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Provenance evolution of the northern Weihe Basin as an indicator of environmental changes during the Quaternary

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Abstract

The Weihe Basin is an intracontinental rift basin in central China that provides an ideal location for studying the interactions between regional tectonics and monsoonal climate change. In this paper, we present detrital zircon U–Pb ages from sediments from Core LYH drilled in the northern margin of the basin. We use these to illuminate changing sediment transport processes, provenance and palaeo-environments during the Quaternary. The sediments are dominated by zircon age groups of 100–400 Ma and 400–550 Ma, and three secondary age peaks at 700–1100 Ma, 1700–2100 Ma and 2400–2600 Ma. Multidimensional scaling plots support the conclusion that the Central Loess Plateau and the Luo River are the dominant sources of sediments to the core site. Before *c.* 1.06 Ma, the Qinling Mountains and the Wei River, as well as the Yellow River, had minor influence on the sedimentation at the core site. These results are consistent with the existence of a palaeolake prior to 1.06 Ma, which allowed sediments supplied to the south and east edge of the basin to be reworked to the northern side of the Weihe Basin. Subsequently, the Luo River has provided a steady source of sediments to the northern Weihe Basin.

1. Introduction

Locon monsoonal climate changeated on the southern margin of the Ordos Block, the Weihe Basin is a Cenozoic intracontinental rift basin bounded by the Qinling Orogenic Belts to the south and the Central Loess Plateau (CLP) to the north (Fig. 1). The basin lies in a transition zone of both tectonics (the Eurasian Plate and the edge of the Tibetan Plateau) and climate (the arid north and humid south). Such an environment is highly sensitive to evolution in the structural setting and strength of the East Asian Monsoon (Guo *et al.* 1998; Clift et al. 2010; Sun & Wang, 2005). The thick sedimentary section (up to 7000 m in the southeast) has the potential to record past tectonic activity and to provide valuable constraints on monsoonal climate change (Rits *et al.* 2017*b*).

Core LYH was drilled along the northern margin of the Weihe Basin. Rits *et al.* (2016) interpreted the sedimentary history and reconstructed environmental changes in the uppermost 221 m of the core dating back to ∼1 Ma by using several parameters including sedimentary structures, palaeontological data, colour reflectance, grain-size and geochemistry analysis. This study concluded that the core was drilled in a distal alluvial fan setting and that the sediments displayed rapid alternations of fluvial, shallow lacustrine and aeolian environments. It has been suggested that the Luo River and the CLP are important sources for the sediments in the upper part of the core (Rits *et al.* 2017*a*, *b*). Based on this, we here provide robust evidence constraining sediment provenance change in Core LYH, which is representative of deposits in the northern Weihe Basin.

Zircon is one of the most stable minerals during sediment erosion and transport. Because this phase is generally resistant to abrasion during sedimentation, it commonly occurs as a heavy mineral in many clastic sedimentary rocks. The high U–Th–Pb isotopic closure temperature of *c.* 750 °C also makes it hard to reset during burial. The zircon U–Pb isotope composition directly reflects the zircon crystallization age (Griffin *et al.* 2004; Condie *et al.* 2005) so that zircon U–Pb dating is widely used in sediment provenance research as the age spectra are often diagnostic of unique source terrains and it has been used to effect in Asian fluvial and aeolian systems (Iizuka *et al.* 2010; Stevens *et al.* 2013; He *et al.* 2014; Bird *et al.* 2015; Nie *et al.* 2015, 2018).

