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# A first paleomagnetic and rock magnetic investigation of calcareous nodules from the Chinese Loess Plateau

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A detailed paleomagnetic and rock magnetic investigation was carried out on calcareous nodule layers embedded in the loess-paleosol sequences near Baoji city, southern Chinese Loess Plateau. The anisotropy of low-field magnetic susceptibility confirms that calcareous nodules retain the primary sedimentary fabric of original deposits. Rock magnetic properties demonstrate that calcareous nodules have the same mineralogy and grain sizes as loess-paleosol deposits. Characteristic remanent magnetizations of calcareous nodules have directions consistent with those of adjacent loess and paleosol deposits. The Punaruu event, previously found from loess deposits in the upper part of loess unit L13 in Weinan, southern Chinese Loess Plateau, is observed at the corresponding stratigraphic level in the calcareous nodule layer. These observations indicate that the calcareous nodule layers preserve primary remanent magnetizations of original deposits before calcification, and that they can contribute to paleomagnetic studies in the Chinese Loess Plateau.

**Key words:** Calcareous nodule, loess, paleomagnetism, rock magnetism, magnetostratigraphy, polarity transition, Punaruu event.

## 1. Introduction

Aeolian sediments of the Chinese Loess Plateau (CLP) in north-central China cover an area of about 440,000 km$^2$ (Liu, 1985). They are regarded as one of the best terrestrial records of paleoclimatic changes over at least the last 2.6 Myr (e.g., Evans and Heller, 2001; Guo *et al.*, 2002). Moreover, many short-lived geomagnetic episodes, e.g. the Mono Lake, Laschamp, Blake, and Santa Rosa, have been observed from different sections (e.g., Zhu *et al.*, 1994a, 1999; Zheng *et al.*, 1995; Fang *et al.*, 1997; Guo *et al.*, 2002; Pan *et al.*, 2002; Yang *et al.*, 2004). In addition, some studies show that loess units can also record geomagnetic secular variations (Heslop *et al.*, 1999; Zhu *et al.*, 2000a). These observations suggest that the aeolian sediments have the potential of recording short-lived geomagnetic episodes as short as $<$ a few kyr in duration.

A number of calcareous nodule layers ranging from about 30 cm to $>$200 cm in thickness are intercalated within the loess-paleosol sequences. The nodule layers were originally deposited as aeolian sediments, and were then changed to the present form by subsequent leaching of calcareous phases from the overlying paleosols (Chen *et al.*, 1998; Sun *et al.*, 2000). Therefore, the leaching process could have disturbed the primary sedimentary fabric and the paleomagnetic records. However, no magnetic studies of these calcareous nodules have been made. In this study, we carried out the first detailed paleomagnetic and rock magnetic investigation of the calcareous nodules from Baoji, southern CLP.

## 2. Geological Setting and Paleomagnetic Sampling

The Baoji loess-paleosol section is located at Linghui village (34.41°N, 107.12°E), about 5 km north of Baoji city and 200 km west of Xi'an city, Shaanxi province (Fig. 1). The section is about 160 m in depth, and consists of 37 loess-paleosol layers overlying the Pliocene red clay. Detailed pedostratigraphic descriptions of each loess and paleosol unit together with magnetostratigraphy data were given by Rutter *et al.* (1991).

A total of 449 oriented core samples were collected from 26 calcareous nodule beds using a portable gasoline-powered drill, and oriented with a magnetic compass. In addition, 145 oriented block samples were also collected from adjacent loess-paleosol units to compare with their paleomagnetic results, especially those around magnetic polarity boundaries.

In the laboratory, the oriented cores were further cut into cylindrical specimens 2.2–2.5 cm in height. The block samples were first cut into of about 2.2 cm cubes using a knife, and then ground down into 2 cm cubic specimens using sandpaper.

