 2, which is the dominant remanence carrier, can also be explained in this way. A similar remanence component was identified in a systematic study of loess and palaeosol horizons spanning the whole of the LP (Eyre 1994) and found to be present in equal amounts, irrespective of lithology or degree of weathering. This lack of dependency on weathering suggests that post-depositional oxidation processes are not the controlling influence on the origin of these grains. A more likely explanation is that the grains represent a detrital fraction that underwent partial oxidation prior to deposition. Taking into consideration the history of their formation, from initial erosion, transportation to the marginal deserts and subsequent deposition on the LP, such an explanation seems plausible. This, as well as the presence of significant amounts of haematite and the low values of both χ_l and χ_{fd}, implies that the magnetic mineralogy is dominated by detrital minerals as opposed to pedogenic/weathering products.

THE REVERSAL RECORD

The results of TH cleaning at 300 °C are given in Fig. 6. The transition between N and R polarity directions occurred between 89 and 90 m and was characterized by several large swings in declination and inclination, during which time the NRM intensity was at a minimum. For an accumulation rate of 22.6 cm kyr^{-1} this gives an approximate time of 4.4 kyr for the directional changes, consistent with the results from early reversal studies (e.g. McElhinny 1973). Interblock variation did not exceed intrablock variation (McIntosh 1994) and thus the large directional swings do not appear to have been caused by sampling uncertainties. Multiple specimens taken from the same stratigraphic horizon showed that for a range of NRM intensities the results were repeatable (Fig. 7) and further highlighted the good interblock correlation. The most obvious features of the directional record were the shallow inclinations prior to and during the reversal and the steep inclinations after the reversal. During the transition itself, several swings to R polarity directions were observed, representing periods of rapid change. For example, the directional swing between 89.28 and 89.36 m, defined by multiple specimens and several intermediate points (Fig. 7c), spanned approximately 440 yr.

The directions have been converted to their corresponding VGPs and plotted in Fig. 8. For the purpose of clarity the data have been arbitrarily split into three subsets: 87.14–89.08 m, 89.08–90.05 m and 90.05–90.99 m. Between 87.14 and 89.08 m (Fig. 8a) the VGPs traced a jerky, irregular path about high latitudes with a dominantly clockwise sense of motion. A number of 'excursions' over western Europe and the northern Atlantic were observed between 87.77–88.09 m and 88.83–88.91 m. The transition from N to R polarity (89.08–90.05 m, Fig. 8b) occurred in several phases, the first of which described a large loop over Australia and the Pacific Ocean. In the second phase the VGPs oscillated over Africa and the north Atlantic, crossing the equator three times. This

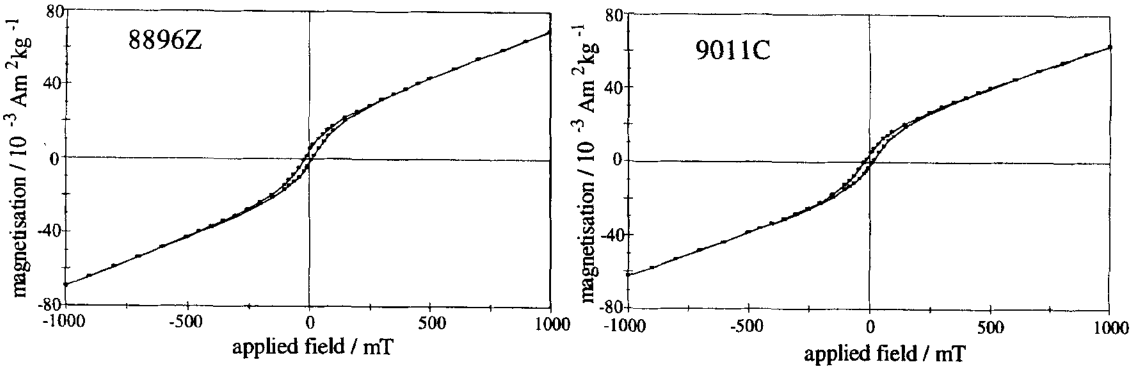

Figure 5. Examples of magnetic hysteresis loops showing typical behaviour.