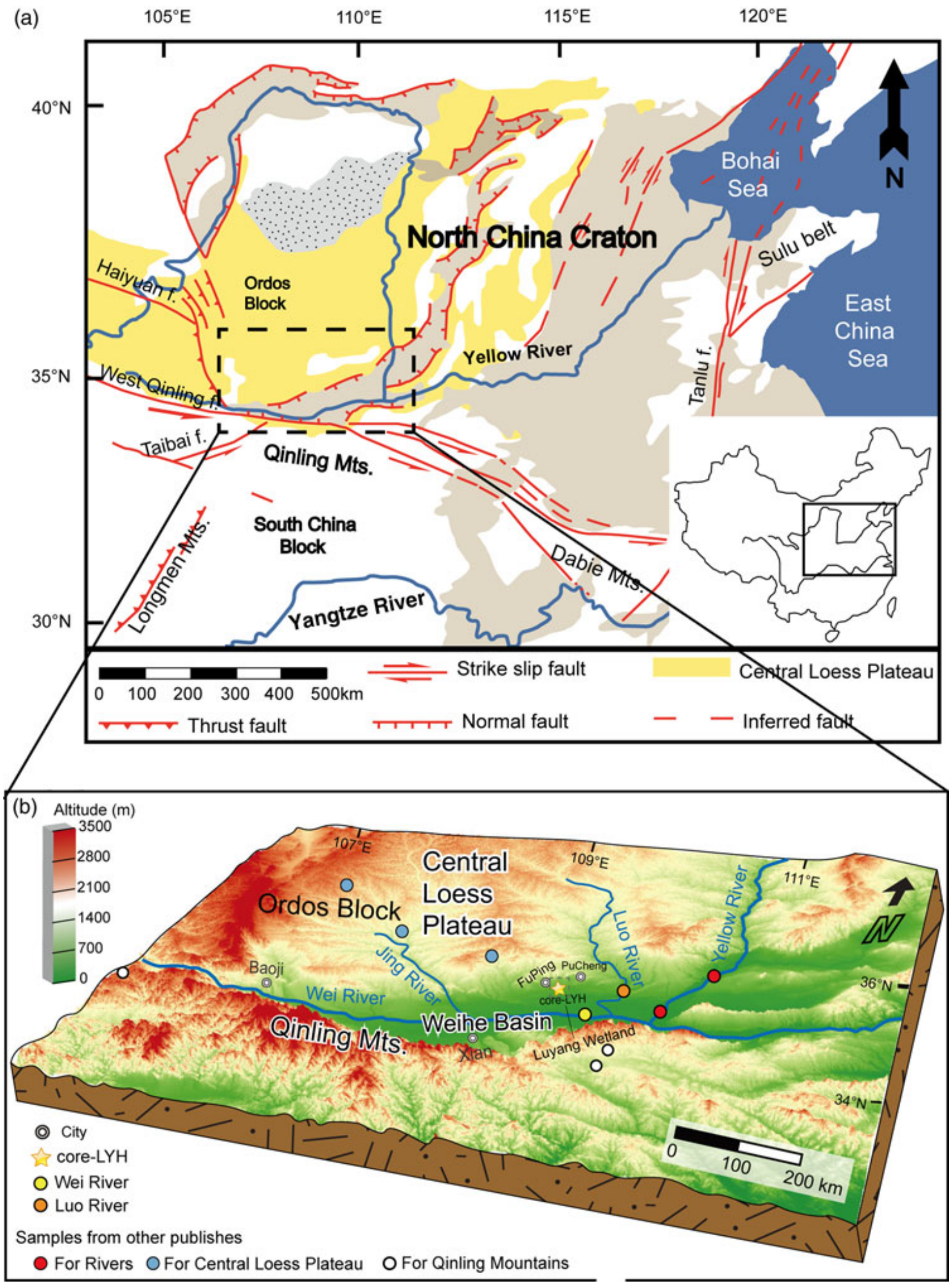

Fig. 1. (a). Sketch map of the research area. (b) The digital elevation model of the Weihe Basin and the sample locations.

Here we present a provenance study of the sediments in Core LYH using detrital zircon U–Pb ages. Our objectives are to determine the dominant source of the sediments in the northern Weihe Basin and to provide explanations for changes in source area during the course of the Quaternary.

2. Geological settings

The Weihe Basin is a large intracontinental rift basin in Central China that trends SW–NE (Fig. 1). The development of the basin was controlled by its southern and northern boundary faults (Zhang *et al.* 1995). Several rivers transport sediments to the Weihe Basin. The Yellow River flows through the eastern part, whereas the Wei River drains from west to east before its confluence with the Yellow River at Tongguan (Fig. 1). The Luo and Jing Rivers, the two largest tributaries of the Wei River, both drain the CLP. Although the Luo River now lies *c.* 25 km east of the core site, it has reached the core site on multiple past occasions (Rits *et al.* 2017*b*). There is a highland on the east side of the Jing River. This highland blocked the sediments of the river from the Jing River to the Luyang Lake. (Fig. 1b). The climate in the Weihe Basin is semi-arid and is influenced by both the East Asia Summer Monsoon and the East Asia Winter Monsoon (Sun & Wang, 2005). Regional precipitation decreases gradually from the southeast to the northwest (Du & Shi, 2012). Dust storms frequently occur in the region during spring and bring large amounts of windblown material to the basin (Ding *et al.* 2001).

Table 1. The zircon percentage of the major five age groups in Core LYH

	100–400 Ma (%)	400–550 Ma (%)	700–1000 Ma (%)	1700–2100 Ma (%)	2400–2600 Ma (%)
LYH-1	30	21	15	22	12
LYH-2	24	39	17	16	5
LYH-3	19	38	13	26	4
LYH-4	32	41	13	10	4
LYH-5	36	9	1	32	22
LYH-6	32	45	4	13	6
LYH-7	27	25	34	8	6

Core LYH was drilled at 34° 48′ 43.49″ N, 109° 31′ 53.95″ E to a depth of 1097.18 m. The core site lies between the towns of Fuping and Pucheng at the northern edge of the Weihe Basin proximal to the southern margin of the CLP (Fig. 1). This area currently consists of a wetland complex with small ponds and is characterized by extreme evaporation and poor drainage, resulting in alkaline soils and water salinity values matching marine levels. The total recovery rate of the core was over 95 % (Rits *et al.* 2016). In this study, we focus on the top 600 m of the core, which covers almost the entire Quaternary.

3. Material and methods

Seven samples were collected from Core LYH at depths of 23.46–25.19 m, 143.54–146.16 m, 172.52–174.34 m, 262.35–267.5 m, 401.02–402.29 m, 431.22–432.3 m and 544.47–546.76 m, which correspond to 60 ka, 600 ka, 730 ka, 1.06 Ma, 1.4 Ma, 1.54 Ma and 1.86 Ma respectively (Fig. 2). All the samples were collected from fine sandy layers, and at least 2 kg was taken for each sample.

Detrital zircon U–Pb age measured from zircon sand grains extracted from the sediments was compared with data from modern river samples and from samples obtained from the CLP and the Qinling Mountains. Samples were collected from the Wei River and the Luo River (Table 1). All the fluvial samples were taken from the riverbed, while avoiding cities, dams and other sources of possible contamination. We used detrital zircon U–Pb data obtained from previous studies for the middle reaches of the Yellow River (two samples), the CLP (three samples) and the Qinling Mountains (three samples) (Fig. 1a) (Lease *et al.* 2007; Qin *et al.* 2009; Yang *et al.* 2009; Pullen *et al.* 2011; Kong *et al.* 2014; Li *et al.* 2014; Nie *et al.* 2015; Fenn *et al.* 2018).

Zircon grains were extracted from bulk sediments by conventional heavy liquid and magnetic separation techniques. About 200 zircon grains were randomly selected under a binocular microscope. The grains were mounted in epoxy discs and were polished to expose their surfaces (He *et al.* 2014). U–Pb analyses were performed on polished grain mounts by laser ablation – inductively coupled plasma mass spectrometry (LA-ICP-MS) at Nanjing Normal University, China, using an Agilent 7700x ICP-MS coupled to a Photon Machine 193 nm laser ablation system with an in-house sample cell. All U–Th–Pb isotope measurements were calibrated using zircon standard GJ-1 (601 ± 12 Ma) or 91500 (1065.4 ± 0.6 Ma). Accuracy was controlled by the Qinghu zircon standard with an age of 159.5 ± 0.2 Ma. Isotopic ratios were calculated using Igor Pro-Iolite software. Following Compston *et al.* (1992), $^{206}Pb/^{238}U$ ages were used for zircons younger than 1.0 Ga, whereas $^{207}Pb/^{206}Pb$ ages were used for older grains.

