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Vegetation and climate change in the Hetao Basin (Northern China) during the last interglacial-glacial cycle

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ABSTRACT

The Hetao region of China is noted for research on ancient humans. However, a lack of detailed records of vegetation and climate changes in this region has hindered understanding of human dispersal. We reconstructed the vegetation and climate changes during the last Pleistocene using pollen records from a continuous lacustrine sediment section in the Hetao Basin. The vegetation type was forest-steppe dominated by *Pinus* and *Artemisia* during the last interglacial periods. During the last glacial periods, the vegetation shifted to a Chenopodiaceae – *Artemisia* desert steppe with an *Artemesia* steppe between 44 and 34 ka BP. The steppe ecosystem, in the Hetao region during milder periods of the last glacial, was suitable for herbivores that may have provided sufficient prey for ancient humans. The vegetation changes indicate an altered climate characterized by colder and drier conditions that were probably influenced by global cooling and a decline of northern insolation variations from the last interglacial to glacial periods.

1. Introduction

Climate change was an important influence on ancient human evolution and dispersal patterns (deMenocal, 2004; Carto et al., 2009; Eriksson et al., 2012; Maslin et al., 2014; Breeze et al., 2016). However, researchers from China have reached different conclusions on ancient human dispersal patterns in response to climate (Liu et al., 2016, 2017). Evidence from Fuyan Cave in Hunan (Liu et al., 2015; Wu and Xu, 2016) and Beiyao site (Tang et al., 2017) indicates that some ancient humans moved into East Asia during the interglacial age. Fossils from the Shuidonggou in Ningxia (Gao et al., 2008; Nian et al., 2014), Wulanmulun in Inner Mongolia (Dong et al., 2014; Chen et al., 2014), and Tianyuan Cave in Beijing (Shang et al., 2007) suggest that ancient humans appeared during the last glacial periods. Previous studies only focused on the fossil strata (Gao et al., 2008; Li et al., 2014) and there are inadequate consecutive climatic change records linked to ancient human habitats in these regions. The Hetao Basin lies on the northern part of the Ordos Plateau, which is an area significant for ancient human evolution studies (Fig. 1a). The wide plain and numerous lakes there were favorable for herbivores, as well as for ancient human habitation, during the last Pleistocene (Dong et al., 2014). Fossils attributed to ancient humans (often referred to as “Hetao Man”) and many artifacts have been discovered at the Salawusu and Shuidonggou sites (Teilhard de Chardin and Licent, 1924). Additional ancient human and associated artifacts were found at the Wulanmulun site (Dong et al., 2014; Chen et al., 2014), Salawusu site (Wu et al., 1999), and Shuidonggou site (Gao et al., 2013). Mammal fossils have also been found at Baotou (Huang et al., 1989; Nie et al., 2008). Some of the climate changes in the Hetao Basin, surrounding Ordos Plateau and Chinese Loess Plateau have been reconstructed (Li et al., 2000; Li, 2006; Yang et al., 2018; Zan et al., 2010, 2018), but records of vegetation and biome changes are scarce. The response of vegetation and biomes to climate might be more important than climate change itself in revealing the living environment of ancient humans. Successive records of palaeovegetation changes might provide a better understanding of the background in which ancient humans evolved. In the present study, a consecutive profile was collected from the Bingfanggou in the Hetao Basin for pollen analyses. On the basis of absolute dating results (Yang et al., 2018), we reconstructed a regional vegetation sequence that can be used to infer climate changes during the late Pleistocene. The reconstructed record of regional vegetation change and climatic variability provides further insight into the occupation history of ancient humans during the last glacial period.

2. Regional setting

The Hetao Basin is surrounded by Langshan and Sertengshan to the northwest, Daqingshan to the northeast and the Ordos Plateau to the