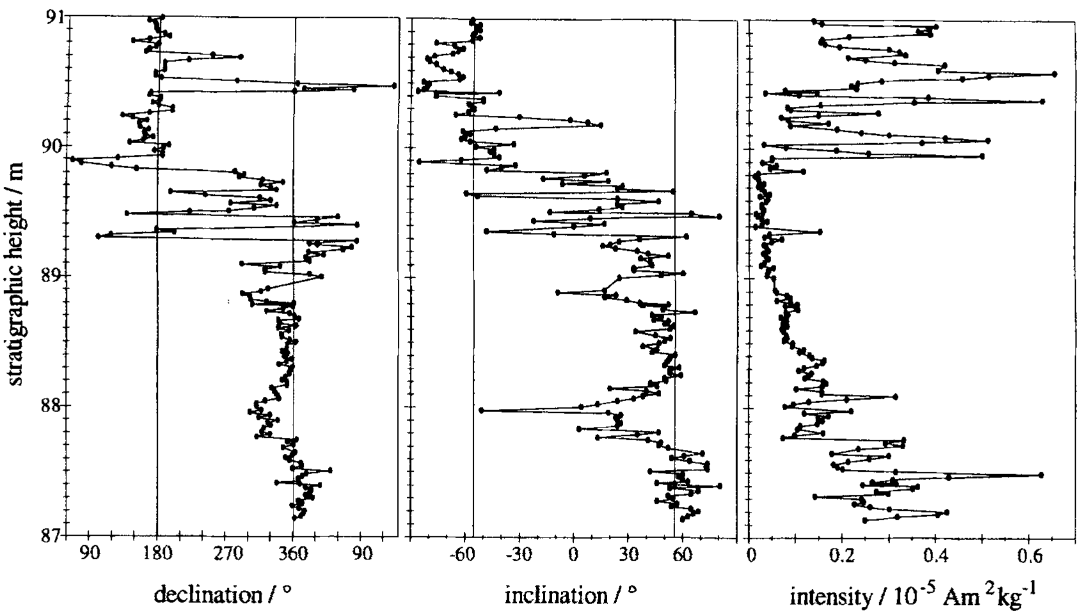

Figure 6. Stratigraphic variation of NRM after TH cleaning at 300 °C. The directions expected for a geocentric axial dipole at Lanzhou (36°N, 103.8°E) are indicated.

was followed by a large clockwise 'rebound' over the southern Pacific. Between 90.05 and 90.99 m (Fig. 8c) the VGP exhibited a (nearside) clockwise loop towards SE Australia/New Zealand followed by a pair of (farside) loops over the southern tip of South America, before reaching high southern latitudes.

RELATIVE PALAEOFIELD INTENSITY

In order to determine relative palaeofield intensity (RI) in sediments, a suitable parameter must be found to normalize the NRM with respect to the amount of magnetic material contributing to the NRM [see Tauxe (1993) for a comprehensive review]. In addition to this it is important that the deposits exhibit magnetic homogeneity so that some confidence can be placed on the reliability of the resulting RI curves. This has led to the proposal of a number of criteria for the suitability of a particular sediment for RI determination. The basic requirements, set out by King, Banerjee & Marvin (1983) and Tauxe (1993), amongst others, are that the NRM should be carried by magnetite in the 1–15 μm grain-size range and that within this range the grain size should show only limited variation, concentration should change by less than a factor of 10 and the results of normalization should be repeatable using a number of different magnetic parameters. Clearly the loess fails the first of these criteria, in that a mixture of magnetite, maghemite and haematite carries the NRM. However, they each carry the same palaeomagnetic direction, suggesting that they were 'activated' simultaneously during the magnetization process and effectively behave as a single component.

Fig. 9 shows the stratigraphic variation of χ_l, χ_{fd}, ARM and SIRM. ARM was acquired in an AF of 170 mT with a biasing field of 90 μT and measured using a Molspin spinner magnetometer. That part of the NRM remaining after 170 mT demagnetization was vectorially subtracted from the measured ARM. The remanence parameters have been AF demagnetized to 40 mT, removing the contribution of the magnetically soft components. Each of the parameters varied by less than a factor of 1.4, clearly within the limits set out in the previous paragraph. An increase in SIRM (Fig. 9d) and χ_l (Fig. 9a) between 90.4 and 90.8 m was not observed in ARM and probably represents a subtle shift to slightly coarser material. ARM, which is particularly sensitive to stable SD grains (Maher 1988), attained maximum values at *ca.* 89 m (Fig. 9c), implying a small increase in finer material. There was no increase in χ_{fd} (Fig. 9b) as one would expect if this were a consequence of pedogenic enhancement.

