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Middle Miocene eolian sediments on the southern Chinese Loess Plateau dated by magnetostratigraphy

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ABSTRACT

We present the results of a magnetostratigraphic grain size and geochemical investigation, of a well-preserved sequence of eolian sediments of Miocene age at Duanjiapo, on the southern Chinese Loess Plateau. The paleomagnetic results demonstrate that the basal age of the studied interval is about 11 Ma. The results of the grain size and geochemical analyses show strong similarities between the eolian Miocene silts and the overlying Red Clay and loess units. This leads us to conclude that all formations have a similar eolian origin, although the Miocene silts include evidence of fluvial sediments derived from river originating in the Qinling Mountains, to the south of the study site. Our results indicate that the accumulation of eolian dust in the southern Chinese Loess Plateau area began at least 11 Ma ago.

1. Introduction

In Northern China, the Cenozoic history of inland desertification and the initiation of the East Asian monsoon are manifested in thick eolian dust deposits, including the Quaternary loess–paleosol and underlying Red Clay in the Chinese Loess Plateau (CLP) (e.g., Liu, 1985; Kukla and An, 1989; Ding et al., 1998; Guo et al., 2002). These eolian deposits constitute a useful proxy for paleoclimatic and paleoenvironmental conditions and have been used to constrain the evolution of the monsoon, the onset of Asian desertification and the tectonic history of the Tibetan Plateau (An et al., 2001; Guo et al., 2002). Age for the inception of eolian deposition is a key question and has been of interest for the last three decades. In the 1980s, studies of the Chinese loess–paleosol sequences demonstrated that eolian dust deposition extended back until at least 2.6 Ma BP (Liu, 1985; Kukla, 1987; Kukla and An, 1989; Ding et al., 1992). In the 1990s, work on the underlying Red Clay sediments demonstrated that they were also of wind-blown in origin, and therefore that the eolian record extended back to 7–8 Ma (Sun et al., 1997, 1998; Ding et al., 1998; An et al., 2001; Qiang et al., 2001).

Guo et al. (2002) confirmed an eolian origin of a 22-6.2 Ma sedimentary sequence in Qin'an, western CLP, thereby further extending the date of initiation of Asian desertification to at least 22 Ma ago. In the eastern CLP, an 11 Ma Red Clay section was reported in Shilou (Xu et al., 2009). However, there is no published record of an eolian sequence older than 7 Ma in the southern CLP area. Consequently the aims of the present study were to attempt to locate and accurately date loess deposits predating 7 Ma in this area.

Our study focuses on the Duanjiapo section (34°12′N, 109°12′E) (Fig. 1), in Lantian county, southern CLP. The Neogene deposits in Lantian area are an important stratigraphical key site in preserving a record of Late Neogene terrestrial deposition and they have also been a fertile ground for recovery of late Neogene fossil mammals for more than 50 years (e.g. Liu et al., 1960; Zhang et al., 1978; Li et al., 1984). Over the last decade, knowledge about the Lantian sequence has increased considerably as multidisciplinary investigations on geology and vertebrate paleontology were resumed in the area in 1990s (summarized in Zhang et al., 2013). These investigations have contributed significantly to the understanding of sedimentological, stratigraphical, paleoenvironmental and paleontological aspects of the Lantian sequence (Zhang et al., 2002; Kaakinen and Lunkka, 2003; Qiu et al., 2003; Zhang, 2003; Andersson and Kaakinen, 2004; Chen and Zhang, 2004; Qiu et al., 2004a,b; Chen, 2005; Kaakinen, 2005; Li and Zheng, 2005; Zhang, 2005; Zhang and Liu, 2005,; Kaakinen et al., 2006; Qiu et al., 2008; Zhang et al., 2008; Passey et al., 2009; Suarez et al., 2011; Zhang et al., 2013).

In Lantian, the late Neogene sediments underlying the Pleistocene loess–paleosol deposits are grouped to the Bahe and Lantian formations.

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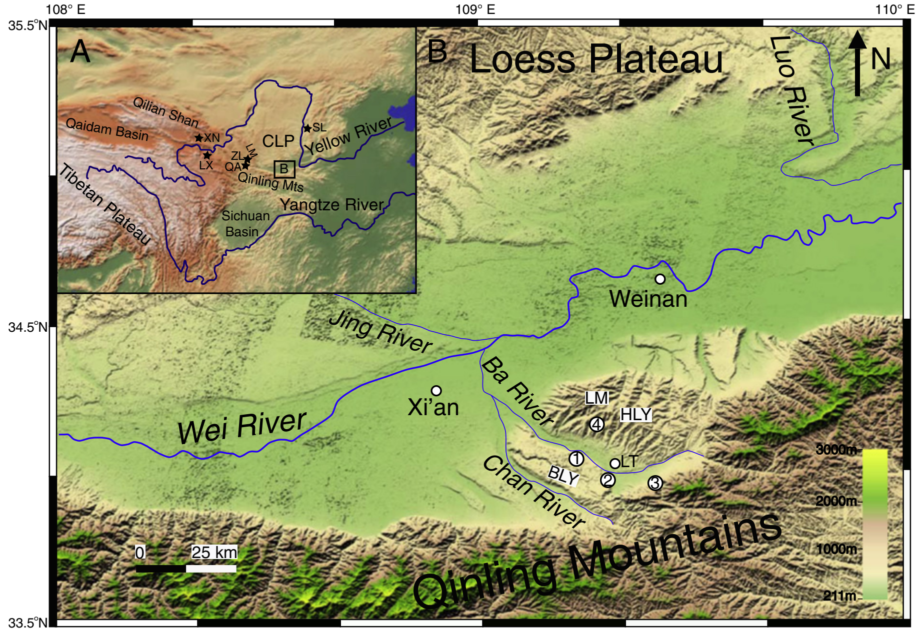

Fig. 1. A. Location of the Chinese Loess Plateau, Weihe Basin and the main study sites. B. Location of the Duanjiapo (DJP) section in the Lantian region on the southern Loess Plateau. CLP—Chinese Loess Plateau; LM—Liupan Mountains; QA—Qin'an; SL—Shilou; LX—Linxia; ZL—Zhuanglang; BLY—Bailuyuan; HLY—Henglingyuan; LM—Lishan Mountain; ①—Duanjiapo; ②—Liujiapo; ③—Gongwangling; ④—Chenjiawo.