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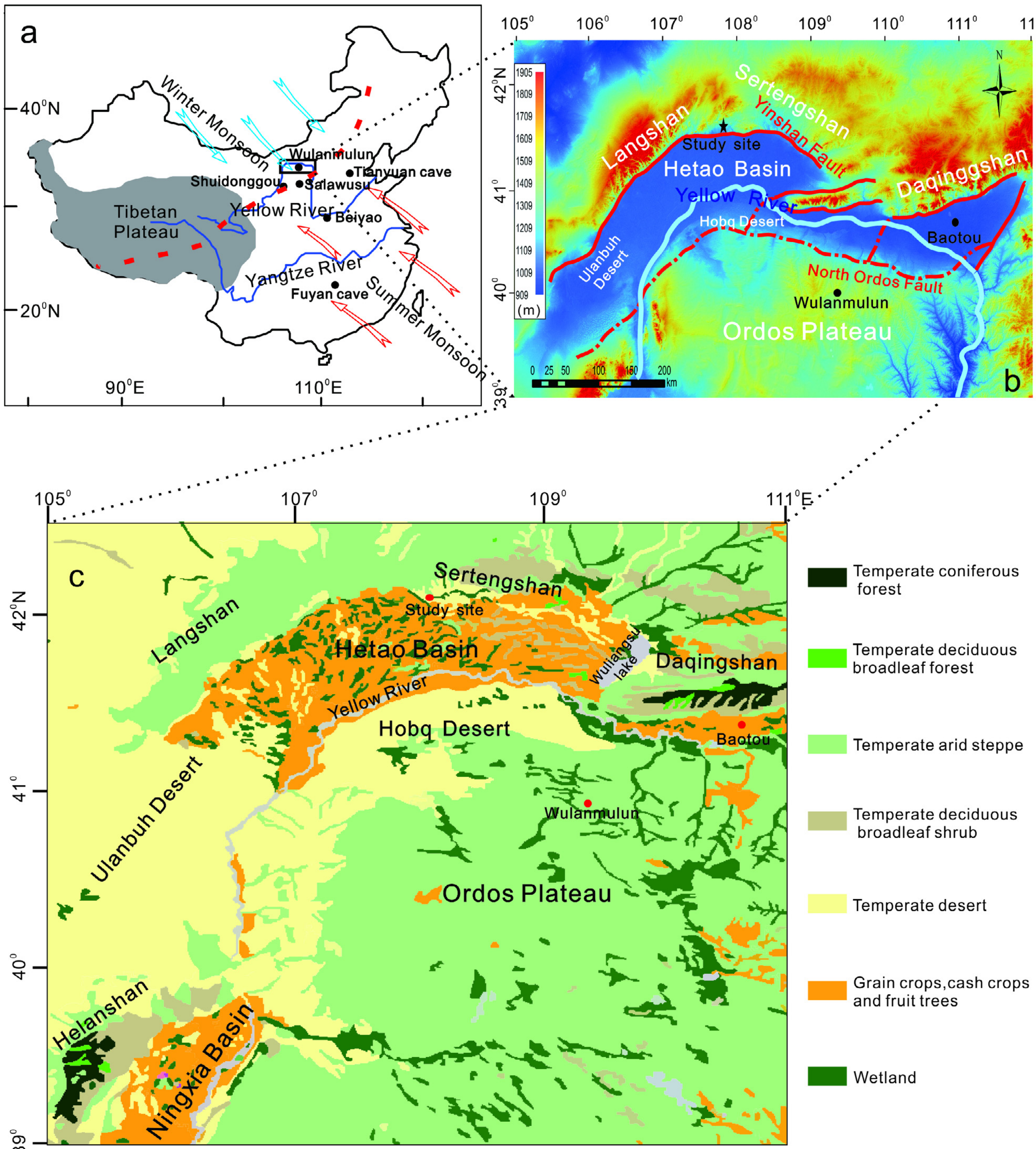

Fig. 1. a. Map of China showing some ancient human sites discussed in the text; b. Digital elevation map of the Hetao region; c. Vegetation map of the Hetao region (Revised from the Vegetation Map of China, 2008).

south (Fig. 1). The depth of Quaternary sediments in the basin is about 1800 m (Li, 2006). The Yellow River flows eastward along the southeast margin of the basin. The Ulan Buh Desert and Hobq Desert are distributed to the southwest and south in the basin (Fig. 1b). This is a transition area from semi-arid to arid with average annual temperature and precipitation ranging from 5.6 to 7.8 °C and 130 to 215 mm, respectively (Guo et al., 2008). More than 70% of the yearly precipitation falls in summer. The Hetao Basin, located on the junction between steppe and desert vegetation zone, contains vegetation which is sensitive to climate change. The modern vegetation of the Hetao Basin is a desert steppe type, characterized by herbs and shrubs, including *Stipa tianshanica, Stipa glareosa, Artemisia frigida, Aneurolepidium chinense, Salsola passerine, Filifolium sibiricum, Lespedeza davurica, Leymus secalinus, Artemisia scoparia, Hippophae rhamnoides,* and *Rosa hugonis*. In addition, there are patches of forest distributed on the surrounding mountains and these are mainly dominated by *Pinus, Picea, Ulmus,* and *Populus* (Editorial Board of China's Physical Geography, 1985). The composition and distribution of modern vegetation in this region is mainly affected by precipitation and soil moisture (Wang et al., 1996).

The Bingfanggou section belongs to the first terrace of the northern side of the Hetao Basin (41°17′22.80″N, 107°47′14.42″E) as shown in Fig. 1. The section is 17-m thick and divided into five parts according to distinct lithologic characteristics (Fig. 2). The top portion (Unit 1, the surface to 2.51 m) consists of massive, clast-supported conglomerates