## 3. Results and Discussion

### 3.1 Anisotropy of magnetic susceptibility

Magnetic fabrics of 24 specimens from eight calcareous nodule layers were analyzed by means of anisotropy

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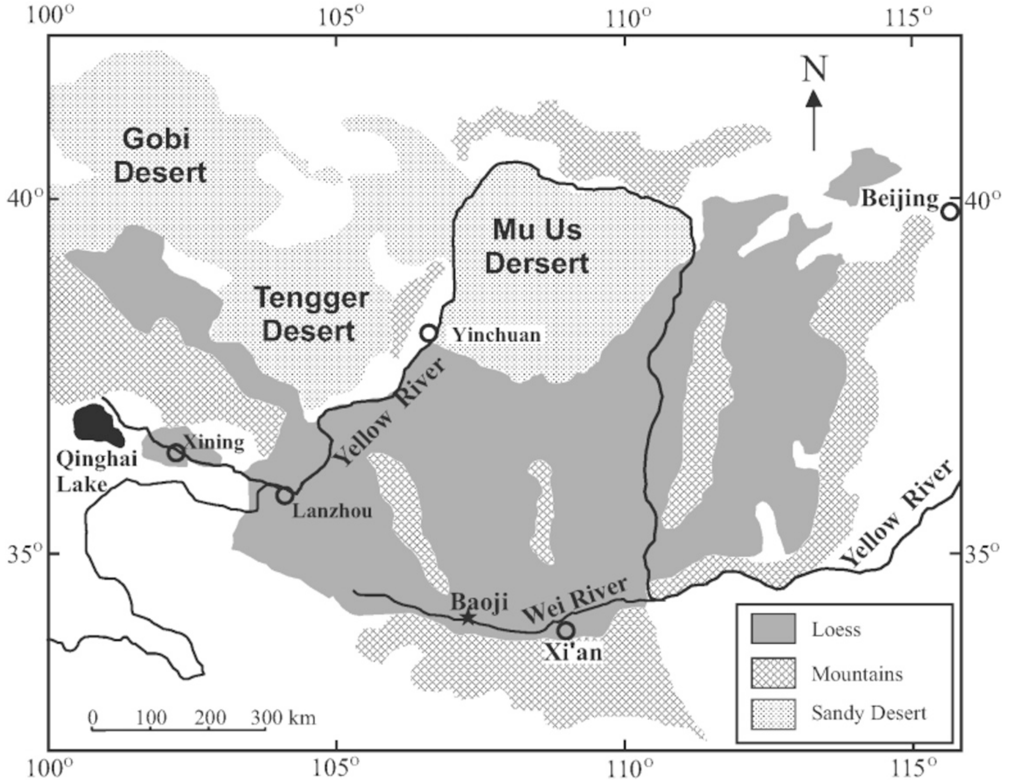

Fig. 1. A sketch map of loess distribution in central China. The Baoji section is marked with a star.

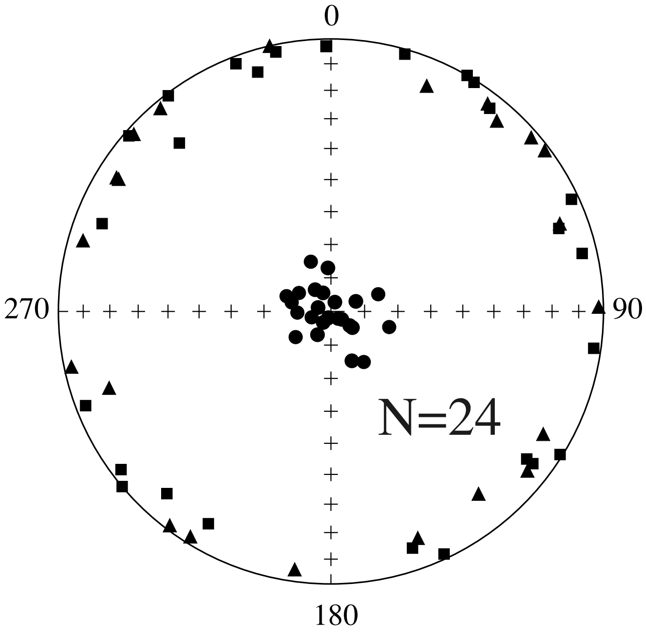

Fig. 2. Lower hemisphere equal area projections of the AMS data from eight different calcareous layers. The squares, triangle, and circles represent directions of the maximum, intermediate, and minimum susceptibility, respectively.