The relatively thick and continuous sequence of reddish clay-silt sized sediments in the Lantian Formation has been studied intensively and is shown to represent eolian Red Clay (Yue, 1989; Zheng et al., 1992; Sun et al., 1997; An et al., 2000). Stratigraphy and sedimentology of the underlying Bahe Formation are generally well-constrained (see Kaakinen and Lunkka, 2003; Kaakinen, 2005; Zhang et al., 2013 and references therein), but detailed studies of the fine-grained deposits in the Bahe Formation remain under-represented-although they constitute volumetrically significant proportion of the formation. In order to assess the origin of the fine-grained facies in the late Miocene Bahe Formation, this paper presents the results of a comparison of its grain size and geochemical characteristics with the overlying Red Clay and loess deposits. We also present a detailed magnetostratigraphic investigation of the Bahe Formation to provide an independent magnetic age determination for the sequence and for calibrating the precise ages for the sampled horizons. Our overall aim is to improve the understanding of the sedimentary processes, and especially eolian activity and its spatial variability, over the last 11 Ma of the CLP.

2. Regional geological background

The Lantian area, located at the southernmost edge of the CLP and on the northern flank of the Qinling Mountains (Fig. 1), is well known for the discovery of the remains of *Homo erectus* found at the Gongwangling and Chenjiawo sites, and for the rich assemblages of mammalian fossils within the Cenozoic sequences (Liu et al., 1960; An and Ho, 1989; Zhang et al., 2002; Qiu et al., 2003; Zhang et al., 2008, 2013).

A more than 1000 m thick sequence of terrestrial clastic sediments has been deposited along the flanks of Lishan Mountain as a result of the uplift of the Qinling and Lishan mountains during the Cenozoic era, and a large number of outcrops have been incised and exposed by the rivers and natural streams (Zhang et al., 1978; Porter et al., 1992; Kaakinen, 2005). Although the Neogene deposits are frequently overlain by Quaternary loess, they are occasionally exposed in the many erosional gullies.

During the 1960s, the Institute of Vertebrate Paleontology and Paleoanthropology and the Institute of Geology, Chinese Academy of Sciences, conducted detailed stratigraphic studies and established a lithostratigraphic framework for the region: Liu et al. (1960) and Jia et al. (1966) subdivided the Cenozoic strata into the Honghe, Bailuyuan, Lengshuigou, Koujiacun, Bahe and Lantian Formations, capped by the loess–paleosol sequence and spanning from Eocene through Pleistocene (Zhang et al., 1978; Fig. 2). More recent studies (Zhang et al., 2002; Kaakinen and Lunkka, 2003; Kaakinen, 2005; Zhang et al., 2013) have refined the stratigraphic scheme for the Bahe and Lantian formations and provided well-resolved ages for the deposits and faunas.

The Bahe and Lantian formations have proven to cover one of the most complete late Miocene sequence in China with diversified fossil faunas representing typical elements of late Miocene "*Hipparion* fauna" (cf. Schlosser, 1903; Kurtén, 1952). The recent work (as summarized in Zhang et al., 2013) recognized three stratigraphically superpositioned mammalian assemblages (biozones) of the Late Miocene and showed the Bahe *Hipparion* fauna (biozones BH1 and BH2 of the Bahe Formation) to be distinct from and predate the Baode *Hipparion* faunas that are present in the Lantian Fm (biozone BD). These biozones can tentatively be correlated with the European Vallesian "age" (land-mammal based faunal unit), early to middle Turolian, and late Turolian, respectively.

In the present study, we focus on the Late Neogene strata at Duanjiapo, in the Bailuyuan Plateau. From the top of the Bailuyuan to the base near the Ba River, there is a sedimentary record which includes the Pleistocene loess–paleosol sequence, the Lantian Formation and the Bahe Formation (Liu et al., 1960; Jia et al., 1966; Zhang et al., 1978; Fig. 2). However, the upper part of the Bahe Formation was not exposed in Duanjiapo, and therefore we sampled the upper part at Liujiapo, 5 km east of Duanjiapo. Overall, the entire section examined is 438 m thick and contains 3 lithological units: the lower part is the Bahe Formation with a thickness exceeding 246 m; the central part comprises the 60 m thick Lantian Formation (Red Clay); and the uppermost part is a 132 m thick Quaternary loess–paleosol sequence.

2.1. The Bahe Formation

The Bahe Formation is well preserved in the Lantian region, and is about 300 m thick in the Bailuyuan Plateau. Liu et al. (1960) and Zhang et al. (1978) divided the Bahe Formation into two parts: the upper part being dominated by red-brown and yellowish mudstones

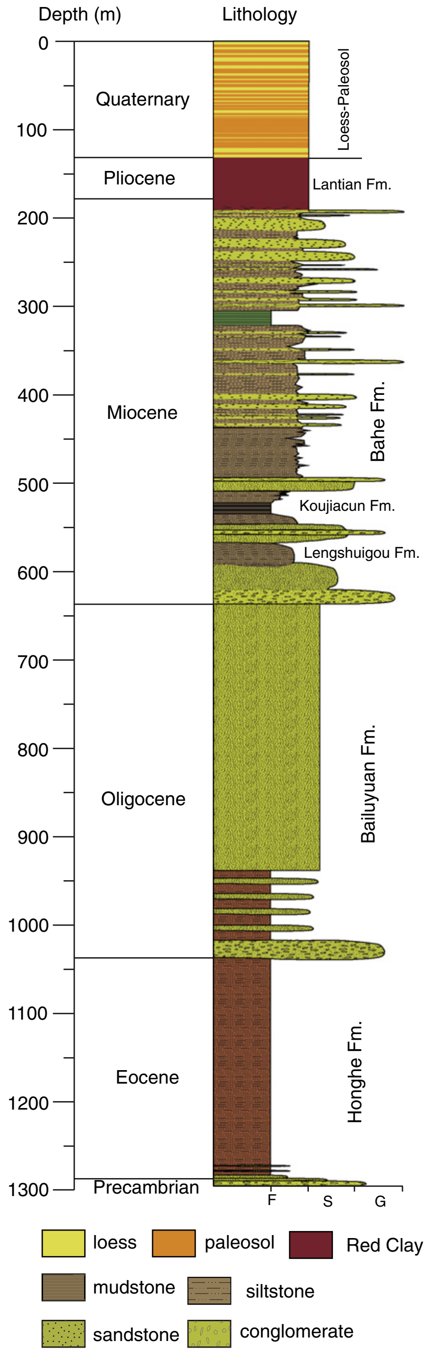

Fig. 2. Lithostratigraphical column of the Lantian region (after Zhang et al., 1978).