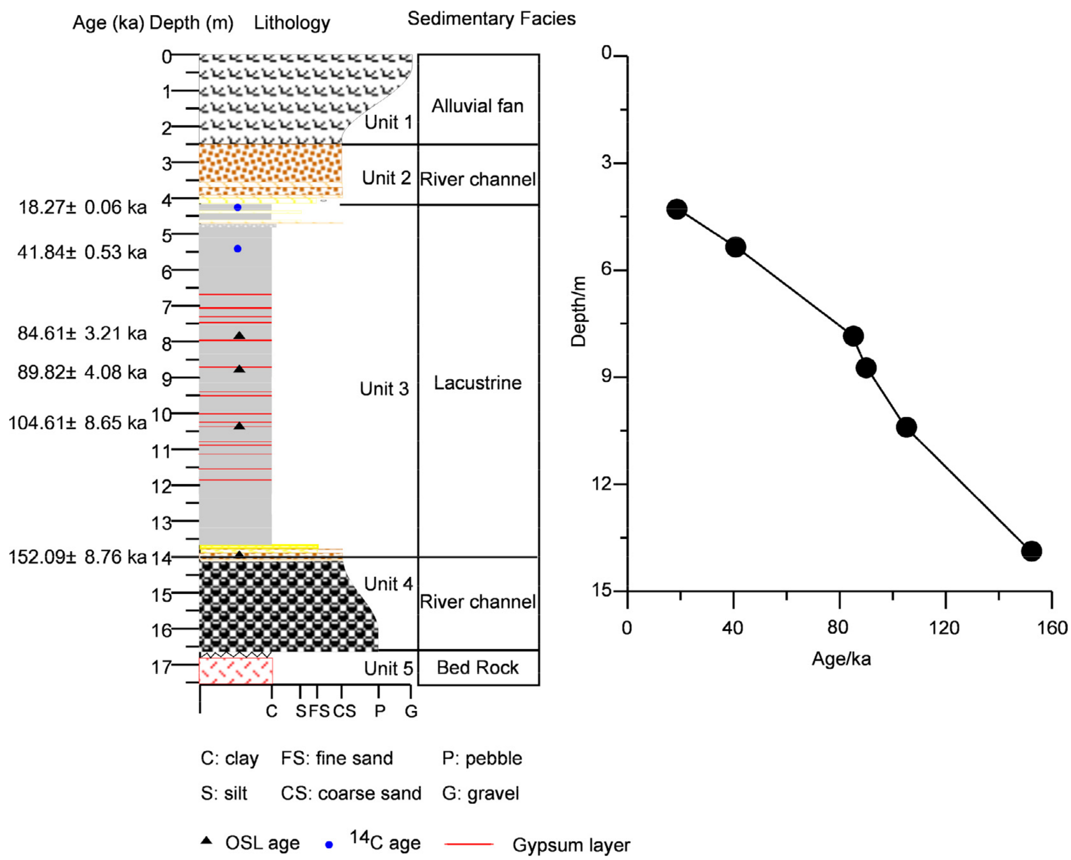

Fig. 2. Lithology, OSL and ^{14}C dating, sedimentary facies and age-depth model of the Bingfanggou section (Revised from Yang et al., 2018).

(Yang et al., 2018). Unit 2, 2.51–4.05 m, is gray coarse sand with cross bedding. Unit 3, 4.05–13.88 m, is laminated carbonate-rich silty clay, with gypsum layers. Unit 4, 13.88–16.66 m, consists of well-sorted pebbles and interbedded gray sand. The lower portion (Unit 5, 16.66-? m) is a compacted brown red mud bedrock. This study focused on the lacustrine sediment portion (Unit 3) of this section (Fig. 2).

3. Materials and methods

The chronological sequence of the Bingfanggou sections was established by Yang et al. (2018). Ages of the lacustrine sediment strata were determined using AMS^{14}C and OSL dating techniques (Yang et al., 2018) (Fig. 2). Thus, the ages of the lacustrine sediment strata spanned from 151.2 to 17.2 ka BP. The age of each pollen sample was calculated based on linear interpolation. A total of 94 samples were collected at 20-cm intervals for pollen and spore analysis throughout the section. Sediment (30–50 g per sample) was used for pollen and spore analysis. The preparation process followed the palynological procedures described by Moore et al. (1991). The samples were initially treated with 10% HCl, 39% hydrofluoric acid, and 5% K_2CO_3 to remove carbonates, silicates, and humic substances, respectively. The material remaining after the acid digestion was subjected to heavy liquid floatation with a $ZnBr_2$ solution (gravity between 1.8 and 2.0). All of the samples were concentrated with a centrifuge and washed with distilled water after each step. Finally, the prepared specimens were stored in glycerol and microscopically identified at 400 × and 600 × magnification. All of the samples were identified at the Institute of Geomechanics, Chinese Academy of Geological Sciences based on published pollen plates (Xi and Ning, 1994; Wang et al., 1995) and modern pollen slides.

4. Results

The 94 samples were analyzed and at least 200 pollen grains from each sample originating from terrestrial plants were identified. A total of 53 types of sporopollen were identified in all of the samples. The herb and shrub taxa were dominated by Chenopodiaceae, *Artemisia*, Poaceae, Sapindaceae, *Ephedra, Nitraria,* Asteraceae, Ranunculaceae, *Elaeagnus,* Polygonaceae, and Caryophyllaceae, as well as other taxa with low percentages. The main arboreal taxa were *Pinus* and *Picea* with frequent occurrences of *Betula, Juglans, Ulmus,* and *Quercus*. Aquatic taxa and pteridophyte spores, such as those from *Typha*, Cyperaceae, *Myriophyllum,* and *Selaginella*, were also identified. The most common 19 families and genera selected are shown in Fig. 3. The percentages of tree, shrub, and herb pollen taxa were calculated based on the terrestrial pollen sum of each sample. The pollen assemblage was characterized by a high percentage of herb and shrub taxa (mean 74.7%) and a low percentage of tree taxa (mean 25.3%). The non-arboreal pollen assemblages were dominated by Chenopodiaceae (mean 31.6%), *Artemisia* (mean 24.9%), and Poaceae (mean 4.7%). The arboreal pollen assemblages were primary *Pinus* (mean 21.9%) and *Picea* (mean 2.4%). The percentages of broadleaf taxa were mostly less than 1.0%. The pollen concentration of samples ranged from 102.8 to 1012 grains/g. The ratio of *Artemisia* (A) to Chenopodiaceae (C) ranged from 0.25 to 2.53. The ratio of arboreal pollen (AP) to nonarboreal pollen (NAP) ranged from 0.03 and 1.41. Based on relative abundances of the dominant pollen taxa and variations in the A/C and AP/NAP ratios, four major zones (Zone I to Zone IV) with three subzones (Zone IVa, IVb, and IVc) were divided during the late Pleistocene from bottom to the top (Fig. 3). The detailed description of vegetation zone is described below.