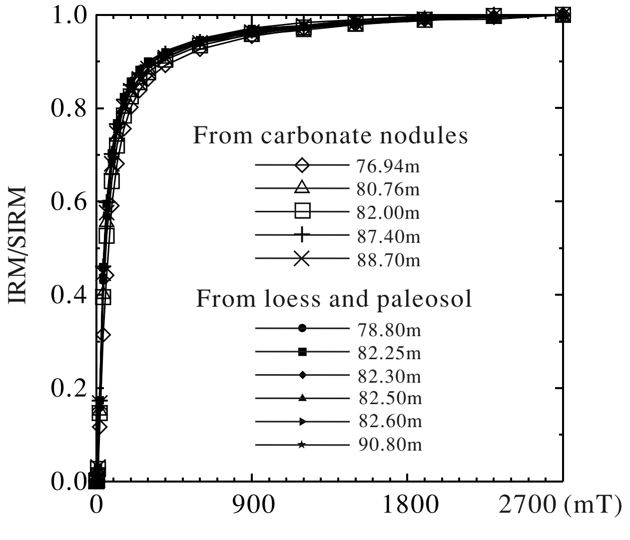

Fig. 3. Stepwise acquisition of isothermal remanent magnetization (IRM) in progressively increasing fields up to 2.7 T for eleven representative samples. Five samples are from calcareous nodule layers, the remaining six samples are from loess and paleosol deposits.

of magnetic susceptibility (AMS) to examine whether the calcareous nodule layers preserve primary sedimentary fabrics. The maximum ($K_{\mathrm{max}}$), intermediate ($K_{\mathrm{int}}$), and minimum ($K_{\mathrm{min}}$) axes of the AMS ellipsoids are plotted on equal-area projections (Fig. 2). All specimens have horizontal Kmax and Kint directions, and vertical Kmin directions, the same as loess and paleosol deposits (Fang *et al.*, 1997; Yang *et al.*, 2004; Zhu *et al.*, 2004). This result suggests that the calcareous nodule layers do preserve the primary sedimentary fabric.

### 3.2 Rock magnetic properties: mineralogy and grain size

Rock magnetic experiments were performed on representative specimens from the loess, paleosol, and calcareous

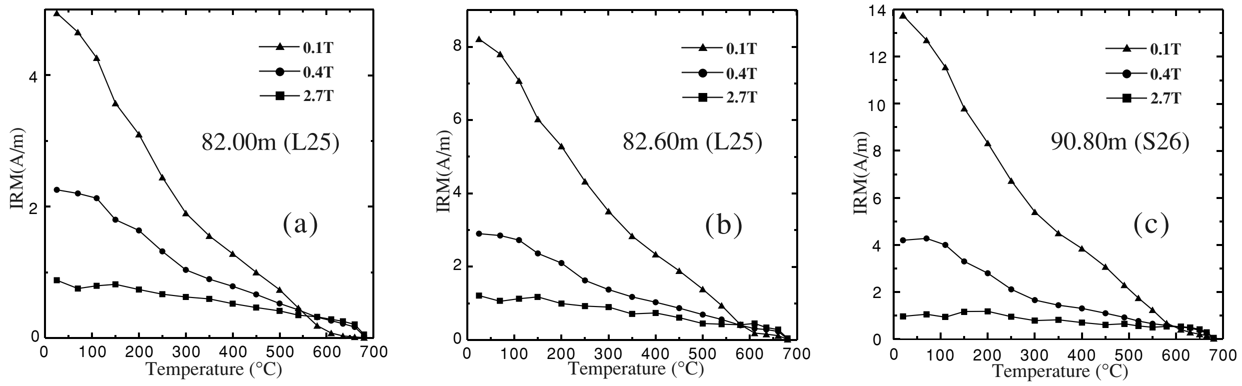

Fig. 4. Three-component IRM thermal demagnetization of representative calcareous nodule (a), loess (b), and paleosol (c) samples.