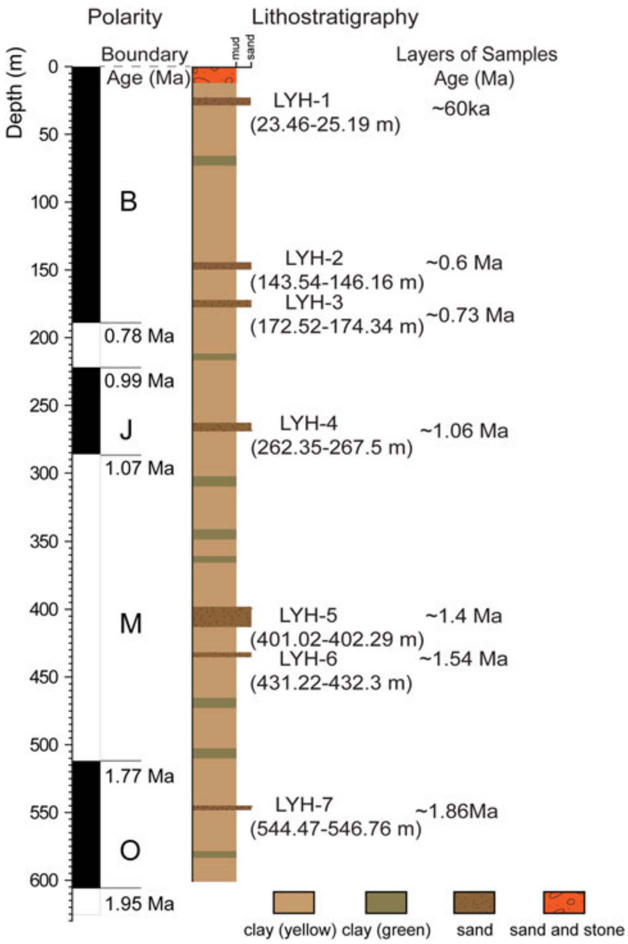

Fig. 2. Left: a brief geomagnetic polarity timescale map. B represents the geomagnetic polarity event ‘Brunhes epoch’ (0–0.78 Ma) at 0–190 m of this core. J represents the geomagnetic polarity event ‘Jaramillo event’ (0.99–1.07 Ma) at 223–285 m of this core. M represents the geomagnetic polarity event ‘Matuyama epoch’ (1.07–1.77 Ma) at 285–510 m of this core. O represents the geomagnetic polarity event ‘Olduvai event’ (1.77–1.95 Ma) at 510–605 m of this core. Right: the lithological map of Core LYH and the depth of samples collected from the core.

100–120 zircon grains were dated for each sediment sample in this study (Andersen, 2005; Vermeesch, 2004). We filtered the data to use only zircon ages that are <5 % discordant. The non-metric multidimensional scaling (MDS) plots in the ‘R’ program were used to distinguish the relationship among detrital zircon datum of samples (Vermeesch *et al.* 2016).

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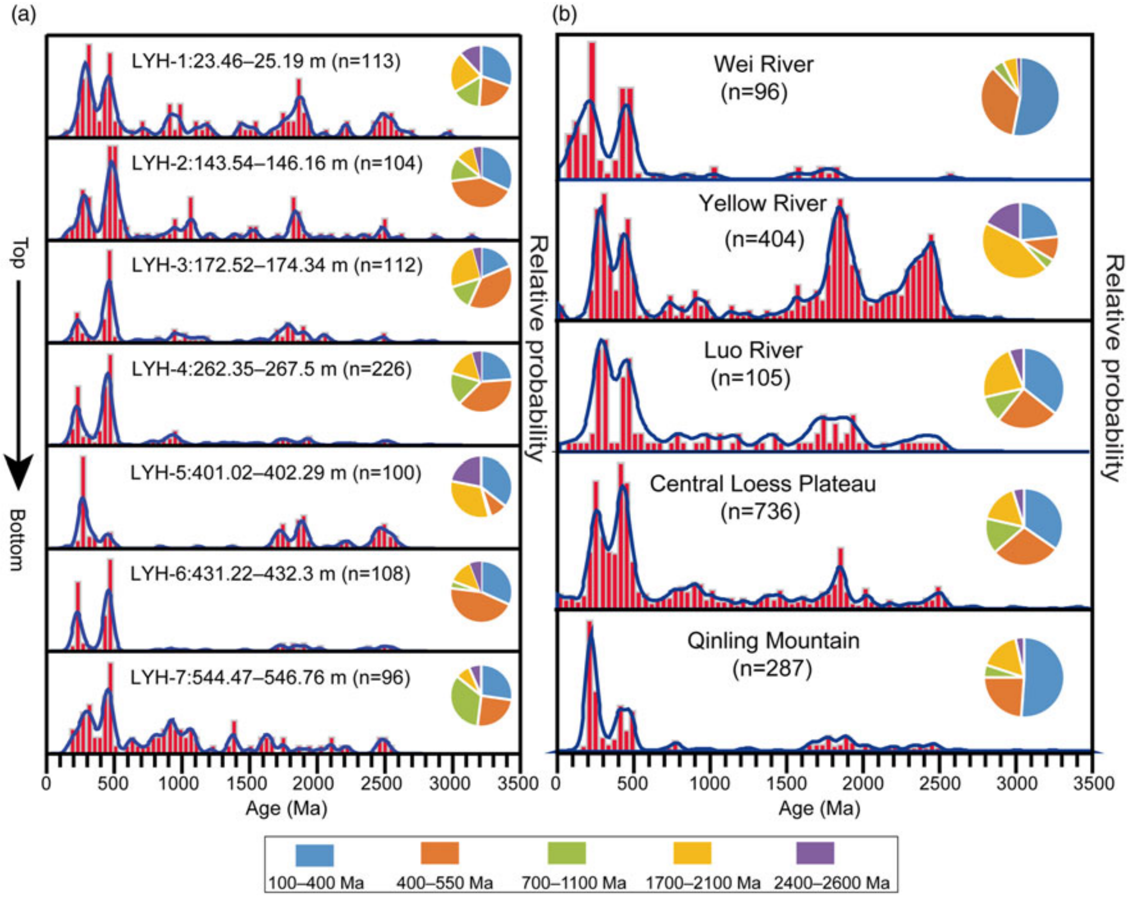

Fig. 3. (a) Detrital zircon U–Pb age distribution of the samples from Core LYH and the pie charts of five major age groups for each sample. (b) Detrital zircon U–Pb age and pie charts of the potential sources, including the modern rivers and the tectonic units. The data of the Yellow River are from Yang *et al.* (2009), Kong *et al.* (2014) and Nie *et al.* (2015). The data of the Central Loess Plateau are from Pullen *et al.* (2011), Bird *et al.* (2015), Nie *et al.* (2015) and Fenn *et al.* (2018). The data of the Qinling Mountains are from Lease *et al.* (2007), Qin *et al.* (2009) and Li *et al.* (2014). Samples were collected from the Wei River, at 34° 36′ 23.8″ N, 109° 47′ 22.5″ E, and from the Luo River, at 34° 46′ 31.3″ N, 109° 52′ 39.7″ E.