The NRM showed much more dramatic fluctuations, varying by a factor of 98 (Fig. 9e), with the highest values observed between 89.9 and 91.0 m. Several distinct peaks in intensity could be seen in this region that did not correspond to peaks in any of the mineral magnetic parameters. There was no obvious correlation with any part of the mineral magnetic record. When the NRM was normalized with respect to either χ_l, ARM or SIRM the ensuing RI curves (Fig. 10) were identical, both in form and amplitude, thus satisfying the criterion of repeatability of results. Given that there was no clear evidence for a palaeosol horizon within the record and there was no visible difference between specimens exhibiting low or high RI values, there is no reason to assume significant changes in the remanence acquisition process.

These results then show that a long period of low RI preceded the directional transition, which occurred between 89 and 90 m. Upon the establishment of fully reversed directions (*ca.* 89.9 m), the RI exhibited rapid recovery to a value higher than that seen at the beginning of the record. Several directional excursions were observed during this period. Superimposed on the general asymmetric RI trend was a high-frequency amplitude fluctuation, especially obvious during the 'post-transitional' recovery phase. These fluctuations were defined by more than one point and so can be differentiated from random noise fluctuations. Since the record does not include a significant period of stable-polarity behaviour it is

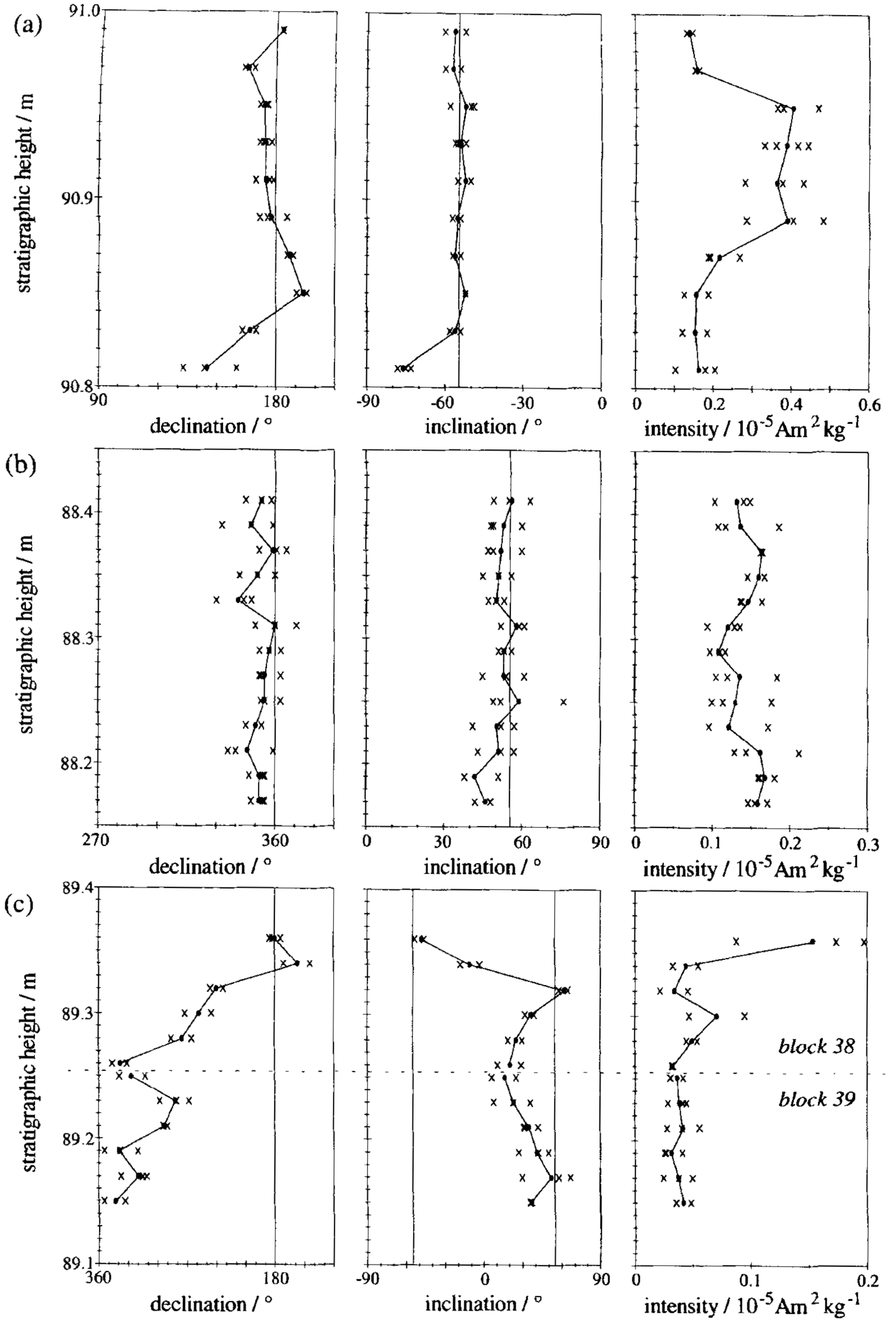

Figure 7. Within-horizon variability of NRM after TH cleaning at 300 °C for parts of the record showing (a) stable R polarity directions, (b) stable N polarity directions and (c) rapidly changing directions. Solid circles indicate Fisher mean directions.

difficult to ascribe the fluctuations to either transitional processes or secular variations of the stable geomagnetic field.

DISCUSSION

The magnetization process in loess is poorly understood and hence its influence on the record is difficult to assess. Both chemical (Heller & Liu 1984) and detrital (Kukla & An 1989) processes have been suggested; the relative importance of each might vary, depending on the extent of secondary weathering and/or pedogenesis. In strongly developed palaeosols and weathered loess horizons the release of iron through pedogenesis can lead to the formation of chemical-remanence-bearing iron oxides (see Hus & Han 1991). This is likely to be significant in the southern parts of the LP where warmer and more humid conditions prevailed throughout the depositional history.

In contrast, the breakdown of iron-bearing silicates is not observed in a loess section near Xifeng, Gansu Province (northern LP, Fig. 1) (Guo *et al.* 1993). There is no evidence for significant amounts of pedogenically produced material in the Lanzhou loess, at least for the older (>0.5 Ma) material,