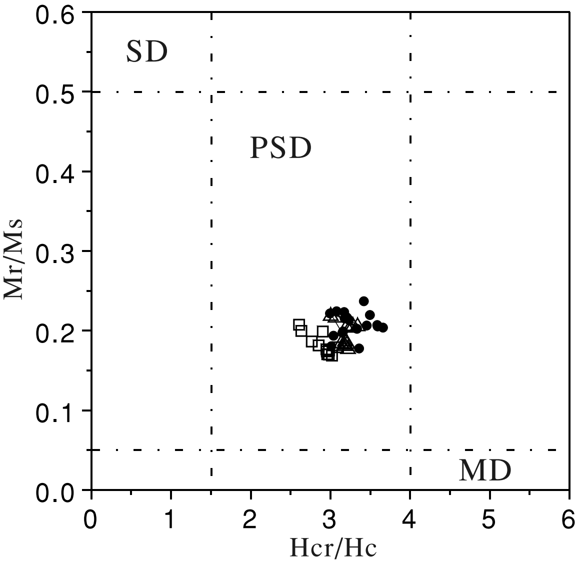

Fig. 5. Hysteresis ratios plotted on a Day diagram of the representative calcareous nodule (solid circle), loess (open triangle), and paleosol (open square) samples. SD, single domain; PSD, pseudo-single domain; and MD, multidomain. Mr, remanent magnetization; Ms, saturation magnetization; Hcr, remanent coercive force; Hc, coercive force.

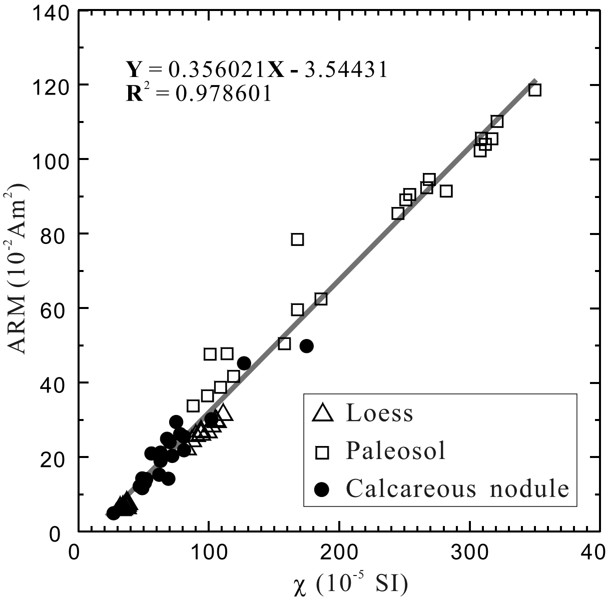

Fig. 6. Low-field magnetic susceptibility ($\chi$) versus anhysteretic remanent magnetization (ARM).

nodule layers. The results are summarized in Figs. 3, 4, 5, and 6. Acquisition curves of isothermal remanent magnetization (IRM) in stepwise increasing fields up to 2.7 T climb more steeply before 200 mT for both calcareous nodule and loess-paleosol specimens (Fig. 3), which suggests the presence of low coercivity magnetic carriers (magnetite and/or maghemite). The curves rise slowly above 200 mT, but saturation is not fully reached even at 2.7 T (Fig. 3), which indicates presence of high coercivity magnetic carriers (goethite and/or hematite).

Different coercivity fractions of the IRM for both calcareous nodule and loess-paleosol specimens were imparted in successively smaller fields of 2.7, 0.4, 0.1 T along three mutually orthogonal directions (Lowrie, 1990). Thermal demagnetization of the soft (<0.1 T), medium (0.1–0.4 T), and hard (0.4–2.7 T) coercivity fractions shows distinct unblocking temperatures (Fig. 4). The hard and medium coercivity fractions exhibit strong evidence for unblocking of hematite at 680°C. The soft coercivity fraction shows unblocking of magnetite at 580°C. The curve of the medium coercivity fractions is significantly inflected at 300°C (Fig. 4), suggesting that the specimen possibly includes maghemite. These results are consistent with those of previous studies that deduced the presence of magnetite, maghemite and hematite in the Chinese loess-paleosol deposits (e.g., Maher and Thompson, 1992; Liu *et al.*, 1992; Liu *et al.*, 2003).