4. Results

4.a. Core LYH

Seven samples taken from Core LYH display multiple zircon age peaks. All samples have two major age populations, 100–400 Ma and 400–550 Ma (Fig. 3a). Sample LYH-7 has several other age groups, indicating contributions from complex, heterogeneous sediment sources. Sample LYH-5 has abundant grains dated at 1700–2100 Ma and 2400–2600 Ma. From sample LYH-4 to the top sample LYH-1 there are similar zircon age distributions, with two major age populations of 100–400 Ma and 400–550 Ma, and some secondary age populations dating to 700–1100 Ma, 1700–2100 Ma and 2400–2600 Ma.

By using the percentage of zircons in the five major age groups found in the cored sediments (i.e. 100–400 Ma, 400–550 Ma, 700–1100 Ma, 1700–2100 Ma and 2400–2600 Ma), we simplify the age spectra, which allows clear change in the core to be assessed (Fig. 3a).

Sample LYH-7 (1.86 Ma) shows a scattered zircon age distribution, with the age group 700–1100 Ma giving the highest contribution, at 34 %. The 100–400 Ma and 400–550 Ma populations each contribute *c.* 25 %. Sample LYH-6 (1.54 Ma) is mainly composed of grains dating at 400–550 Ma (45 %) and 100–400 Ma (32 %); however, the content of age population 700–1100 Ma is only 4 %. Sample LYH-5 (1.4 Ma) is dominated by age groups 100–400 Ma and 1700–2100 Ma, representing 36 % and 32 %, respectively, but lacks zircons of the 700–1100 Ma group. Samples LYH-4, LYH-3 and LYH-2, deposited at 1.06 Ma, 0.73 Ma and 0.6 Ma, respectively, all display similar age distributions, with the maximum contribution of 40 % from age group 400–550 Ma and *c.* 20 % of 100–400 Ma zircons. The contents of 700–1100 Ma and 1700–2100 Ma age groups are all *c.* 15 % in these younger samples. The least abundant zircon population is the 2400–2600 Ma group, with a contribution of only 4 %. Sample LYH-1 shows almost equal contributions from different age groups, being all at *c.* 20 %. However, zircons from the 100–400 Ma and 1700–2100 Ma populations are relatively abundant (Table 1; Fig. 3a).

The zircon age spectra of the older sediments (samples LYH-7, LYH-6 and LYH-5) show clear changes, while the zircon age distributions of the samples above LYH-4 show little variability.

4.b. River sediments

The detrital zircon U–Pb age distributions of the river sediments display multiple age populations with clear differences in their relative abundances (Fig. 3b). The five most common and diagnostic age groups were used to discriminate the provenance. The Wei River has the highest content of age groups 100–400 Ma and 400–550Ma, with 53 % and 35 % being recorded respectively. In contrast, the content of the other three age groups is less than

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Table 2. The zircon percentage of the major five age groups in the modern rivers and the tectonic units

	100–400 Ma (%)	400–550 Ma (%)	700–1000 Ma (%)	1700–2100 Ma (%)	2400–2600 Ma (%)
Wei River	53	35	5	6	1
Luo River	36	25	11	23	6
Yellow River	25	19	10	29	17
Central Loess Plateau	30	36	10	12	2
Qinling	49	44	6	0	0

6 %. Sediments from the middle reaches of the Yellow River contain more Palaeo-Proterozoic zircons (i.e. 1700–2100 Ma (29 %) and 2400–2600 Ma (17 %)). The 100–400 Ma and 400–550 Ma zircons, comprising 25 % and 19 %, respectively of the Wei River load, are also important age groups in samples from the Yellow River. Although Luo River sediments have a zircon age spectrum similar to that measured in the middle reaches of the Yellow River, these show a relatively higher contribution of 100–400 Ma zircons and lower input from the 1700–2100 Ma populations. The 700–1100 Ma age group contributes *c.* 10 % to the Luo River, somewhat more than found in the sediments of the Wei River (Table 2).

4.c. Central Loess Plateau and the Qinling Mountain sediments

The CLP is composed of regular cyclic loess and palaeosol layers, which reflect variations in the strength of the East Asian Monsoon (Ding *et al.* 2001; Porter *et al.* 2001; Sun *et al.* 2010). The detrital zircon ages from the loess show two dominant groups of 100–400 Ma and 400–550 Ma (Fig. 3b). The 700–1100 Ma and 1700–2100 Ma groups constitute 15 %, while the 2400–2600 Ma age group accounts for only 2 % (Fig. 3b).

The Qinling Mountains lie to the north of the Yangtze Craton and south of the North China Craton (Fig. 1). The Meso-Neoproterozoic orogeny had the greatest effect on this belt, followed by a Late Palaeozoic marine transgression from the direction of the Songpan Ganzi terrane (Wei *et al.* 1999; Wang *et al.* 2001*a*; Dong & Santosh, 2016). Moreover, the Qinling Mountains were strongly affected by deformational, metamorphic and magmatic events during the Mesozoic to Cenozoic, particularly during the Triassic Indonesian Orogeny (Liu & Zhang, 1999; Zhang *et al.* 2004). The Qinling Mountains and the Weihe Basin are part of a significant mountain-basin system in Central China (Yin & Nie, 1993; Meng & Zhang, 2000). The major age populations of bedrocks in the Qinling Mountains are 100–300 Ma, 350–550 Ma and 700–900 Ma (Fig. 3b).

4.d. Statistical analysis

The MDS plots enable quantitative comparison of similarities with the CLP and the Qinling Mountains and with different rivers (Fig. 4). Solid lines mark the closest relationships between different samples, while dashed lines indicate the second closest associations.

We discuss the result given by the MDS plot combined with the geological settings. The MDS plots clearly show that sediments from Core LYH have the same characteristics as the CLP and Luo River sediments. Only samples LYH-6 and LYH-4 have a close relationship with the Qinling Mountains and the Wei River, while sample LYH-5 is most similar to the Yellow River (Fig. 4).

5. Discussion

5.a. Provenance discrimination

Core LYH lies on the northern margin of the Weihe Basin, in close proximity to the southern edge of the CLP and the northern side of the Qinling Mountains. The Wei, Luo and Yellow Rivers are all potential sources for the core sediments.