and sandy mudstones, with interbedded sandy conglomerates and sandstones; and the lower part characterized by whitish sandstones and red-brown mudstones. Kaakinen and Lunkka (2003) were the first to study the sedimentology and stratigraphy of the Bahe Formation using the facies analysis approach. They portrayed the facies associations and interpreted them as emerging from a dominantly low sinuosity fluvial depositional system and low-energetic conditions, with occasional ponded water or shallow lakes in the distal floodplain. Lithologically, the formation is dominated by thick and laterally pervasive floodplain deposits that characteristically show indications of paleosol formation (Kaakinen and Lunkka, 2003; Andersson and Kaakinen, 2004; Kaakinen, 2005; Zhang et al., 2013). Magnetic polarity stratigraphy (Kaakinen, 2005; Zhang et al., 2013) demonstrates that the time span of deposition of the entire Bahe Formation is ca. 7–11 Ma.

Until now, 53 species have been recovered from the Bahe Formation (rodents, lagomorphs, insectivores, carnivores, artiodactyls, perissodactyls, and proboscideans). Systematic studies on most of the fossil mammal groups have been published (e.g., Qiu et al., 2003; Andersson and Werdelin, 2005; Qiu et al., 2004a,b; Li and Zheng, 2005; Zhang, 2005; Qiu et al., 2008; Zhang et al., 2008), and they reveal the dominance of rodents and ungulates in the mammal communities. In addition to mammalian remains, the localities have yielded remains of fish, amphibians, reptiles, freshwater mollusks and charophytes.

The lower part including the bottom of the Bahe Formation is nearly entirely made up of the red-brown component of the fine-grained deposits. Zhang et al. (1978) thought there was an unconformity in another section that shows the underlying Lengshuigou Formation, but we find it is very difficult to trace the Bahe Formation there. Our detailed field investigations on fine grained facies of Bahe Formation indicated that the redbrown component of the fine-grained deposits in the studied section typically exhibits a consistently massive sedimentary structure with no bedding, carbonate concretions and clay coatings on grains (Fig. 3). Although these alone are not diagnostic features for the eolian origin, they are essentially similar to those in the overlying eolian deposits of the Lantian Formation. This observation, therefore, raised question about the origin of the silts in the Bahe Formation.

2.2. The Lantian Formation (Red Clay)

The Lantian Formation ("Red Clay" or "Hipparion red earth"), is a widespread deposit underlying the loess–paleosol sequence in the CLP (e.g. Ding et al., 1998; Sun et al., 1998; An et al., 2000; Qiang et al.,

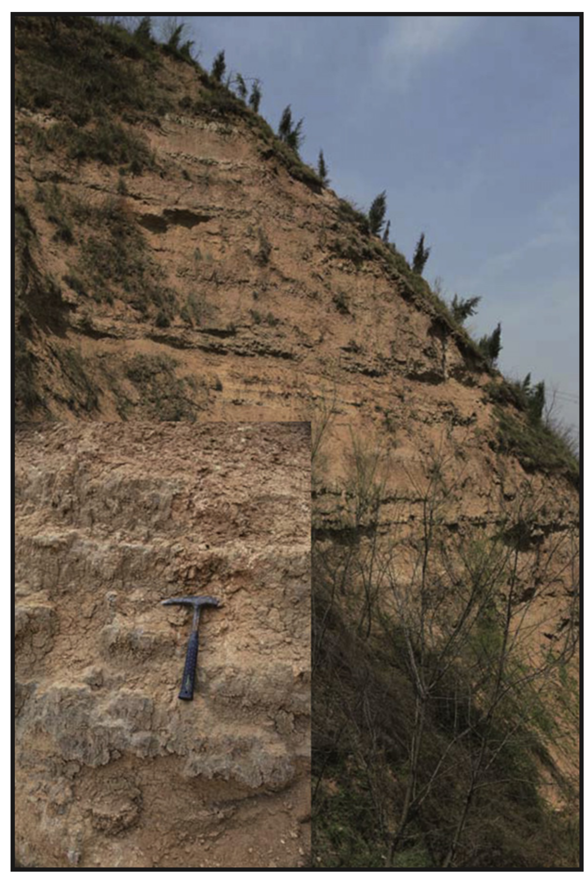

Fig. 3. The fine-grained facies in the lower part of the Bahe Fm. The loessic sediment has undergone strong pedogenesis resulting in the strong red color. It contains about 10 paleosol horizons rich in carbonate nodules and looks very similar to the overlying eolian Red Clay.

2011). This section underwent relatively strong pedogenesis, resulting in a light red to deep red color and contains more than 10 horizons rich in carbonate nodules. In addition, small amounts of fluvial sand also occur in the lower part of the Lantian Formation (Sun et al., 1997; Kaakinen and Lunkka, 2003). Zheng et al. (1992) first concluded that the Red Clay may be of eolian origin and dated the lower boundary in the Lantian area at about 5.0 Ma, after which Sun et al. (1997) and An et al. (2000) independently dated the basal age of the Lantian Formation to 6.8 Ma and 7.3 Ma, respectively. A paleomagnetic age of 7 Ma for the boundary was also received in more recent magnetostratigraphic studies by Kaakinen (2005) and Zhang et al. (2013).

Mammalian fossils have only been found from the lowermost part of the Lantian Formation, and they are remarkably different from those of the Bahe Formation by the abundance of suids and cervids in the assemblage (Zhang et al., 2002, 2013). Historically, the Red Clay was determined to be 62 m thick, including a ~2 m thick basal conglomerate layer (Sun et al., 1997). In the present paper we assign the ~2 m thick conglomerate layer to the underlying Bahe Formation with the basal age of the Lantian Formation is ~7 Ma.