Hysteresis parameters of 42 specimens were measured using a MicroMag to further evaluate if the formation of calcareous nodules had affected grain sizes of the magnetic minerals. These were divided into eighteen calcareous nodule specimens from different layers, twelve loess specimens from L9 and L25, and twelve paleosol specimens from S4, S5, and S26. The Day plot (Day *et al.*, 1977) of the results (Fig. 5) shows the magnetic grains of all the specimens are of pseudo-single domain (PSD) size, the range of which is very narrow and similar to those of loess and paleosol samples from other sections (e.g., Zhu *et al.*, 1994b; Pan *et al.*, 2001; Deng *et al.*, 2004). Slight differences

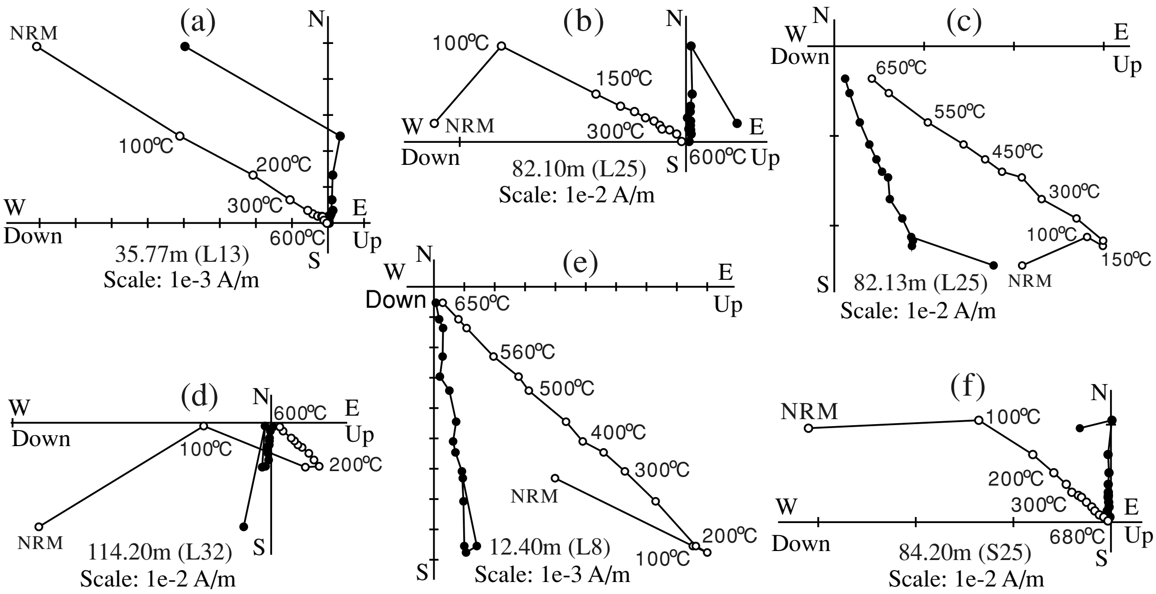

Fig. 7. Orthogonal vector projections of the representative calcareous nodule (a–b), loess (e), and paleosol (f) specimens. Solid (open) symbols represent the projections onto the horizontal (vertical) plane. The level of each sample shows depth from the top.

in Hcr/Hc between calcareous nodules and loess-paleosols (Fig. 5) should not be caused by formation of calcareous nodules, but reflect different magnetic assemblages of different loess-paleosol units. The differences are within the range of fluctuations for loess and paleosol deposits (e.g., Zhu *et al.*, 1994b).

The result of low-field susceptibility ($\chi$) versus anhysteretic remanent magnetization (ARM) reveals that the relative grain sizes of magnetic minerals in calcareous nodule and loess-paleosol specimens are almost the same (Fig. 6). This result together with the Day plot shows that no significant change in magnetic grain size occurred during formation of the calcareous nodules.

### 3.3 Paleomagnetic results

Stepwise thermal demagnetization of the natural remanent magnetization (NRM) was first carried out on 90 pilot specimens, up to 680°C at 30–50°C intervals. The remanent magnetization was measured using 2-G Enterprise cryogenic magnetometers at the paleomagnetic laboratories of Kobe University and the Institute of Geomechanics, Chinese Academy of Geological Sciences.