The U–Pb zircon age spectra of the sediments in the core reveal a dominance by 100–400 Ma and 400–550 Ma populations. These two age groups also exist in sediments and sedimentary rocks from the Qinling Mountains and the CLP (Fig. 3b). However, zircons from Core LYH are most similar in age spectra to those of the CLP (Fig. 3a), probably suggesting that the CLP has been the most important source. Previous research has argued that the Luo River, drained by the CLP, has an important influence over the sedimentary evolution of the northern Weihe Basin (Rits *et al.* 2017*b*). Our results confirm the importance of this river since the core sediments also show a similar zircon age pattern to that measured in the Luo River sediments. The content of zircon with ages of 1800–2000 Ma and 2300–2500 Ma in Yellow River sediments is relatively high. However, with the exception of sample LYH-5, such grains do not appear in Core LYH deposits, indicating that the contribution of the Yellow River to Core LYH has been minimal.

The sediments on the CLP are dominantly aeolian in origin (Pullen *et al.* 2011). It might thus be expected that sediments in Core LYH could also be of aeolian origin. However, based on the existence of many fluvial sedimentary features, such as bedding and loading structures and a much higher sedimentation rate than that in the aeolian sequences of the CLP, Rits *et al.* (2016) have argued that most of sediments were deposited by fluvial transport. Thus, we conclude that sediments carried by the Luo River dominate over those brought directly to LYH Core location by aeolian transport.

A large amount of sediment eroded from the Qinling Mountains is preserved in the Weihe Basin. These sediments record information on the erosion of the Qinling Mountains in the Cenozoic. However, because the basin stratigraphy tilts towards the south, most of the sediments derived from the Qinling Mountains are trapped along the southern margin. This structure also means that the Wei River has received abundant sediment from the Qinling Mountains. Some sediments in Core LYH (e.g. samples LYH-6 and LYH-4) show some influence from the Qinling Mountains and the Wei River. Marked changes in the overall structure are unlikely, because geological cross-sections across the Weihe Basin show that older sediments from the Pliocene and Miocene also tilt toward the south (Rits *et al.* 2017*b*). As a result, our conclusion that the core sediments have been influenced by flux from the Qinling Mountains and the Wei River implies a major change in environmental conditions.

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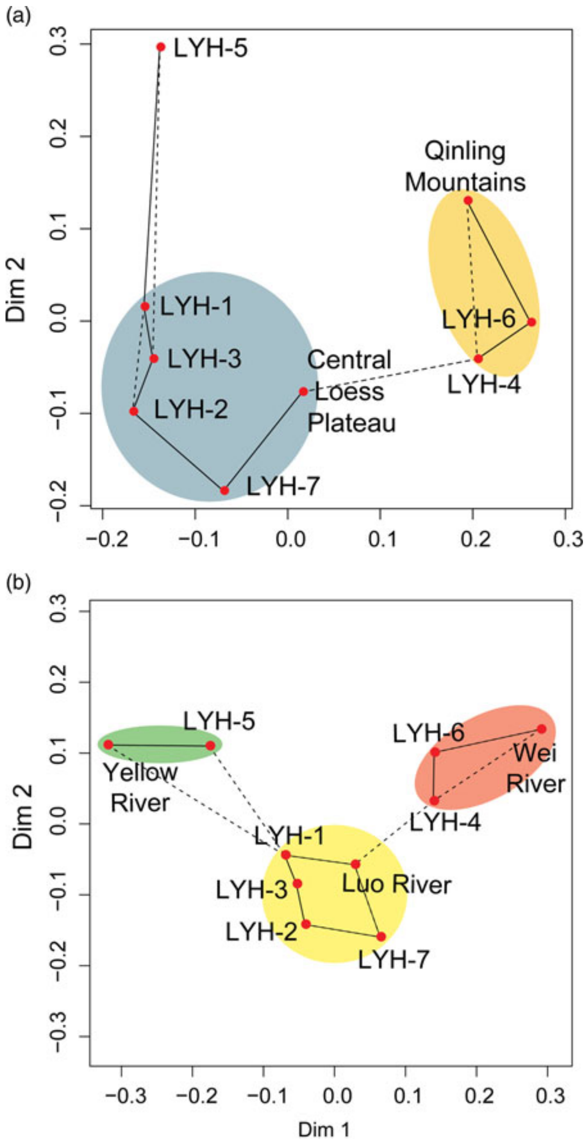

Fig. 4. (a) Non-metric MDS plots of samples between Core LYH and the CLP and Qinling Mountains, showing quantitative comparison of similarities. (b) Non-metric MDS plots of samples between Core LYH and the modern rivers.

In particular, it implies drainage of the Sanmen palaeolake, which is considered to be the depocentre for the Sanmen Formation. There is disagreement about the time that the lake disappeared (Pan *et al.* 2005). The Sanmen palaeolake covered large parts of the Weihe Basin during the Quaternary, and gradually reduced and finally disappeared in the Middle to Late Pleistocene, except for fragments in some low-lying areas, such as Luyang Lake (Wang *et al.* 2001*b*). Our study reveals that the Qinling Mountains and the Wei River contributed sediments to the site of Core LYH (sample LYH-4) before 1.06 Ma, indicating that the lake may have existed at that time. When the lake shrank after 1.06 Ma and became disconnected from the Wei River, sediments from the Qinling Mountains were no longer able to be transported from the south to the north via transport on the lake bottom. Similarly, the influence of Yellow River sedimentation on sample LYH-5 might also indicate the presence of the palaeolake in the basin at that time, because currently the Yellow River cannot reach the core site due to a structural horst that serves as a natural barrier between the Yellow River and the core site.

As a result, changes in the sources of sediment to Core LYH must have occurred during the Quaternary. The CLP and the Luo River are the main sources of the sediments; however, some variations occurred at 1.06 Ma. Before that time, the core site also received sediments from the Qinling Mountains, the Wei River and the Yellow River. However, after 1.06 Ma, only the CLP and the Luo River delivered sediments to the core site. We conclude that a palaeolake must have existed in that region before 1.06 Ma in order to explain the provenance of some sediment from the south. This region was then located in a semi-humid area (DS Rits, unpub. PhD thesis, Nanjing Normal Univ., 2017). Precipitation is limited and the evaporation is large, so the lake could not have been too deep, and the water level would have fluctuated greatly with changing climate. When the lake enlarged, this would allow sediments from the south and the east to reach the core site on the northern side of the basin. Conversely, when the extent of the ancient lake was large enough, sediments from both the south and north reached the palaeolake. However, when the lake was small, sediments supplied to the southern side of the basin could not enter the lake directly and then be transported north to the coring location, limiting supply to that place from northern sources. Recent research has shown that the Yellow River ran through the Sanmen Gorge at 0.9 Ma, which implies that the Sanmen palaeolake must have disappeared prior to that time (Shang *et al.* 2018). Our data imply the presence of the Sanmen palaeolake before 1.06 Ma, which in turn requires that the palaeolake started to shrink at about 1.06 Ma. It is clear that the lake that existed in the Weihe Basin could be just the remains of the Sanmen palaeolake, but does not constrain the time that the Yellow River flowed through the Sanmen Gorge, because of the different location and geological setting.