2.3. Loess–paleosol sequence

The 132 m thick Quaternary loess–paleosol sequence consists of 38 loess and paleosol layers (Zheng et al., 1992). A large amount of research on the loess–paleosol units has confirmed them to be of eolian origin and with a basal age of 2.6 Ma (Yue, 1989; Zheng et al., 1992; Sun et al., 1997; An et al., 2000). *Homo erectus* was discovered in the Pleistocene loess in Lantian in the 1960s, and magnetostratigraphic dating found that the age of the fossil-bearing strata at Gongwangling was about 1.15 Ma, and that of the Chenjjiawo locality was about 0.65 Ma (An and Ho, 1989).

3. Sampling and methods

3.1. Magnetostratigraphy

Paleomagnetic samples from the Bahe Formation were collected in 2012. The surface layer of the outcrop was removed to prevent the possibility of disturbance by post-depositional processes. About 1200 block samples were taken at a sampling interval of 20 cm, using a magnetic compass in the field to orient them. We were unable to sample the conglomerates and these are not considered further. 621 block samples were cut into cubes of dimensions 2 × 2 × 2 cm and their low-field magnetic susceptibility was measured using a Bartington Instruments MS2 meter at a frequency of 470 Hz. Subsequently the samples were subjected to progressive thermal demagnetization in an ASC-48 thermal demagnetizer. The thermal demagnetization was carried out up to 690 °C in 20 steps at an interval of 50 °C below 550 °C, and 20–30 °C above. The remanence was measured using a 2G three-axis cryogenic superconducting magnetometer (model 755R). The magnetic susceptibility and paleomagnetic measurements were performed at the State Key Laboratory of Loess and Quaternary Geology, Institute of Earth Environment, Chinese Academy of Sciences.

3.2. Grain size analysis

Samples were collected for grain size analysis at intervals of 10 cm along the whole section. Samples were subjected to the standard chemical pre-treatment for loess, including the addition of 30% H_2O_2 and 10% HCl solution to remove organic matter and carbonates, respectively (Lu and An, 1999; Sun et al., 2002), finally the samples were dispersed with 0.5 N (NaPO3)6 and ultrasonic. The grain size distribution was measured using a Malvern Mastersizer S Laser diffraction particle analyzer (analytical range 0.02–2000 μm).

3.3. Geochemistry

3.3.1. Analysis of major, trace and rare earth elements (REE)

Twenty eight samples were collected from the loess–paleosol sequence, Red Clay, the Bahe Formation silt, and fluvial sand from the Qinling Mountains. Acid leaching was performed to remove carbonates (Chen et al., 2001; Yang et al., 2009). Subsequently, major element concentrations were measured using X-ray fluorescence (XRF) spectrometry. The trace element abundance, including the abundance of rare earth elements, from 16 bulk samples was measured using an inductively coupled plasma mass spectrometer (ICP–MS) with indium (In) as the internal standard. The analytical error of both XRF and ICP–MS is <10%.

3.3.2. Sr/Nd ratios

Ten samples were measured for Sr and Nd isotopic composition. The Sr–Nd isotopic ratios of acid-insoluble residues of the bulk samples were determined by thermal ionization mass spectrometry (TIMS) following the method of Chen et al. (2007). $^{87}Sr/^{86}Sr$ is normalized to $^{86}Sr/^{88}Sr = 0.1194$ and $^{143}Nd/^{144}Nd$ to $^{146}Nd/^{144}Nd = 0.7219$. The analytical blank was <1 ng for Sr and <60 pg for Nd, respectively. Reproducibility and accuracy were checked by running the strontium standard NIST SRM 987 and neodymium standard JNdi-1, with a mean for $^{87}Sr/^{86}Sr$ of 0.710248 ± 0.000005 (external ± 2σ, n = 6) and for $^{143}Nd/^{144}Nd$ of 0.512120 ± 0.000008 (external ± 2σ, n = 6).

The stratigraphic positions of samples analyzed are shown in the Fig. 5.

4. Results and discussion

4.1. Magnetic polarity stratigraphy

The studied sections are biostratigraphically and paleomagnetically well constrained (Zhang et al., 2002; Kaakinen, 2005; Zhang et al., 2013). For example, the presence of *Hipparion* and related faunas throughout the sequence suggests a late Miocene age for the Bahe Formation, supported by *Progonomys* and a variety of small mammals discovered from the lower part of the sequence (Zhang et al., 2002; Zhang et al., 2013). The paleomagnetic dating (Kaakinen, 2005; Zhang et al., 2013) is consistent with the fossil record showing that the Bahe Formation accumulated during 7–11 Ma.

Most of the samples yielded a stable characteristic remanent magnetization (ChRM) component after stepwise thermal demagnetization up to 580 °C, which indicates that the dominant ChRM carrier is magnetite. However, some of the samples had to be heated to 690 °C in order to determine a stable ChRM component (Fig. 4), suggesting the presence of high-coercivity hematite.

Demagnetization results were evaluated using orthogonal diagrams (Zijderveld, 1967), and the principal component direction was calculated using principal component analysis based on a minimum of four consecutive steps (Kirschvink, 1980; Jones, 2002). More than 4–8 successive points in the orthogonal diagrams [the ChRM directions with (Maximum Angular Deviation, MAD) of <15°] were used to calculate the direction of the ChRM during the establishment of the polarity sequence (Fig. 4). To remove outliers and transitional directions, we further rejected normal and reverse ChRM directions with Virtual Geomagnetic Poles (VGP) exceeding 45° from the mean normal and reverse VGP respectively. Among the 621 discrete samples, 573 (92%) provided reliable ChRM directions. The magnetic polarity sequence can be readily calibrated to the Geomagnetic Polarity Time Scale (GPTS) (Ogg and Smith, 2004), and the results indicate an almost continuous magnetic polarity sequence from C3Bn to C5n.2n, with an age range of 7.0–11.0 Ma (Fig. 5).