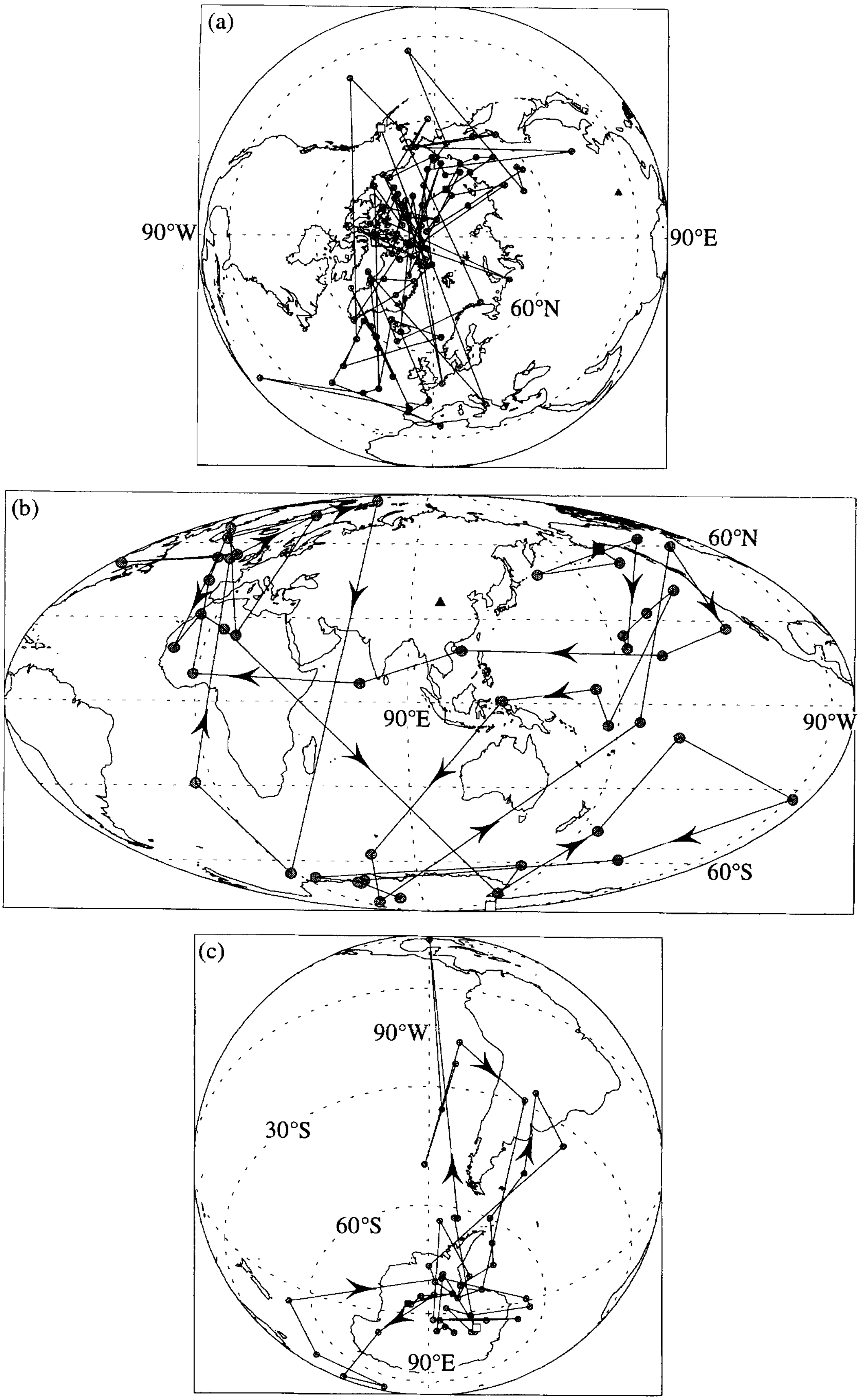

Figure 8. VGP path for (a) 87.14–89.08 m, (b) 89.08–90.05 m and (c) 90.05–90.99 m. Solid (open) squares indicate the first (last) point in each portion of the record and the solid triangle the locality.