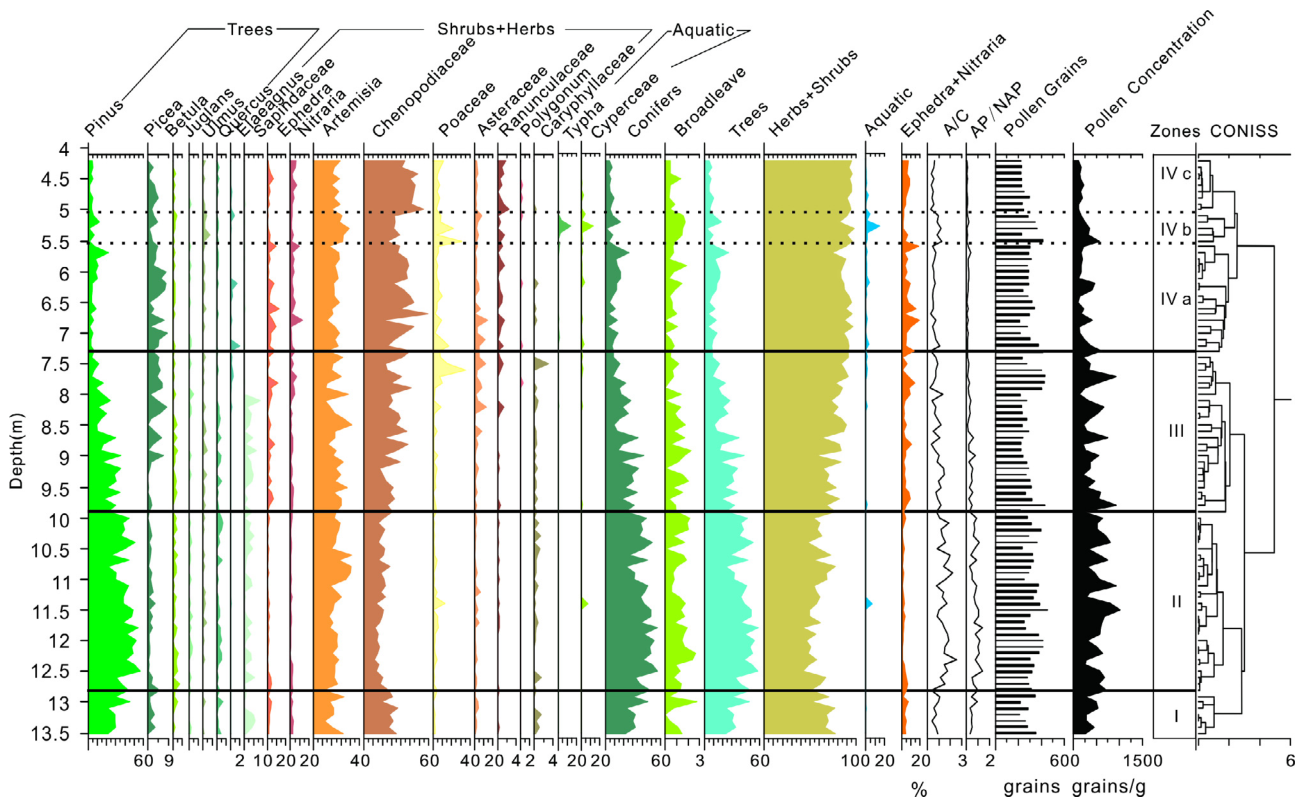

Fig. 3. Main pollen percentage diagram for the Bingfanggou sequence plotted against the depth.

4.1. Zone I (13.5–12.7 m, 146.8–135.9 ka BP)

In the oldest part of the time sequence record, arboreal pollen taxa, mainly derived from conifers *Pinus* and *Picea,* accounted for 22.9–50% (mean 33.9%). *Pinus* ranged from 21.5% and 45% (mean 31%) and *Picea* ranged from 0 and 5.1% (average 1.9%). Taxa of deciduous broadleaved trees had low abundances (mean 0.99%) and included *Quercus, Betula, Juglans* and *Ulmus*. Nonarboreal pollens accounted for 50–77.1% (mean 66.1%) of the total and were dominated by Chenopodiaceae and *Artemisia*. The abundances of Chenopodiaceae and *Artemisia* ranged from 18.8% to 36.4% (mean 29.1%) and 9.9% to 33% (mean 21.1%), respectively. Sapindaceae, Asteraceae, *Ephedra, Nitraria,* and Poaceae occurred at moderately high percentages (averaging 4.4%, 2.8%, 2.3%, 1.9%, and 1.9%, respectively). Other shrubs and herbs appeared with low and erratic percentages. These included Lamiaceae, Caryophyllaceae, Brassicaceae, Rosaceae, Euphorbiaceae, Solanaceae, Ranunculaceae, and Rubiaceae. The AP/NAP ratio ranged between 0.3 and 1 with a mean of 0.55.

4.2. Zone II (12.7– 9.9 m, 135.9–100.4 ka BP)

Zone II was characterized by a steady increase in the arboreal taxa pollen content (range 22.6–58.5%, mean 42.8%), while nonarboreal type pollen decreased to a mean of 57.2% (range 41.5–77.41%). The pollen contents of coniferous *Pinus* increased to a mean of 40.4% (range 21.2–56.2%) and reached the highest values through the entire sequence. The deciduous broadleaved trees, mainly consisted of *Quercus, Betula, Juglans, Ulmus, Carpinus,* and Oleaceae, increased to a higher mean (1.4%) than Zone I. In contrast, *Picea* declined to an average of 1%. Nonarboreal taxa remained dominated by *Artemisia* which slightly increased compared with Zone I and ranged from 16.8% to 41.5% (mean 25.9%). Poaceae also increased in Zone II, ranging from 0 to 12.5% (mean 2.5%). The xerophytic plants represented by Chenopodiaceae (10.8–30.4%, mean 18.9%), *Ephedra* (mean 1.1%) and *Nitraria* (mean 0.9%) all markedly decreased. Sapindaceae (mean 4.4%) and Asteraceae (mean 2.8%) maintained the same percentages compared with Zone I. Other mesic and arid herbs with low and erratic percentages, including Solanaceae, Caryophyllaceae, Rosaceae, *Elaeagnus*, Ericaceae, Lamiaceae, Brassicaceae, Euphorbiaceae, Ranunculaceae, and Thalictrum appeared occasionally. Hydrophilous Cyperaceae was present in one sample with a high (7%) percentage.