The palaeomagnetic sequence and correlations for the whole Duanjiapo section are based on previous studies (Yue, 1989; Zheng et al., 1992; Sun et al., 1997; Kaakinen and Lunkka, 2003; Kaakinen, 2005; Zhang et al., 2013). The Matuyama/Gauss boundary was

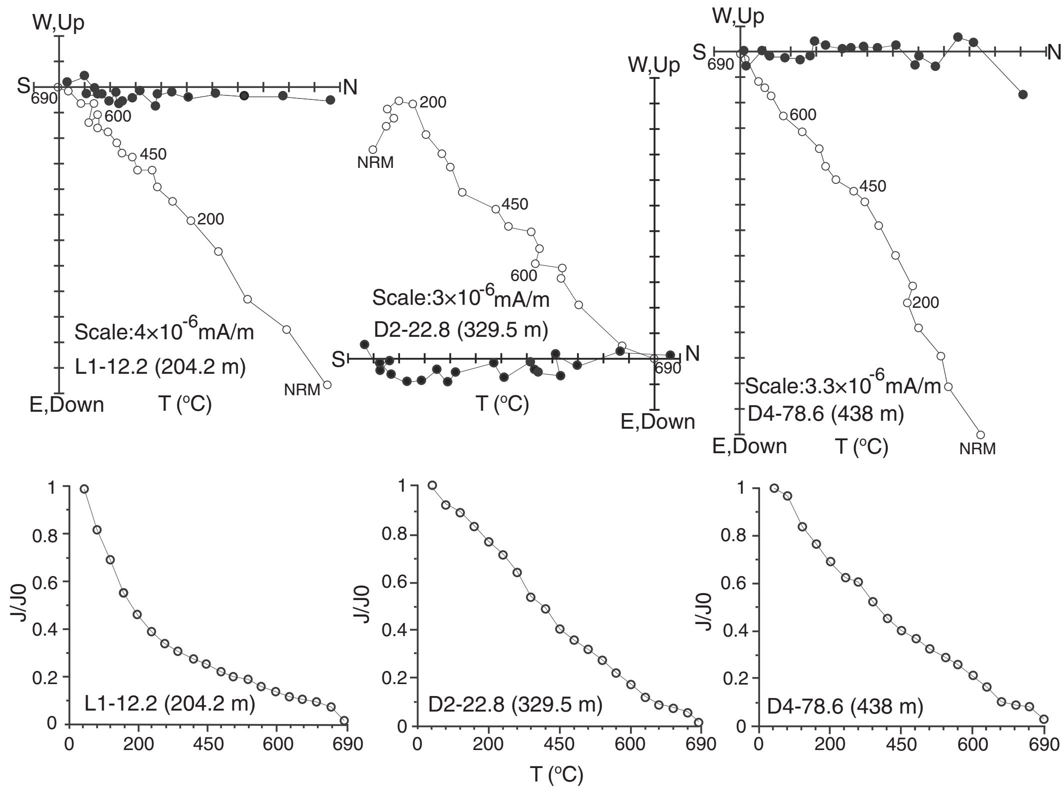

Fig. 4. Orthogonal projections of progressive thermal demagnetization of NRM and normalized intensity decay plots of samples from the Bahe Fm.

identified ~1.5 m above the lithological transition between the loess–palaeosol sequence and the Red Clay (Zheng et al., 1992). The base of the Red Clay contains Chron 3B, which has an age of about 7 Ma (Sun et al., 1998; An et al., 2000). The 246 m-thick Bahe Formation records almost all of the palaeomagnetic events from C3Br.1n onwards. More than ~3 m of the base of the Bahe Formation near the Bahe River was not exposed and therefore could not be sampled. Extrapolation of the accumulation rate below the oldest geomagnetic boundary leads to an estimated basal age of 11 Ma (Fig. 5). This result confirms the previously presented age for the base of the Bahe Formation (Kaakinen, 2005; Zhang et al., 2013), and provides a robust framework for the detailed sampling in the sequence.

4.2. Evidence for an eolian origin of the Bahe Formation

4.2.1. Grain size distribution

The grain size distribution of sedimentary deposits is a proxy for the study of eolian processes and is widely used in the study of loess-Red Clay (Lu and An, 1999; Sun et al., 2002; Fan et al., 2006; Prins et al., 2007; Vandenberghe, 2013). Comparison of the grain size distribution of the Miocene Bahe Formation silt with those of Red Clay and Quaternary loess and paleosol samples (Fig. 6) shows bimodal distributions to all samples with silty fraction being dominant. The Fig. 5 further indicates that the grain size frequency and cumulative frequency distributions for Bahe Formation silt and Quaternary silt are essentially similar, with the mean grain size of both units varying from 10 to 30 μm. The >63 μm fraction, which is considered to be transported by rolling and saltation, is very small and the ~20 μm fraction is the principal constituent of the three deposits. These findings suggest that the origin of the Bahe Formation silt is similar to that of the overlying Red Clay and eolian loess (Fig. 6).

4.2.2. Geochemistry

Analysis of the major and trace element composition of chemically insoluble residues as well as rare earth element (REE) concentrations and ratios has been used widely for understanding the origin and provenance of clastic sediments (Tayor and McLennan, 1985; McLennan et al., 1993; Guo et al., 2002; Yang et al., 2007; Liang et al., 2009; Sun et al., 2010; Zhang et al., 2012). For example, Liang et al. (2009) have demonstrated that the major and trace element composition of the Qin'an Miocene loess is similar to that of the overlying Pleistocene and Pliocene loess, supporting an eolian origin of the Miocene deposits. Also the REE composition of the Qin'an Miocene loess is consistent with that of the Plio–Pleistocene loess both closely resembling the UCC (Upper Continental Crust). In Lantian, the geochemical characteristics point to an eolian origin of the late Miocene Bahe Formation silts: The major and trace element composition of the late Miocene silt of the Bahe Formation and that of the Quaternary loess are almost identical (Fig. 7). The REE compositions of the fluvial sand from the Qinling mountain exhibit large differences in the concentrations of Eu–Tm–Yb–Lu, and the characteristics of the Miocene silts and loess–paleosol suggest that they are mainly derived from the same source regions as the widespread loess–paleosol deposits (Fig. 8).