5.b. Evolution of the Luo River

Above we argued that the CLP and the Luo River were the main sources of sediments to the core site during the Quaternary. The Luo River, a second-order tributary of the Yellow River, originates in the CLP and flows proximal to the Luyang Wetland. Rits *et al.* (2017*a*) reconstructed the evolutionary history of the Luo River using geological and geomorphological constraints and concluded that during the Middle to Late Pleistocene (until ~240–200 ka), an alluvial fan of the Luo River contributed sediments to the site of Core LYH. This study indicates that the Luo River provided sediments to the drilling site since at least 1.86 Ma. However, sample LYH-7 and modern Luo River sediments clearly show some differences, with additional age peaks (600–800 Ma) and more Palaeozoic zircons in sample LYH-7 (Fig. 3a). Alluvial fans have the potential to receive sediment from contrasting sources when their catchment is large enough so that the zircon U–Pb age composition of the resulting deposits could be complex. The fact that sample LYH-7 exhibits multiple ages implies erosion from a number of sources, while the sedimentary facies of the deposit implies formation on an alluvial fan. After 1.06 Ma (sample LYH-4), the U–Pb age spectra of the sediments in the core show a close relationship with the modern Luo River, indicative of this being the primary sediment supplier, or another river with a dominant source in the CLP. We argue that before 1.06 Ma, the Luo River contributed less to the core site due to sediment transport within the lake, but that after 1.06 Ma, the Luo River's contribution to the

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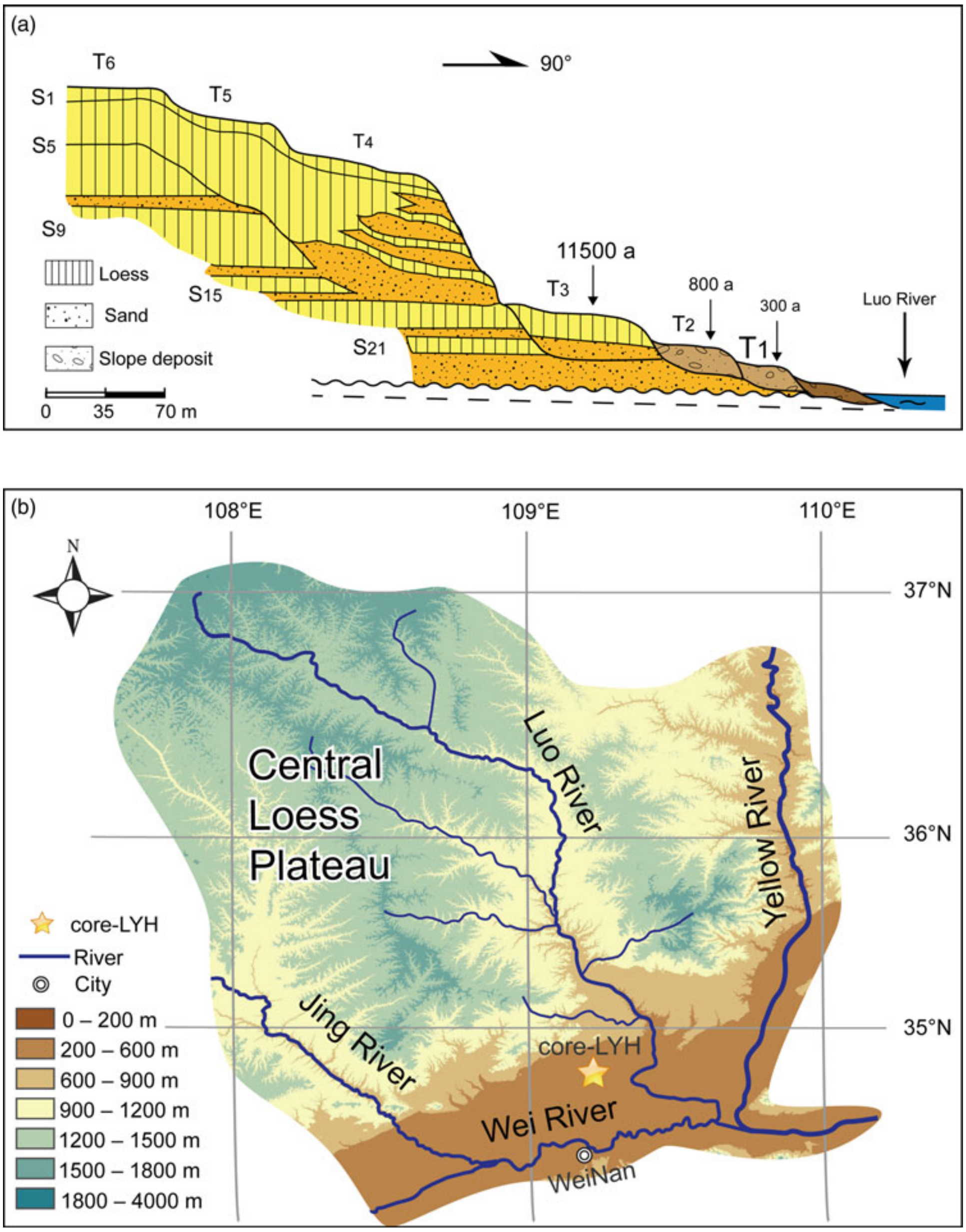

Fig. 5. (a) The terrace profile of the Luo River (modified from Zhu, 1989). (b) The digital elevation map of the Luo River drainage.

supply gradually increased as supply from southern and eastern sources reduced.