4.3. Zone III (9.9–7.3 m, 100.4–75.4 ka BP)

Zone III was marked by a large increase in nonarboreal taxa pollen contents (range 56.5–91.5%, mean 77%). This was mainly attributed to Chenopodiaceae (range 17–51.4%, mean 31.8%) increase, while *Artemisia* (range 12.9–41.6%, mean 25.3%) slightly decreased. Sapindaceae (mean 4.1%) and other xerophytic herbs and shrubs including Asteraceae (mean 4.8%), *Ephedra* (mean 2.9%), and *Nitraria* (mean 2.1%) all showed significant increase compared with the values of Zone II. Poaceae also increased to a mean of 4.8% in this zone. Hydrophilous Cyperaceae was present in some samples with a mean of 0.27%. Arboreal taxa remained dominated by *Pinus* and *Picea*, the former ranging from 3.7 to 35.6% (mean 18.3%) and the latter ranging from 0 to 8.2% (mean 2.9%). The deciduous broadleaved trees, mainly consisting of *Quercus* and *Betula,* decreased to means of 1%. Other broadleaved trees, such as *Juglans, Ulmus,* and *Carpinus,* were present in only a few samples.

4.4. Zone IV (7.3–4.2 m, 75.4–17.2 ka BP)

In general, Zone IV was dominated by nonarboreal pollen (range 73.8–97.3%, mean 91.0%), mainly consisting of Chenopodiaceae (mean 42.5%) and *Artemisia* (mean 26.5%). Arboreal pollen ranged from 2.7% to 26.2% (mean 9.0%). The xerophytic taxa, including Asteraceae (mean 5.1%) and *Nitraria* (mean 2.9%), all displayed an increased trend. Poaceae (mean 8.9%), Cyperaceae (mean 1.9%) and *Typha* (mean 1.4%) also markedly increased compared with their values in Zone III. *Pinus* (mean 5.3%) dominated arboreal pollen taxa and decreased, while *Picea* (mean 2.8%) slightly increased. Deciduous broadleaved trees pollen decreased or occurred only sporadically.

Based on the variations of the pollen assemblages, Zone IV can be divided to three subzones. Subzone IVa (7.3–5.5 m, 75.4–43.6 ka BP) was dominated by the shrubs and herbs taxa (range 73.8–96.4%, mean 88.3%), especially Chenopodiaceae. Chenopodiaceae pollen displayed a large increase (range 19.2–69.2%, mean 42.9%), while *Artemisia* pollen decreased to a mean of 23.0% (range 13.7–28.2%). The xerophytic plants, such as Asteraceae (mean 5.5%), *Ephedra* (mean 4.4%), and *Nitraria* (mean 3.5%) all markedly increased. Poaceae and Cyperaceae also increased in this subzone, the former ranging from 1.9 to 16.9% (mean 6.0%) and the latter from 0 to 3.8% (mean 0.8%). Sapindaceae showed an abrupt decrease with a mean of 0.2%. Hydrophilous *Typha* started to frequently appear. The arboreal pollen taxa, mainly derived from *Pinus* (mean 6.6%), showed significant decline to a mean of 11.7%. However, *Picea* increased to a mean of 4.3% compared to values in Zone III. The deciduous broadleaved tree pollen in this subzone, including *Quercus, Betula, Ulmus,* and *Juglans* were present in only a few samples.

Subzone IVb (5.5–5.0 m, 43.6–33.6 ka BP) was characterized by a marked increase in *Artemisia* (range 31–38.8%, mean 32.4%), while Chenopodiaceae decreased to a mean of 32.4% (range 25.2–38.3%). The abundances of Poaceae (mean 14.6%) increased in this subzone. Hydrophilous Cyperaceae and *Typha* also increased with the former fluctuating between 0 and 14.6% (mean 4.4%) and the latter ranging from 0 to 13.4% (mean 3.9%). In contrast, the xerophytic shrubs, including *Ephedra* (mean 1.5%) and *Nitraria* (mean 1.5%), significantly decrease. The arboreal taxa (range 2.7–18.3%, mean 9.0%) showed a gradual decline, dominated by *Pinus* (mean 5.5%) and *Picea* (mean 2.0%). However, the deciduous broadleaved tree pollen, mainly dominated by *Ulmus* (mean 0.7%), had a significant increase to a mean of 1.4%.

Subzone IVc (5.0–4.2 m, 33.6–17.2 ka BP) had a large increase in Chenopodiaceae pollen (range 40.6–64.6%, mean 52.3%), which reached the highest mean value through the whole sequence. Other xerophytic shrubs, such as *Ephedra* (mean 2.2%) and *Nitraria* (mean 3.6%), also showed large increases, while *Artemisia* (mean 24.1%) decreased. Poaceae (mean 6.1%) and Cyperaceae (mean 0.5%) decreased and *Typha* was not found in this subzone. The arboreal taxa (range 4.1–10%, mean 6.4%) showed a continuous decline that was dominated by *Pinus* (mean 3.8%). *Picea* (mean 2.0%) had a percentage similar to Zone IVb. Deciduous broadleaved tree pollen was scarce or absent.