In order to further trace the origin and provenance of the Miocene eolian silts, we compared the Sr and Nd isotope composition of samples from the entire Late Neogene sedimentary sequence from Duanjiapo (comprising Quaternary loess, Red Clay and Bahe Formation silt), with those of deposited dusts from the central CLP, northeastern Tibet, the Ordos desert and from the deserts around the northern fringe of CLP (Fig. 9). These isotope ratios have been demonstrated to be powerful tools for tracing the provenance of eolian deposits (e.g. Biscaye et al., 1997; Garzione et al., 2005; Chen et al., 2007; Li et al., 2009; Yang et al., 2009; Sun et al., 2010; Zhang et al., 2012). The $^{87}Sr/^{86}Sr$ and $^{143}Nd/^{144}Nd$ ratios of sediments are dependent upon their origin and age, and remain largely unchanged during transportation, deposition and weathering (Grousset and Biscaye, 2005). Systematic investigation of silicate Sr–Nd isotopic composition indicates that the Sr–Nd isotopic signature of the CLP and fractions lower than 75 μm of the potential dust sources in China probably have remained relatively stable over the past one million years (Chen et al., 2007; Li et al., 2009).

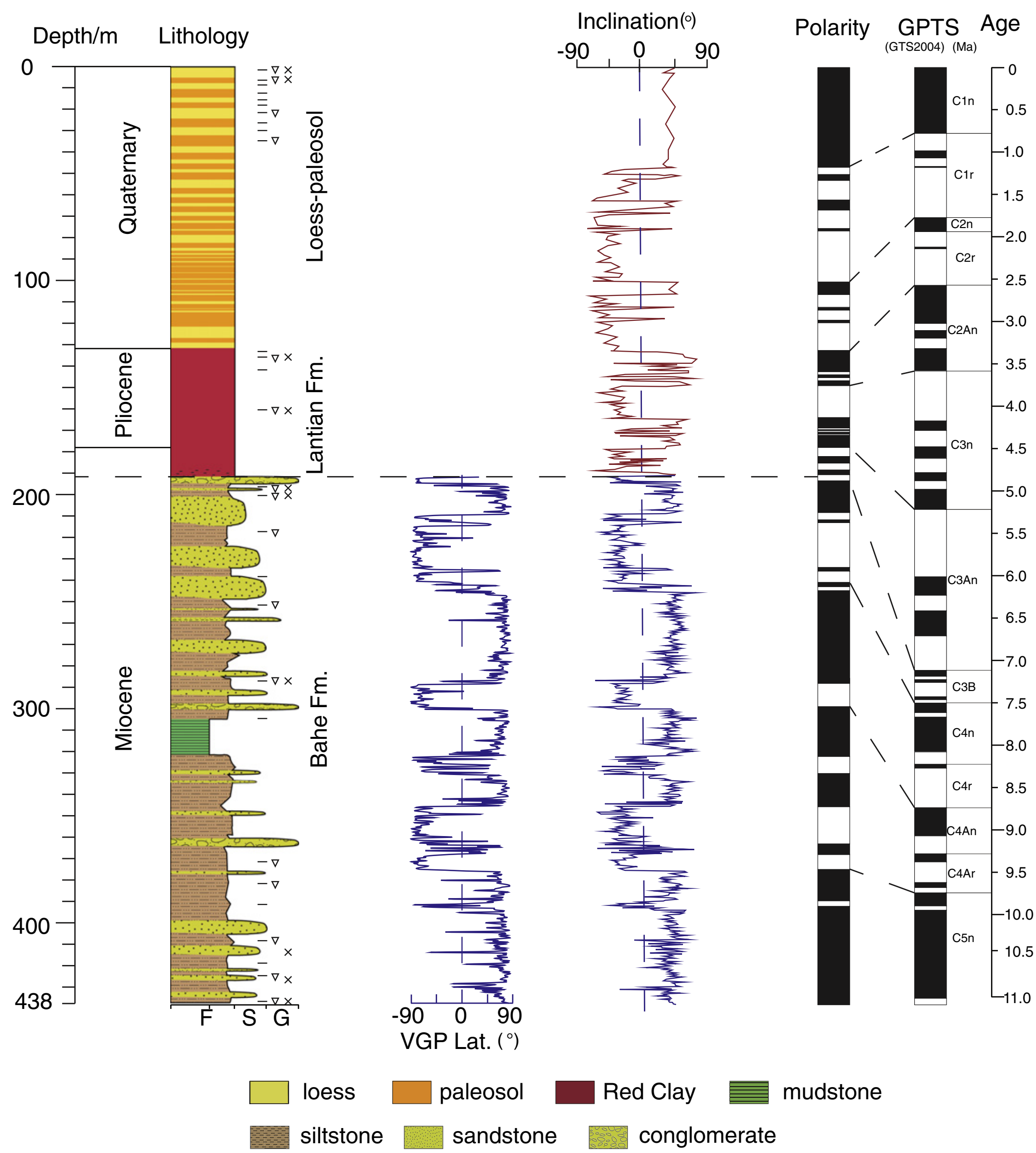

Fig. 5. Lithostratigraphy and magnetostratigraphy of the entire Duanjiapo section and their comparison with the Geomagnetic Polarity Time Scale (GTS04, Ogg and Smith, 2004) (the data between 0–7 Ma are after Zheng et al., 1992; Sun et al., 1997; An et al., 2000), the symbols -, Δ, × represent the sample levels of the major elements, trace elements and REE, Sr–Nd isotopic elements, respectively.

Plots of ε_{Nd} (0) versus $^{87}Sr/^{86}Sr$ (Fig. 9) clearly show that the ratios for the loess, Red Clay and Bahe Formation from the Duanjiapo section, and for three other loess samples from the central CLP (Huanxian, Xifeng, Luochuan) (Chen et al., 2007), are very similar. The ε_{Nd} (0) values of the Bahe Formation silt exhibit a narrow range, from −9.75 to −10.65, with an average of −10.27; and the $^{87}Sr/^{86}Sr$ ratios range from 0.71858 to 0.720159, with an average of 0.71923. Two important observations can be made about the distribution of isotope ratios of the Late Neogene eolian deposits from Duanjiapo: 1) they have a roughly identical Sr–Nd isotopic composition to that of loess from the central CLP; and 2) their values fall within the range of samples from the northeastern margin of the Tibetan Plateau, which in turn is typical of the values of younger upper crustal material. These results indicate that the Bahe Formation silt may be derived from the same source as the wind-blown deposits in the overlying Red Clay and loess deposits which were transported from a distant source, and that this source was very different from the local Qinling Mountains (Zhang et al., 2006).