Previous studies have reported the existence of six terraces in the Luo River (Zheng, 2003). Using the loess and palaeosol sequences on the terraces (Fig. 5), the age of the oldest terrace is constrained at ~1.06 Ma (Zheng, 2003), which is consistent with our findings in favouring a base level fall at that time caused by at least partial draining of the palaeolake. In contrast, compared with many rivers draining the CLP and that could carry sediments to the core area, the Luo River has a large drainage. These other small rivers are unlikely to have affected the sediments at the core site more than the Luo River. Furthermore, the Jing River, which is also a secondary tributary of the Yellow River and also originated from the CLP, had less contribution to the cored sediments because of its distance from the drilling site and the structural barrier of the higher elevation around the river channel.

Because the volume of core material was limited, we tested *c.* 120 zircon grains for each sample to illustrate the provenance changes. Our results show a clear pattern of provenance of evolution, although this could be improved and refined with larger datasets, such as those provided in the nearby study of Nie (2018). Nonetheless, the data we present are statistically meaningful and provide important constraints on the age of formation of the Luo River and the evolution of drainage in the Weihe Basin.

6. Conclusion

Detrital zircon U–Pb ages were analysed for the sediments from Core LYH, drilled in the northern Weihe Basin, to investigate provenance and environmental changes in this area since 1.86 Ma. During this period, we observed changes in the provenance of the sediment in the core. All the samples are dominated by

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two zircon age groups, 100–400 Ma and 400–550 Ma, and three secondary age populations at 700–1100 Ma, 1700–2100 Ma and 2400–2600 Ma. The relative sizes of the different population groups together with MDS statistical analysis reveal that the CLP and the Luo River have been the dominant sources of sediment to the core site.

Before *c.* 1.06 Ma, the Qinling Mountains and the Wei River, as well as the Yellow River, supplied some of the sediment accumulating at the core site. This connection may be related to the existence of a palaeolake that occupied the Weihe Basin before 1.06 Ma. When the palaeolake was large enough, sediments supplied from both the south and the east reached the palaeolake and could then be reworked and transported to the core site on the northern side. However, when the lake became smaller, sediment supply to the southern edge of the lake reduced and transport north to the core site was prevented. After 1.06 Ma, only the Luo River coming from the north was able to supply sediment to the core site. The provenance of sediments in Core LYH has been essentially stable and dominated by the Luo River and/or similar stream since 1.06 Ma.

Supplementary material. To view supplementary material for this article, please visit https://doi.org/10.1017/S0016756819000244.

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References

Andersen T (2005) Detrital zircons as tracers of sedimentary provenance: limiting conditions from statistics and numerical simulation. *Chemical Geology* **216**, 249–70.

Bird A, Stevens T, Rittner M, Vermeesch P, Carter A, Andò S, Garzanti E, Lu HY, Nie JS, Zeng L, Zhang HZ and Xu ZW (2015) Quaternary dust source variation across the Chinese Loess Plateau. *Palaeogeography Palaeoclimatology Palaeoecology* **435**, 254–64.

Clift PD, Tada R and Zheng HB (2010) Monsoon evolution and tectonics–climate linkage in Asia: an introduction. In *Monsoon Evolution and Tectonics–Climate Linkage in Asia* (eds PD Clift, R Tada and HB Zheng), pp. 1–4. Geological Society of London, Special Publication no. **342**.

Compston W, Williams IS, Kirschvink JL, Zhang Z and Ma G (1992) Zircon U-Pb ages for the Early Cambrian time-scale. *Journal of the Geological Society, London* **149**, 171–84.

Condie KC, Beyer E, Belousova E, Griffin WL and O' Reilly SY (2005) U-Pb isotopic ages and Hf isotopic composition of single zircons: the search for juvenile Precambrian continental crust. *Precambrian Research* **139**, 42–100.

Ding ZL, Sun JM, Yang SL and Liu TS (2001) Geochemistry of the Pliocene red clay formation in the Chinese Loess Plateau and implications for its origin, source provenance and paleoclimate change. *Geochimica et Cosmochimica Acta* **65**, 901–13.

Dong Y and Santosh M (2016) Tectonic architecture and multiple orogeny of the Qinling Orogenic Belt, Central China. *Gondwana Research* **29**, 1–40.

Du J and Shi CX (2012) Effects of climatic factors and human activities on runoff of the Weihe River in recent decades. *Quaternary International* **282**, 58–65.

Fenn K, Stevens T, Bird A, Limonta M, Rittner M, Vermeesch P, Andò S, Garzanti E, Lu HY, Zhang HZ and Zeng L (2018) Insights into the provenance of the Chinese Loess Plateau from joint zircon U-Pb and garnet geochemical analysis of last glacial loess. *Quaternary Research* **89**, 645–59.

Griffin WL, Belousova EA, Shee SR, Pearson NJ and O' Reilly SY (2004) Archean crustal evolution in the Northern Yilgarn Craton: U-Pb and Hf-isotope evidence from detrital zircons. *Precambrian Research* **131**, 231–82.

Guo ZT, Liu TS, Federoff N, Wei LY, Ding ZL, Wu NQ, Lu HY, Jiang WY and An ZS (1998) Climate extremes in Loess of China coupled with the strength of deep-water formation in the North Atlantic. *Global and Planetary Change* **18**, 113–28.

He M, Zheng H, Bookhagen B and Clift PD (2014) Controls on erosion intensity in the Yangtze River basin tracked by U-Pb detrital zircon dating. *Earth-Science Reviews* **136**, 121–40.

Iizuka T, Komiya T, Rino S, Maruyama S and Hirata T (2010) Detrital zircon evidence for Hf isotopic evolution of granitoid crust and continental growth. *Geochimica et Cosmochimica Acta* **74**, 2450–72.

Kong P, Jia J and Zheng Y (2014) Time constraints for the Yellow River traversing the Sanmen Gorge. *Geochemistry, Geophysics, Geosystems* **15**, 395–407.

Lease RO, Burbank DW, Gehrels GE, Wang Z and Yuan D (2007) Signatures of mountain building: detrital zircon U/Pb ages from northeastern Tibet. *Geology* **35**, 239–42.

Li Y, Zhou HW, Li QL, Xiang H, Zhong ZQ and Brouwer FM (2014) Palaeozoic polymetamorphism in the North Qinling orogenic belt, Central China: insights from petrology and in situ titanite and zircon U-Pb geochronology. *Journal of Asian Earth Sciences* **92**, 77–91.