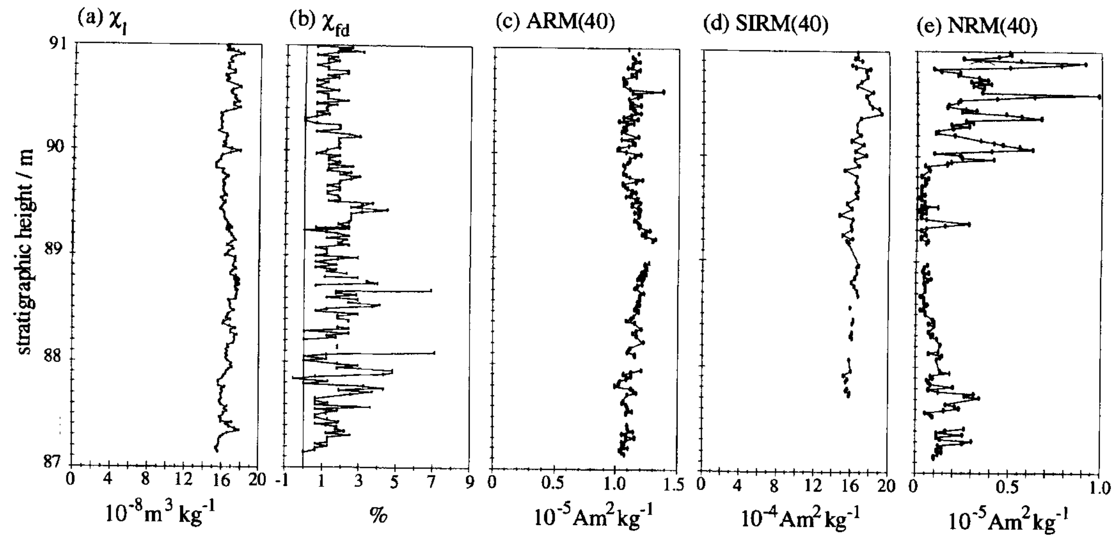

Figure 9. Stratigraphic variation of (a) χ_l, (b) χ_{fd}, (c) ARM(40), (d) SIRM(40) and (e) NRM(40). The remanence parameters have been AF demagnetized to 40 mT.