The Quaternary loess was probably transported from the Gobi-desert zone in central Asia to the CLP by the northwest Asian winter monsoon (An et al., 2001; Guo et al., 2002). The Sr and Nd isotope compositions together with the results of grain size and major and trace element analyses all indicate that the Bahe Formation silt has a similar source to that of the loess and Red Clay. Consequently we conclude that the southern CLP area began to accumulate eolian dust in the Middle Miocene, at least ~11 Ma ago, similar to the eastern CLP (Xu et al., 2009). In fact, the 11 Ma eolian sediments might not be the onset of eolian dust in the southern CLP, we suppose there may be eolian deposit even earlier than 11 Ma in the underlying strata, but it need much more work to find the evidence.

4.3. Implications of the results for Late Cenozoic eolian deposition and the local depositional environments

The earliest eolian deposits reported in China all date from the Late Oligocene to the Early Miocene (viz., Linxia, 29 Ma, Garzione et al., 2005; Zhuanglang, 25 Ma, Qiang et al., 2011; Junggar Basin, 24 Ma, Sun et al., 2010; Qin'an, 22 Ma, Guo et al., 2002), and this interval clearly corresponds to a fundamental climatic transformation in East Asia (Guo

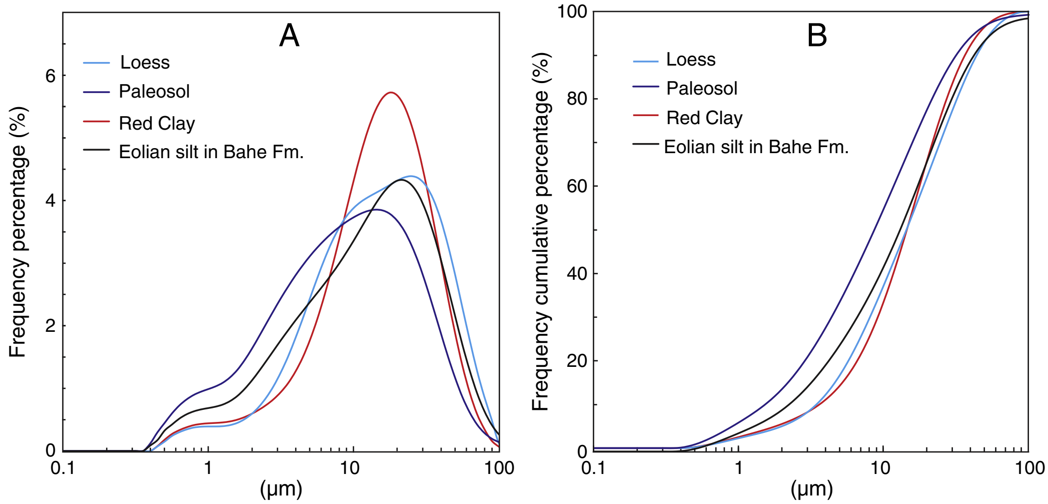

Fig. 6. Comparison of grain-size (A, B), between the Miocene eolian silts in Bahe Fm. and Quaternary loess (Pliocene Red Clay).

et al., 2008). Prior to 2009, the oldest eolian sequences reported from the CLP were at Linxia (Wang et al., 1999; Garzione et al., 2005), Qin'an (Guo et al., 2002), and Xining (Lu et al., 2004), all of which are on the western CLP, west of the Liupan Mountains. In contrast, it was thought that there were no eolian sequence older than 8.35 Ma (Jiaxian, Qiang et al., 2001) on the eastern CLP because of the different tectonic background of the eastern CLP area, delimited by the Liupan Mountains (Hao and Guo, 2004). However our results, together with those of the recent study by Xu et al. (2009) in Shilou, demonstrate that eolian deposition extends back at least to 11 Ma in the southern and eastern CLP areas. The 11 Ma datum has no obvious tectonic or paleoclimatic significance, and thus it is possible that there are even older eolian deposits on the southern CLP. In addition, it is clear that the Liupan Mountains were not a barrier to dust transport and deposition, and that dust derived from the inland deserts of Central Asia was deposited well beyond the Loess Plateau, and may even have reached the lower reaches of the Yangtze River (Zhang et al., 2007). The eastern CLP was continuously uplifted from the Late Cretaceous to the Early Miocene (C.Y. Liu et al., 2006; J.F. Liu et al., 2006), and consequently the older eolian dust deposits were susceptible to erosion. We have a careful hypothesis that the eolian dust could be stopped by the mountains around the CLP and then deposited in the basins in the upward side and preserved for a long time (e.g., at Shilou and Duanjiapo). It is possible that the entire CLP may have started to accumulate eolian dust since at least the Middle Miocene.

Finally, we suggest the possibility that the lithological changes documented at the study site, and elsewhere, may reflect tectonic as well as paleoclimatic processes. The onset of the accumulation of wind-blown Red Clay was almost simultaneous across the CLP, at 7–8 Ma in the Late Miocene (An et al., 2001). Many previous studies assume that the onset of eolian Red Clay accumulation indicates a marked change in environmental and climatic conditions including changes in the atmospheric circulation patterns across the CLP, linked to the uplift of Tibet (An et al., 2001; Kaakinen and Lunkka, 2003; Fan et al., 2006). However, an alternative explanation for the initiation of Red Clay accumulation since 7–8 Ma may be that this datum corresponds to the cessation of the uplift of the basement of the eastern CLP, and that it was only from this time onwards that the region became sufficiently physically stable enough to accumulate sediments (Liu et al., 2006; Yue et al., 2007).