Liu S and Zhang G (1999) Process of rifting and collision along plate margins of the Qinling orogenic belt and its geodynamics. *Acta Geologica Sinica* **73**, 275–87 (in Chinese).

Meng QR and Zhang GW (2000) Geologic framework and tectonic evolution of the Qinling orogen, central China. *Tectonophysics* **323**, 183–96.

Nie JS, Pullen A, Garzione CN, Peng WB and Wang Z (2018) Pre-Quaternary decoupling between Asian aridification and high dust accumulation rates. *Science Advances* **4**, eaao6977.

Nie JS, Stevens T, Rittner M, Stockli D, Garzanti E, Limonta M, Bird A, Andò S, Vermeesch P and Saylor J (2015) Loess Plateau storage of Northeastern Tibetan Plateau-derived Yellow River sediment. *Nature Communications* **6**, 8511. doi: 10.1038/ncomms9511.

Pan B, Wang J, Gao H, Guan Q, Wang Y, Su H, Li B and Li J (2005) Paleomagnetic dating of the topmost terrace in Kouma, Henan and its indication to the Yellow River's running through Sanmen Gorges. *Chinese Science Bulletin* **50**, 657–64.

Porter SC, Hallet B, Wu X and An Z (2001) Dependence of near-surface magnetic susceptibility on dust accumulation rate and precipitation on the Chinese Loess Plateau. *Quaternary Research* **55**, 271–83.

Pullen A, Kapp P, McCallister AT, Chang H, Gehrels GE,Garzione CN, Heermance RV and Ding L (2011) Qaidam Basin and northern Tibetan Plateau as dust sources for the Chinese Loess Plateau and paleoclimatic implications. *Geology* **39**, 1031–4.

Qin J, Lai S, Grapes R, Diwu C, Ju Y and Li Y (2009) Geochemical evidence for origin of magma mixing for the Triassic monzonitic granite and its enclaves at Mishuling in the Qinling orogen (central China). *Lithos* **112**, 259–76.

Rits DS, Balen RTV, Prins MA and Zheng H (2017a) Evolution of the alluvial fans of the Luo River in the Weihe Basin, central China, controlled by faulting and climate change: a reevaluation of the paleogeographical setting of Dali Man site. *Quaternary Science Reviews* **166**, 339–51

Rits DS, Beets CJ, Prins MA, Balen RTV, Troelstra SR, Luo C, Wang B, Li X, Zhou J and Zheng H (2017b) Geochemical characterization of the middle and late Pleistocene alluvial fan-dominated infill of the northern part of the Weihe Basin, Central China. *Palaeogeography, Palaeoclimatology, Palaeoecology* **482**, 57–69

Rits DS, Prins MA, Troelstra SR, Van Balen RT, Zheng Y, Beets CJ, Wang B, lI XQ, Zhou J and Zheng HB (2016) Facies analysis of the Middle and Late Quaternary sediment infill of the northern Weihe Basin, Central China. *Journal of Quaternary Science* **31**, 152–65.

Shang Y, Prins MA, Beets CJ, Kaakinen A, Lahaye Y, Dijkstra N, Rits DS, Wang B, Zheng HB and van Balen RT (2018) Aeolian dust supply from the Yellow River floodplain to the Pleistocene loess deposits of the Mangshan Plateau, central China: evidence from zircon U-Pb age spectra. *Quaternary Science Reviews* **182**, 131–43.

Stevens T, Carter A, Watson TP,Vermeesch P, Andò S, Bird AF, Lu H, Garzanti E, Cottam MA and Sevastjanova I (2013) Genetic linkage between the Yellow River, the Mu Us desert and the Chinese Loess Plateau. *Quaternary Science Reviews* **78**, 355–68.

Sun XJ and Wang PX (2005) How old is the Asian monsoon system? – Palaeobotanical records from China. *Palaeogeography, Palaeoclimatology, Palaeoecology* **222**, 181–222.

Sun Y, An Z and Clemens SC (2010) Non-stationary response of Plio-Pleistocene East Asian winter monsoon variation to ice volume forcing. In *Monsoon Evolution and Tectonics–Climate Linkage in Asia* (eds PD Clift, R Tada and HB Zheng), pp. 79–86. Geological Society of London, Special Publication no. **342**.

Vermeesch P (2004) How many grains are needed for a provenance study? *Earth Planetary Science Letters* **224**, 441–51.

Vermeesch P, Resentini A and Garzanti E (2016) An R package for statistical provenance analysis. *Sedimentary Geology* **336**, 14–25.

Wang T, Zhang G, Pei X and Wang X (2001a) Neoproterozoic orogeny in the core of the Qinling orogenic belt (China) and its implications for assembly of the North and South China blocks. *Gondwana Research* **4**, 815–16.

Wang SM, Wu XH, Zhang FC, Xue B, Tong GB and Tian GQ (2001b) Study on the environmental changes recorded in the Sanmen lake and the Yellow River running to the east. *Science in China* **31**, 760–68. (in Chinese)

Wei C, Zhan M, Wei J and Yu F (1999) Meso- and neoproterozoic tectono-thermal events and structural evolution in eastern Qinling orogenic belt, China. *Gondwana Research* **2**, 525–9.

Yang J, Gao S, Chen C, Tang YY, Yuan HL, Gong HJ, Xie SW and Wang J (2009) Episodic crustal growth of North China as revealed by U-Pb age and Hf isotopes of detrital zircons from modern rivers. *Geochimica et Cosmochimica Acta* **73**, 2660–73.

Yin A and Nie S (1993) An indentation model for the North and South China collision and the development of the Tan-Lu and Honam Fault Systems, eastern Asia. *Tectonics* **12**, 801–13.

Zhang G, Cheng S, Guo A, Dong Y, Lai S and Yao A (2004) Mianlue paleo-suture on the southern margin of the Central Orogenic System in Qinling-Dabie – with a discussion of the assembly of the main part of the continent of China. *Geological Bulletin of China* **23**, 846–53.

Zhang YQ, Vergely P and Mercier JL (1995) Active faulting in and along the Qinling Range (China) inferred from spot imagery analysis and extrusion tectonics of south China. *Tectonophysics* **243**, 69–95.

Zheng MG (2003) The evolutionary model of river terraces in the mid-tail of Weihe River. Master thesis. p. 546. Northwest University. Published thesis. (in Chinese)

Zhu ZY (1989) The formation of river terraces and evolution of drainage system in the middle Yellow River. *Acta Geographic Sinica* **44**, 429–40.