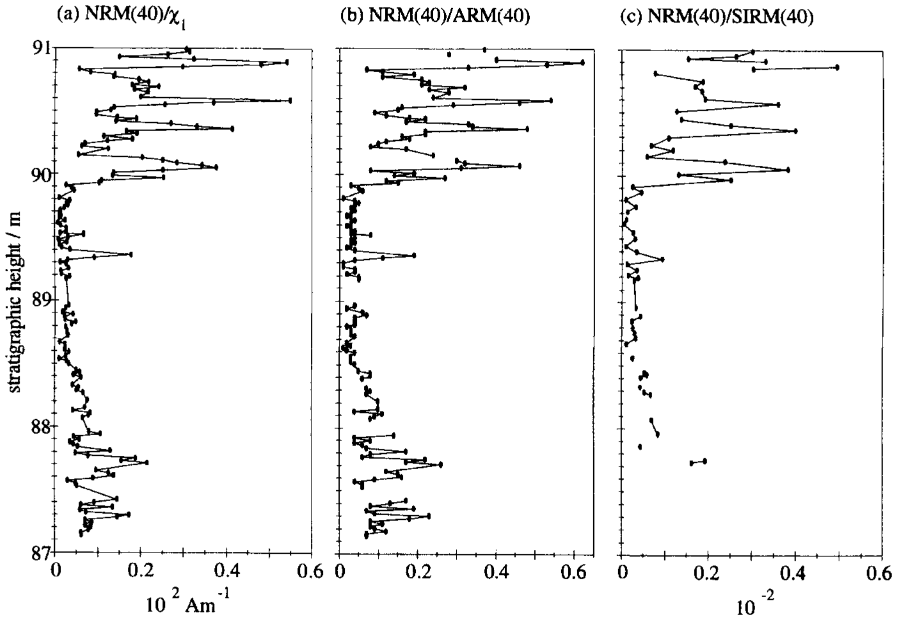

Figure 10. RI estimates determined using (a) NRM(40)/χ_l, (b) NRM(40)/ARM(40) and (c) NRM(40)/SIRM(40).

supporting the idea that soil-forming processes are not important in this region. Sedimentary processes appear to dominate the magnetic mineral variation. The magnetite/maghemite component covaries with the haematite component and both carry the same characteristic directions. It is hard to envisage a geochemical regime capable of producing these minerals simultaneously and thus a detrital origin for both components and the characteristic magnetization is favoured.

The recognition of several short events within Brunhes-age loess (Zhu *et al.* 1994a, Zheng *et al.* 1995) lends support to a process capable of resolving short-term field behaviour. Whilst unconsolidated, the loess grains are subjected to physical disturbances due to solifluction, and this might provide an opportunity for the magnetic grains to align with the applied field.

(Re)magnetization associated with periodic water saturation of continental deposits has been recognised by several authors (Burbank & Li 1985; Hus & Geeraerts 1986; Maillol & Evans 1992). Laboratory experiments confirm the validity of this process (Irving & Major 1964; McIntosh 1993). Such a process, occurring contemporaneously with accumulation, could give rise to a post-depositional remanent magnetization acquired soon after deposition, which becomes fixed once grain mobility falls below some critical level (depending on such factors as depth, water content, consolidation, etc.) In the relatively dry western reaches of the LP, biological activity is low and aridity is high, encouraging rapid carbonate formation (Liu *et al.* 1985), which may act to fix the remanence fairly soon after deposition. In tandem with the high accumulation rates, this might go some way towards explaining the apparent resolution of palaeomagnetic records obtained from these areas. Clearly, there is a pressing need to develop a greater understanding of these processes across the LP in order to define their effects on the palaeomagnetic signal.

If such a process is active in the Jiuzhoutai loess then the palaeomagnetic results described above are quite interesting. Rapid directional changes occur during periods of weak NRM intensity, consistent with results obtained from rapidly accumulated ocean sediments (Clement & Kent 1984; Valet, Laj & Tucholka 1986; Laj, Guitton & Kissel 1987) and lava sequences (Mankinen, Prévot & Grommé 1985; Chauvin, Roperch & Duncan 1990) and in close agreement with a record of the Matuyama–Jaramillo (MJ) R–N transition also obtained from the Jiuzhoutai section (Rolph 1993). The variations in RI from both loess records follow the same pattern (Fig. 11a,b), each displaying strong fluctuations before and after the low field associated with transitional directions. Both are markedly asymmetrical, with pre-transitional field strength significantly weaker than the post-transitional field strength, which recovers more rapidly than the pre-transitional field decays. This behaviour does not appear to be related to changes in the magnetic mineralogy or accumulation rate associated with a change from loess to palaeosol. The high values of RI obtained for the MJ reversal occur in the uppermost parts of a palaeosol (identified using χ_l, χ_{fd} and ARM variation), whilst there was no strong evidence for a palaeosol at any part of the JZT(cave) record. Preliminary results of a study of a younger transition recorded at Jiuzhoutai also show a sharp RI peak immediately after the reversal in directions (Fig. 12). For such an agreement to arise through lithological factors would seem fortuitous.