Typical vector component diagrams are shown in Fig. 7. All calcareous nodule specimens have the same demagnetization characteristic as loess and paleosol specimens (Fig. 7). A stable low temperature component (LTC) for both normal and reverse polarity specimens, isolated between 100 and 200°C, is consistent with the present geomagnetic field direction (Fig. 7). This LTC represents a viscous overprint in the present geomagnetic field. After removing this LTC, a high temperature magnetization component (HTC) decayed toward the origin was isolated between 250°C and 600–680°C for all specimens of both polarities (Fig. 7). Based on the result, the remaining specimens were thermally demagnetized at 100, 200, 300, 350, 400, 450 and 500°C. Characteristic remanent magnetization (ChRM) directions were determined using principal component analysis (Kirschvink, 1980) through five data points at 300, 350, 400, 450, and 500°C. The ChRM directions show that the Matuyama-Brunhes polarity boundary lies in the middle of L8, the Jaramillo subchronozone between L10 and L12, the Olduvai subchronozone from the middle of L25 to the top of S26, and the Gauss-Matuyama boundary at the base of L33 (Fig. 8). These magnetostratigraphic correlations agree with previous results (e.g., Rutter *et al.*, 1991).

All calcareous nodule specimens within the Brunhes and Olduvai magnetozones have normal polarity ChRM directions (Fig. 8). Within the Matuyama, most of the calcareous nodule specimens have reverse polarity ChRM directions, and some show normal polarity or transitional directions. A zone of normal polarity and transitional field directions, regarded as an excursion, was observed from calcareous nodule specimens in the upper part of L13. The demagnetization result of a specimen from this zone (Fig. 7(a)) was the same as for the other specimens (Figs. 7(b) and (f)). Assuming a constant accumulation rate between the Olduvai and Jaramillo subchronozones, this excursion is estimated at 1.11 Ma in age. Thus, it is chronologically correlated with the Punaruu event (Singer *et al.*, 1999). In our study, the Punaruu excursion is defined by only two specimens' data from the calcareous nodule layer corresponding to L13. However, we noted that a geomagnetic excursion correlated with the Punaruu has also been observed in the upper part of L13 in the Weinan section, the southern CLP (Pan *et al.*, 2002). The duplicate records from distant sites confirm real occurrence of an excursion. In Baoji, the Punaruu event is observed in the calcareous nodule layer, while it is in loess deposits in Weinan. The observations at almost the same stratigraphical levels between the two sites suggest calcification did not cause a significant delay in remanence acquisition, and a primary remanence of loess may have been preserved. Many flips in polarity lie within the calcareous nodule layers just above the Gauss-Matuyama (G-M)