5. Discussion

5.1. Ecological and climatic interpretations of pollen

Sugita (1994) suggested that the pollen from lacustrine deposits is mostly from the whole lake basin catchment. The pollen record achieved from the lacustrine sediment can be used to reconstruct the evolution of regional vegetation (Cai et al., 2012). Our study provides the first detailed pollen record from the late Pleistocene in Hetao Basin of Inner Mongolia. The vegetation and climate changes in the region were reconstructed based on the pollen record during the late Pleistocene. Generally, *Pinus* pollen is more easily transported over long distances by wind and water. Thus, *Pinus* pollen seems to be over-represented relative to other parent plants (El-Moslimany, 1990). Although *Pinus* is well-known for its extra representation (Li and Yao, 1990), contributions greater than 30% of the total pollen sum suggest relatively high levels of this taxon in this region (Tong et al., 1996; Wang et al., 1996). Ma et al. (2008) concluded that modern *Pinus* pollens in the Mongolia plateau are derived from pine trees growing in the surrounding mountains. These pine tree species are well adapted to the humid mountain habitat (Zhu, 1987; Wu et al., 2007; Cai et al., 2013). Compared with *Pinus*, *Picea* occupies relatively narrower ecological conditions and a colder climate based on terrestrial records in East Asia (Lü et al., 2004). *Artemisia* and Chenopodiaceae usually grow in arid or semiarid habitats (Li and Yan, 1990). The pollen ratio of *Artemisia* to Chenopodiaceae (A/C) can be used as a humidity indicator in semiarid/arid regions. Higher A/C ratios indicate moisture increases in the region (Tarasov et al., 1997; Li et al., 2005; Cai et al., 2012). *Ephedra* and *Nitraria* are typical xerophytic plants often used as indicators of dry climates (Herzschuh et al., 2004; Li et al., 2005). *Typha* and Cyperaceae generally grow along the edges of water bodies. In our pollen record, Poaceae pollen is associated with the occurrences of *Typha* and Cyperaceae, suggesting that the Poaceae pollen is possibly derived from *Phragmites*. High arboreal pollen (AP)/nonarboreal pollen (NAP) values are usually regarded as a proxy for humidity (White et al., 1997; Wu et al., 2011). The modern natural vegetation of the Hetao Basin is characterized as a desert steppe type. Mixed forest dominated by pine and spruce is distributed on the Daqingshan east of Hetao Basin and on the Helan Mountains ca. 300 km west of the Hetao Basin. Hence, the preserved coniferous pollen of the Hetao Basin was probably transported from nearby mountains by wind or Yellow river. Based on the pattern of modern vegetation distribution in the Hetao Basin, the dominant shrub and herb pollen in our records, such as Chenopodiaceae, *Artemisia*, Asteraceae, *Ephedra,* and *Nitraria,* mainly grew in the basin. The tree pollen was mainly derived from the forests in the surrounding mountains. Poaceae, Cyperaceae, and *Typha* generally grew along the lakeshore. Thus, the pollen record could reflect the regional evolution of vegetation communities and climate change in the Hetao Basin.

5.2. Regional ecological and climatic change and implications for ancient human evolution

Based on the sporopollen diagrams and climatic index records, we reconstructed the vegetation and climate change in the Hetao Basin during the late Pleistocene. Between 147 and 136 ka BP (late MIS 6), the high percentages of *Pinus* (> 30%) indicated that this tree was present in the Hetao Basin region. During this period, the percentage of other tree pollen was usually less than 5%. Thus, the *Pinus* pollen might have been mostly derived from the surrounding mountains. The significant representation of Chenopodiaceae and *Artemisia* suggest that desert steppe vegetation occupied the basin. Therefore, the pollen results indicate that the Hetao Basin was covered by an open forest-steppe during the end of the penultimate glacial. The higher A/C and AP/NAP ratio values suggest that the level of precipitation was appropriate for open forest-steppe vegetation during the period from 147 to 136 ka BP (Fig. 3).

Subsequently, from 136 to 100 ka BP (MIS 5e-c), the arboreal species pollen rapidly increased, manifested by *Pinus* (Fig. 4). The rapid expansion of *Pinus* could indicate the extent of forest increased in the surrounding mountains. At the same time, deciduous broadleaves (mainly *Quercus, Betula,* and *Juglans*) gradually spread to lower elevations. The high percentages of *Artemisia* suggest that a steppe covered the basin. The pollen results indicate that the study area was covered by forest-steppe between 136 ka BP and 100 ka BP. The highest A/C and AP/NAP values with an increase in the broadleaved trees suggest that the climate was warm and wet at the beginning of the interglacial. Additional support for optimal climatic conditions at this time is derived from the highest pollen concentration (Fig. 3). The highest lake level during this period also indicates a humid climate (Yang et al., 2018).