A striking comparison can be made with a record of absolute palaeofield intensity during a reversal obtained from the Steens Mountain volcanic sequence (Prévot *et al.* 1985; Fig. 11c). Remarkable similarities are observed in both the general shape and the fine detail of the records. Unusually high post-transitional palaeointensities have also been obtained from a sequence of Hawaiian lavas (Bogue & Paul 1993) and a long marine-sediment record (Valet & Meynadier 1993), which indicates that this is a feature commonly observed for polarity reversals during the last 4 Myr. Detailed analysis of a number of sedimentary records of the Matuyama–Brunhes reversal (Valet *et al.* 1994) provides further evidence for asymmetric RI behaviour. It would seem that the gradual decay of the field prior to its reversal, followed by rapid recovery, is a significant feature of the reversal process.

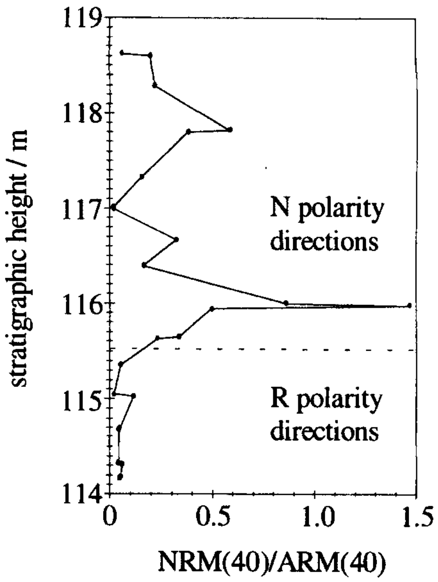

Figure 12. RI variation across the Jaramillo–Kamikatsura reversal record (obtained from the Jiuzhoutai section in the stratigraphic interval 114 to 118 m).

It is important to consider the corresponding directional changes within the context of this behaviour. This is illustrated when the JZT(cave) record is plotted in Cartesian coordinates (Fig. 13), as described by Mary & Courtillot (1993). The data follow the trend expected for the decay and recovery of a geocentric axial dipole, emphasizing that this is the underlying process dominating the reversal behaviour. Large directional swings occur during periods when this dipole term is much reduced. It is possible to attribute these swings to the influence of the non-dipole field, although the precision of the palaeomagnetic data is less well constrained during periods of low NRM intensity.

In terms of the geometry of the transitional field, the record exhibits a complex VGP path showing good serial behaviour.

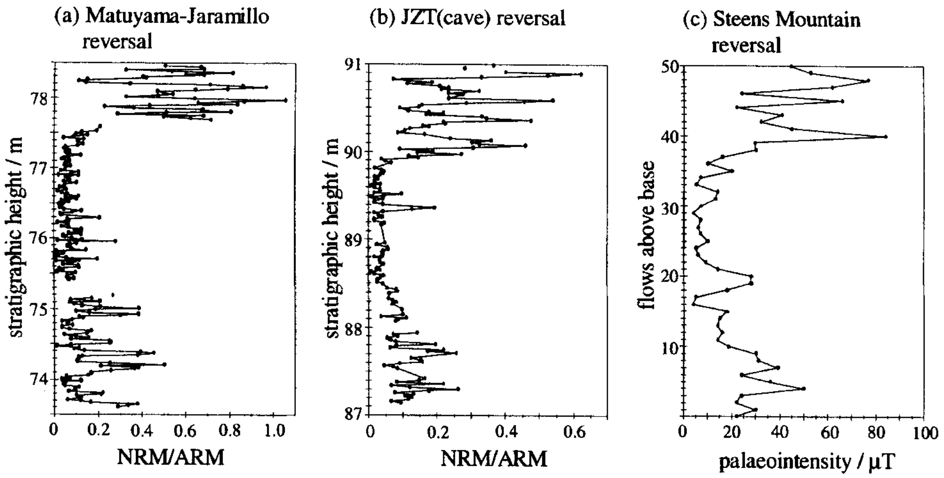

Figure 11. RI variation across (a) the Matuyama–Jaramillo reversal record (Rolph 1993), (b) the JZT(cave) reversal record and (c) palaeointensity variation across the Steens Mountain reversal record (Prévot *et al.* 1985).