During the Middle to Late Miocene, when the sediments of the Bahe Formation and the early Lantian Formation began to accumulate, the occurrence of eolian silts as reworked by or interbedded with sandy conglomerates and sandstones, may reflect the fact that the elevation of the

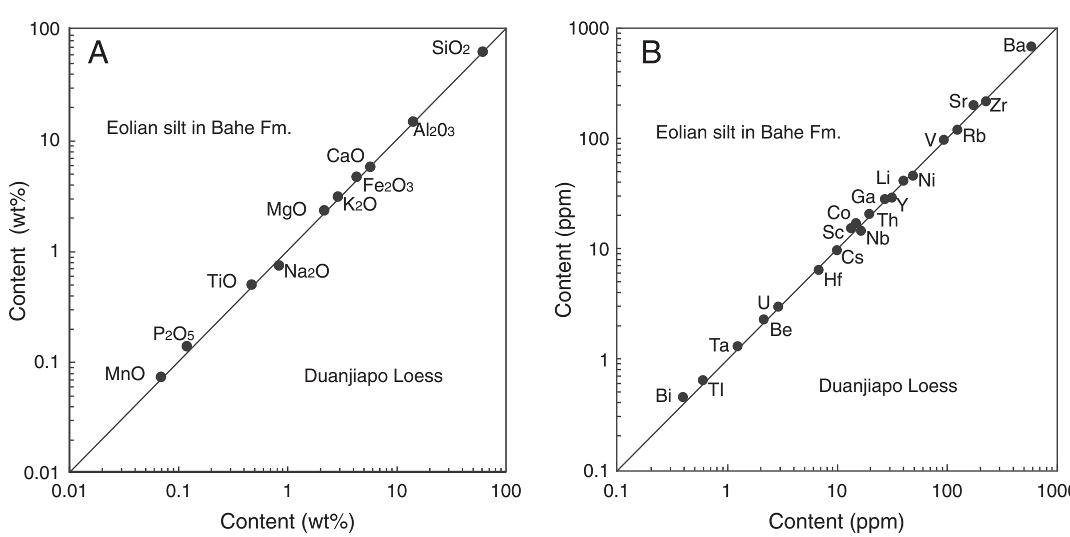

Fig. 7. Concentrations of major elements (A) and trace elements (B) for the Miocene eolian silts in Bahe Fm. and Quaternary loess.

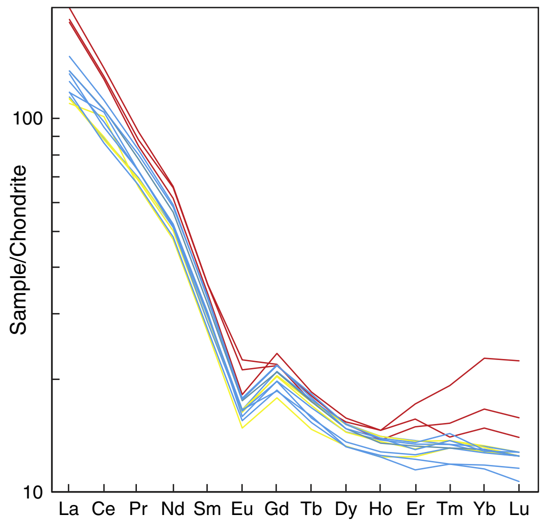

Fig. 8. Comparison of rare-earth elemental (REE) distribution patterns between the Miocene eolian silts in Bahe Fm. (blue lines), Quaternary loess (yellow lines) and fluvial sand from the Qinling Mountains (red lines).

Bailuyuan Plateau was insufficient to prevent the eolian silt deposits from being easily eroded or buried by fluvial sand and gravel originating from the Qinling Mountains. Fluvial erosion continued through the Early Pliocene, and small quantities of fluvial sand occur in the lower part of the Red Clay. However, this sedimentary component gradually diminished and eventually disappeared as the Bailuyuan Plateau continued to rise and at the same time with a vertical incision process of the river, so then the Bailuyuan Plateau became high enough to the river surface. Coarse sand and gravel do occur in the lower part of the Red Clay but they are uncommon in the upper part and are absent in the Quaternary loess–paleosol sequence. It appears, therefore, that eolian loess and fluvial-lacustrine sediments can both be deposited at the same time but in different places, just as the Sanmen paleolake and eolian Red Clay and loess–paleosol deposition in the Weihe Basin coexisted during the Late Miocene to Quaternary (Liu and Xue, 2004). This trend also provides a valuable opportunity to understand the erosional and depositional history of the Qin'an–Tianshui Basin (Guo et al., 2002; Li et al., 2006; Alonso-Zarza et al., 2009).

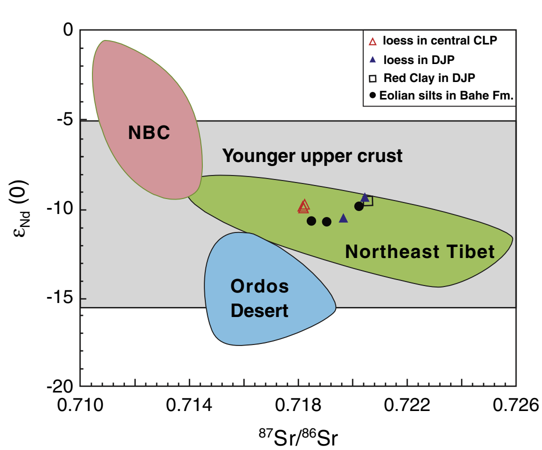

Fig. 9. Sr–Nd isotopic composition of the Neogene eolian sediments (Quaternary loess, Red Clay and Bahe Fm. silts) at Duanjiapo; and isotopic compositions of the central Chinese Loess Plateau loess (from Chen et al., 2007; and Li et al., 2009). NBC—deserts around the northern boundary of China.

The results raise the possibility to understand the onset of eolian dust in the East Asia (An et al., 2001; Guo et al., 2002; Miao et al., 2012). In addition, our findings demonstrate that the onset of eolian accumulation may indicate not only large-scale paleoclimatic changes, but may also reflect the course of local tectonic and geomorphic evolutions. It may also provide information to study the relation between the climate change and tectonics (Molnar and England, 1990; Rea et al., 1998).

5. Conclusions

The geomagnetic polarity stratigraphy of the 246-m-thick Bahe Formation sequence at the Duanjiapo section correlates very well with the geomagnetic polarity zones from C3Br.1n to C5n.2n of the GPTS, and confirms the previous magnetostratigraphic age of 11 Ma for the base of the Bahe Formation. The similarities between the lithological characteristics of the redbrown fine-grained deposits in the Bahe Formation and the Red Clay deposits, as well as essentially similar grain size distribution, element composition and Sr/Nd isotopic signature between the Bahe Formation, the Red Clay and the Quaternary loess not only indicate an eolian origin of the Bahe Formation silt, but also show that the three deposits have a similar provenance area. Our chronology indicates that the eolian dust deposition commenced at least 11 Ma ago on the southern CLP, about 4 Ma earlier than the overlying Red Clay. Finally, we suggest that eolian deposition over the entire CLP may have commenced as early as the Middle Miocene.

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