The transition from about 100 ka to 75 ka BP (MIS 5b-a) shows a rapid increase in nonarboreal pollen, dominated by Chenopodiaceae and *Artemisia*. This indicates an expansion of desert steppe plant communities in the Hetao Basin. At this time, the significance of *Pinus* and deciduous broadleaved trees decreased and indicated reduced forest coverage. Thus, the pollen results show that the vegetation type in the Hetao Basin changed to an open forest-steppe during the transition period. The decrease in the A/C and AP/NAP values implies that the

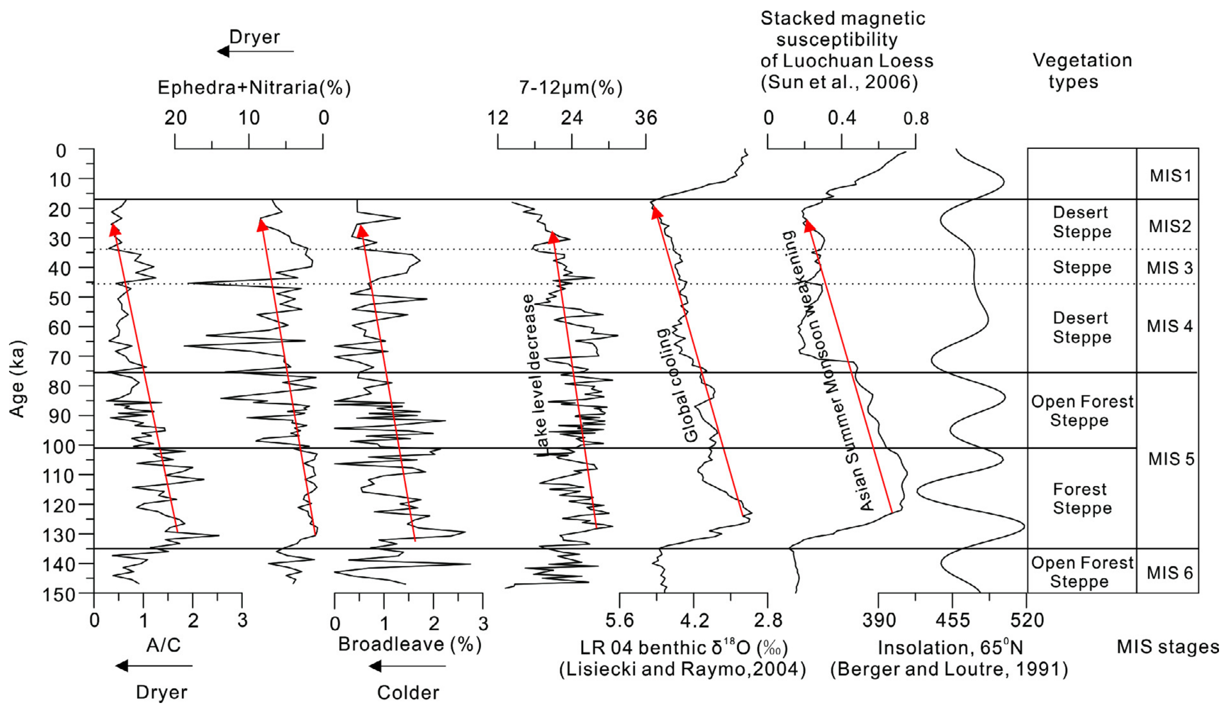

Fig. 4. The A/C ratio, xerophytic pollen percentage (sum of *Ephedra* and *Nitraria*), broadleave trees percentage, 7–12 μm grain size percentage (Yang et al., 2018), and vegetation types in the Bingfanggou section. These data are compared with records from LR04 (Lisiecki and Raymo, 2005), the stacked magnetic susceptibility of Luochuan Loess (Sun et al., 2006); Insolation variation of 65°N (Berger and Loutre, 1991).

climate became drier during this period. The increased percentages of the xerophytic *Ephedra* and *Nitraria* also indicate a dryer climate. An increased percentage of *Picea* suggests that temperatures declined during this period (Fig. 3).

From 75 to 17 ka BP (MIS 4-2), the high percentages of nonarboreal pollen (mean 91.0%) indicate that herbaceous communities dominated the Hetao Basin. The highest proportion of Chenopodiaceae and *Artemisia*, as well as higher abundance of xerophytic shrubs, such as *Ephedra* and *Nitraria*, indicates that a Chenopodiaceae – *Artemisia* desert steppe covered the basin. From 75 ka BP, the lowest A/C and AP/NAP ratio values with the abundance of drought tolerant herbs and shrubs indicate that the climate changed to extremely dry conditions. The high abundance of hydrophilous pollen probably reflects a large area of marsh resulting from a drop in the lake level. An increase of *Picea*, as well as scarce deciduous broadleaves, suggests that the climate was cold during this period. However, from 44 to 34 ka BP, the relatively high A/C and AP/NAP values with increased *Ulmus* support a humid and warm climatic event (MIS 3) (Fig. 3).