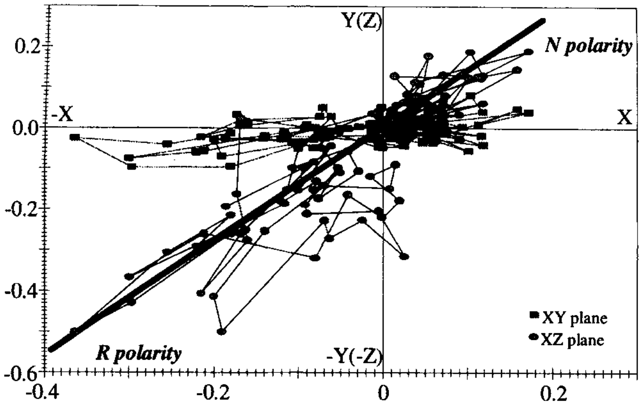

Figure 13. Cartesian representation of the JZT(cave) reversal record following Mary & Courtillot 1993. The directions have been defined by TH cleaning at 300 °C and RI by the parameter NRM(40)/ARM(40).

It describes periods of pre- and post-transitional instability and a transition that occurs in several stages, as is also observed in the MJ reversal record of Rolph (1993). There is no obvious confinement to longitudes over the Americas and their antipode, such as documented by Clement (1991), Laj *et al.* (1991) and others. This is in contrast to results obtained for the Matuyama–Brunhes and Jaramillo–Matuyama reversals from a loess sequence near Weinan, Shaanxi Province (eastern LP, Zhu, Laj & Mazaud 1994b; Fig. 1), which display VGPs that are strongly biased towards Asia/Australia and the Americas. It is interesting to note, however, that the two Jiuzhoutai records do exhibit VGP features over the Americas and Australia. Hoffman (1992) noted a similar bias in transitional VGP clusters obtained from some volcanic sequences and that these features correspond to regions of strong vertical flux of the present non-dipole field at the core–mantle boundary. He suggested that during the transition, when the geocentric axial dipole is much reduced, the influence (i.e. dominance) of these flux features may give rise to time-variant large-scale symmetries in the transitional field. In those records unable to resolve rapid field variations, this bias may appear as a confinement of transitional VGPs to longitudinal sectors between these flux features (over the Americas or their antipode). A similar interpretation of results obtained from deep-sea sediments was given by Clement & Martinson (1992). This may also account for the differences between the Weinan and Jiuzhoutai results.

Another interesting feature seen in both the JZT(cave) and MJ records is the clustering of VGPs over Africa. These are found when both RI and partially demagnetized NRM intensities are at a minimum and may be due to inclination shallowing, producing VGPs *ca.* 90° away from the site longitude (Quidelleur & Valet 1994). However, elsewhere in the two loess records the VGPs show good sequential behaviour. VGPs over Africa have also been observed in volcanic (Mankinen *et al.* 1985) and sedimentary (Clement & Kent 1987; Hartl, Tauxe & Constable 1993) reversal records. Thus an interpretation in terms of inclination shallowing remains equivocal.

CONCLUSIONS

A detailed record of a N–R transition has been obtained from a thick loess sequence in NW China. It may represent a N–R transition bounding a short period of reversed polarity within the JNS. The variation in magnetic mineralogy, dominantly magnetite/maghemite with a covarying haematite contribution, is minimal and appears dominated by detrital, as opposed to pedogenic, processes. A detrital process is the most likely origin of the characteristic NRM.

The transition from N to R polarity directions occurs over a timespan of *ca.* 4400 yr, whilst RI changes over a longer period. Extension of the record to periods of stable polarity either side of the transition is required to establish fully the timing of RI changes. The record suggests that the reversal process is dominated by the decay and recovery of a geocentric axial dipole. The recovery is more rapid than the decay and leads to much higher values for RI. A similar asymmetry is also observed in other records obtained from this site and compares well with the absolute palaeofield intensity record of a reversal obtained from the Steens Mountain volcanic sequence (Prévot *et al.* 1985).

During the transitional period large directional swings are observed that could be the result of the increased influence of the non-dipole field. Comparisons with other reversal records suggest that there are some similarities in the pattern of directional change. Longitudinal movement of transitional VGPs over the Americas and Australia/Asia does not appear important, although VGP features over South America and Australia can be distinguished. In this sense the results do not support the hypothesis of longitudinally confined VGP paths during polarity reversals. This differs from the MB and JM reversals recorded in a loess section located in the eastern parts of the LP, as reported by Zhu *et al.* (1994b). The reasons for the contrasting results obtained from the different loess sections probably reside in the remanence acquisition process(es). Future work should concentrate on improving our understanding of such processes.

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