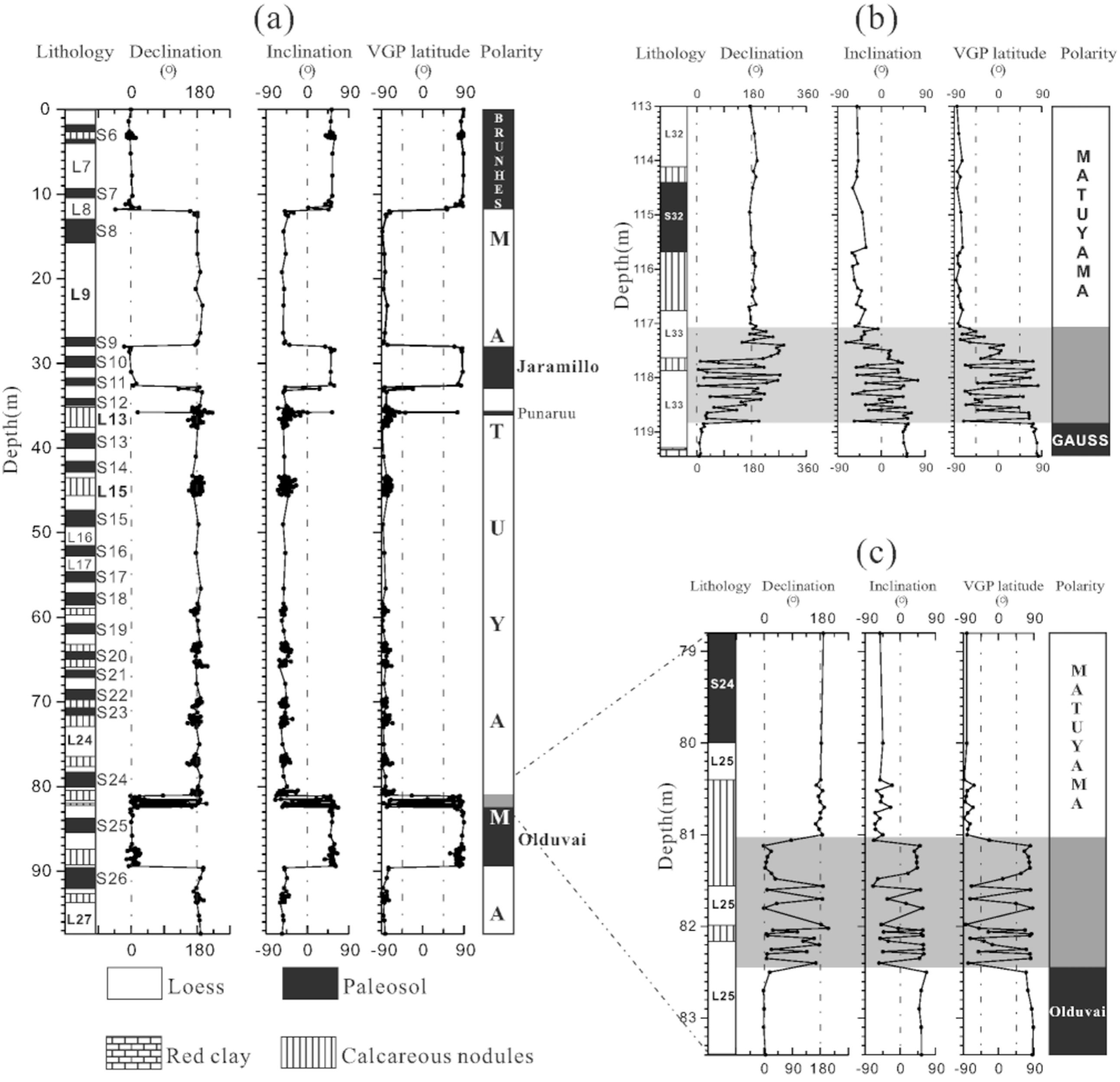

Fig. 8. Stratigraphic plots of the ChRM directions for the whole part from L6 to L27 (a), and for transitional zones at the Gauss-Matuyama (b) and Olduvai-Matuyama (c).

and Olduvai-Matuyama (O-M) transition zones (Figs. 8(b) and (c)). The polarity flips stretch over even into the non-calcified loess deposits. Therefore, it is unlikely that calcification caused such a fluctuated magnetization pattern. The short-lived directional flips around the G-M and O-M polarity transitions have also been observed in several sedimentary paleomagnetic records (e.g., Tric *et al.*, 1991; Heller *et al.*, 1991; Biswas *et al.*, 1999; Zhu *et al.*, 2000b), but the numbers of flips are far fewer than in our data. It is noted that six short-lived geomagnetic excursions besides the Punaruu have been observed from Baoji loess-paleosol deposits, and at least five of them could be well correlated with the ones recognized on the global scale (Yang *et al.*, 2004, 2005). These observations support that filtering effects in paleomagnetic records of loess are negligible for at least the Baoji section, and that the short directional flips around the G-M and O-M polarity transitions may represent fluctuations of geomagnetic field. However, there are still many controversies about fidelity of paleomagnetic records of loess-paleosol deposits, especially about its lock-in depth and smoothing effects of wide lock-in zone (e.g., Zhu *et al.*, 2000a; Pan *et al.*, 2002; Spassov *et al.*, 2003). Therefore, further investigation is needed to confirm that the short-lived polarity flips (especially such multiple and rapid direction fluctuations) reflect the exact field behavior during polarity transitions.

## 4. Conclusions

(1) The calcareous nodule layers preserve the primary sedimentary fabric of original deposits.

(2) The calcareous nodules have almost the same magnetic minerals and grain sizes as the loess and paleosol de-

posits.

(3) The calcareous nodule layers retain primary remanent magnetizations of original deposits before calcification.

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