The detailed pollen record reveals that vegetation cover changed from forest-steppe to desert steppe in the Hetao Basin from the last interglacial to glacial periods, with a typical steppe recovering during MIS 3. Trends of vegetation cover decline based on pollen records from other parts of the Hetao Basin and nearby regions support our interpretations. At the Baotou in the east of Hetao Basin, detailed pollen records demonstrated that forest-steppe, dominated by *Pinus* and *Artemisia,* covered this area during the last interglacial and then changed to desert steppe or steppe during the last glacial (Li et al., 2007). The pollen record in Ningxia Basin indicated that the vegetation changed from coniferous forest to steppe during the late Pleistocene (Yang et al., 2001). The records of pollen and $\delta^{13}C$ on the Chinese Loess Plateau also suggested that forest-steppe covered the CLP during the last interglacial periods and was then replaced by the steppe during the last glacial (Sun et al., 1995, 1996; Jiang et al., 2002; Cai et al., 2013). At Salawusu southeast of the Ordos Plateau, the vegetation changed from forest or forest-steppe between 152 and 72 ka BP to steppe during 72–38 ka BP (Yang, 2013). Thus, the forest or forest-steppe changed to steppe or desert steppe from the last interglacial to glacial periods in Hetao Basin and its surrounding area. The trend of reduced vegetation cover revealed by the pollen record indicates a long-term of climate drying and cooling since the last interglacial. The decreasing lake level between 130 and 17 ka BP suggested by the grain size and carbon isotopes from the same section also indicated a drying climate and supports the pollen record (Yang et al., 2018). A paleolake probably existed between ~150 and 90 ka BP, and then changed to a desert in the Ulan Buh Desert and Hobq Desert area (Chen et al., 2013; Li et al., 2015). The climate drying trend from the last interglacial to glacial periods has also been reported in other sites of North and East China, such as the Chinese Loess Plateau (An et al., 1991; Xiao et al., 1995; Ding and Liu, 1998), Salawusu (Li et al., 2000), Baikal Lake (Shichi et al., 2007), and North West Pacific off the eastern Japan (Sugaya et al., 2016). However, the pollen record indicates that a steppe appeared with a humid and warm climatic event between 44 ka and 34 ka BP. This is consistent with pollen records from areas surrounding the Hetao Basin. During MIS 3, the steppe has covered the Jilantai region on the west of the Hetao Basin (Zhang, 2015). Based on dominant herbivores, Nie et al. (2008) suggested that the steppe covered the Hetao Basin during 40–22 ka BP. At the Wulanmulun site, about 100 km southeast of our study section, detailed pollen records indicated the steppe dominated this area during MIS 3 (Li et al., 2014). Thus, relatively warm-humid conditions were revealed by the pollen record between 44 and 34 ka BP during the dry-cold glacial period. These data are also consistent with other studies in Northwest China (Lehmkuhl and Haselein, 2000; Yang et al., 2004; Yang and Scuderi, 2010; Jiang et al., 2011).

Ancient human remains from the last glacial have been found in areas surrounding the Hetao Basin. Hou et al (2012) found many stone artifacts from Wulanmulun in the northern part of the Ordos Plateau, dating ca. 43 ka BP. Shuidonggou in Ningxia has an Upper Palaeolithic sequence from ca. 40 ka BP (Gao et al. 2013). An ancient human scapula fossil from Salawusu was dated at 35.34 ± 2 ka BP (Shang et al., 2006). Ancient human fossils from the Tianyuan Cave in Beijing appeared to be from 40 to 27 ka BP (Chen et al., 1992; Shang et al., 2007).

Data from the North China Plain, Chinese Loess Plateau, and the southern margin of Mongolia indicated that ancient humans probably entered this region during ca. 40 ka BP. This was about the same time as ancient humans entered the Europe Plains (Gao and Dennell, 2014). Both areas were comparable in climate type and had a grassland vegetation in milder periods during the last glacial. The paleoenvironment in both areas at the time appeared suitable for ancient human habitation. Abundant herbivores in the Hetao area (Nie et al., 2008; Hou et al., 2012) provided food for ancient humans living in the area between 40 ka and 30 ka BP. Thus, the steppe ecosystem with greater biomass could have provided abundant food for these ancient human hunter societies.

Fig. 4 shows that the climatic change trend reconstructed by indexes (A/C and AP/NAP) in the Hetao Basin during the late Pleistocene was consistent with the global cooling trend (Lisiecki and Raymo, 2005) induced by variation in northern insolation (Berger and Loutre, 1991). The insolation variations and global ice volume resulted in the intensity variation of the East Asian monsoon (Ding and Liu, 1998; Sun et al., 2006, Tian et al., 2017, Fig. 4). During the last interglacial (between ~136 ka BP and ~75 ka BP) and the interstadial of the last glacial (~44 ka BP to ~34 ka BP), the increased summer insolation enhanced the East Asian summer monsoon and this brought more precipitation from the Pacific Ocean to the interior of East Asia (Passey et al., 2009). During MIS 4 (from 75 to 44 ka BP) and the MIS 2 (from 34 to 17 ka BP), the global cooling due to low insolation reduced the precipitation in the interior of East Asia. Meanwhile, the expansion of polar ice sheets and mountain glaciers strengthened the Siberia High, which intensified the winter winds and induced aridification of Inner Mongolia and the Chinese Loess Plateau (Ding et al., 1998; Liu et al., 1999; Sun et al., 2006; Tian et al., 2017).

6. Conclusions

The pollen record from Hetao Basin allowed for the reconstruction of the vegetation history from the last interglacial to glacial periods around the Ordos region, Inner Mongolia. From 147 to 136 ka BP, open forest-steppe dominated by *Pinus* and Chenopodiaceae covered the Hetao region. Then, the vegetation changed from a *Pinus* – *Artemisia* forest-steppe between 136 and 100 ka BP to a *Pinus* – Chenopodiaceae open forest-steppe between 100 and 75 ka BP. After 75 ka BP, the vegetation transformed to a Chenopodiaceae – *Artemisia* desert steppe, while an *Artemisia* steppe appeared between 44 and 34 ka BP. The steppe expanded in milder periods during the last glacial in the Hetao region and the region was suitable for herbivores that could have provided food resources for ancient humans. The vegetation changing from forest-steppe to steppe indicated an increased drying and cooling trend in the Hetao Basin during the last Pleistocene. This is consistent with climatic records from other East Asian Monsoon regions, suggesting a global response to the decrease of the northern insolation variations and an increase of global ice volume from the last interglacial to glacial periods.

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Appendix A. Supplementary material

Supplementary data to this article can be found online at https://doi.org/10.1016/j.jseaes.2018.11.024.

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