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Vegetation and climate changes in the western Chinese Loess Plateau since the Last Glacial Maximum

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ABSTRACT

Pollen analysis was conducted for loess deposits from three sites in the western Chinese Loess Plateau, i.e. the loess area west of the Liupan Mountains. Results show that during the Last Glacial Maximum (LGM), in-situ vegetation was dominated by *Artemisia* and some drought–tolerant species such as *Echinops*-type, Chenopodiaceae, *Nitraria*, and *Ephedra*, while coniferous forest (mainly *Picea*) flourished in nearby river valleys. During the Holocene Optimum, *Picea* almost disappeared, and *Echinops*-type, Chenopodiaceae, *Nitraria* and *Ephedra* decreased; vegetation was characterized by *Artemisia*, *Taraxacum*-type, Polygonaceae and Leguminosae, implying the climate was warmer and wetter than during the LGM. During the late Holocene, Chenopodiaceae, indicator of human–managed habitats, increased in the study area, indicating enhanced human activity.

The climate was warmer and more humid in the loess areas east of the Liupan Mountains than in the west during both the LGM and Holocene Optimum. Likewise, a significant difference in specific plant types was observed between the east and west since the LGM. During the LGM, *Pinus* and some broadleaf trees emerged, but no *Picea* forest grew, while in the west, vegetation was characterized by desert shrub and desert steppe in situ, and by dark coniferous forests (mainly *Picea*) in nearby river valleys. During the Holocene Optimum, treeline advanced upward as a result of increased temperature. *Picea* thus withdrew from the western loess areas. Therefore, temperature is the major factor controlling the growth of *Picea* in the Chinese Loess Plateau.

1. Introduction

Over the last 20,000 years, the Earth has experienced a cold extreme (the Last Glacial Maximum: LGM) and a warm period (the Holocene Optimum). Ecological responses to these climatic extremes are useful in facilitating our understanding for climate changes and mechanisms. The Chinese Loess Plateau, characterized by an arid and semi–arid climate, is sensitive to climate changes (Chen et al., 1997; Ding et al., 1999; An, 2000). Therefore, knowledge of natural vegetation during typical cold and warm periods in the Loess Plateau, can not only help us to understand past climate and environmental changes, but also to forecast future trends of climate change and to provide a good reference for ecological management (Jiang et al., 2013).

Vegetation on the Loess Plateau is a long–debated topic. Some researchers insisted that forests developed on the Loess Plateau based on the historical documents (Shi, 1991). However, according to studies of phytoliths (Lü et al., 1999), organic carbon isotope (Liu et al., 2005) and pollen (Ke et al., 1992; Liu et al., 1996; Sun et al., 1997, 1998; Li et al., 2003a; Jiang and Ding, 2005; Cheng and Jiang, 2011), the Loess Plateau was mainly dominated by steppe vegetation, and no dense forest was present. Recently, Jiang et al. (2013, 2014) carried on systemic vegetation studies along a north–south and an east–west transect and concluded that 1) in the Loess Plateau, most areas are covered by thick loess (>20 m) and dominated by steppe vegetation, because rainwater infiltrates quickly and moisture in the surface soil is insufficient to maintain forests; 2) trees can grow in areas of thin loess underlain by bedrocks (e.g. incipient floodplains, low river terraces and deep gullies), where the groundwater table is relatively high; 3) in rocky mountainous areas, bedrock itself can serve as a water–resistant layer which allows the surface soil to retain the rainwater, and forests thus can develop.

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To date, most pollen records on the Loess Plateau were derived from soil–loess sequences east of the Liupan Mountains. However, pollen records in loess area west of the Liupan Mountains were obtained from wetland–lacustrine–loess complex, which are all located in riparian zones of tributaries of the Yellow River (An et al., 2003; Feng et al., 2006; Sun et al., 2007; Tang and An, 2007; Wu et al., 2009). Pollen records from pure loess deposits are scarce. Therefore, two questions arise: (i) did steppe prevailed in the loess area west of the Liupan Mountains? and (ii) if so, were there any differences in specific plant types between the loess areas east and west of the Liupan Mountains?

In this study, we present pollen records from three loess sections in the western Loess Plateau (Fig. 1), with the objective of reconstructing vegetation and climate changes since the LGM and to compare spatial changes in specific plant types between the loess areas east and west of the Liupan Mountains.

2. Sites and stratigraphy

The study area is located in the western Loess Plateau, a loess area west of the Liupan Mountains (Fig. 1). It is characterized by arid and semi–arid climate, with precipitation mainly concentrated in summer. Typical modern vegetation is dry steppe and desert steppe (Editorial Committee of Vegetation Map of China, Chinese Academy of Sciences (2007)).

Three loess sections, located at Weiyuan, Huining, and Jingtai, were logged (Fig. 1). The Weiyuan section (35°08′N, 104°15′E, 2061 m a.s.l.) is situated on the terrace of the Weihe River. The Huining section (36°07′N, 104°52′E, 1911 m a.s.l.) is located on 'Yuan', a high table–land consisting of thick loess. The Jingtai section (37°06′N, 104°28′E, 1883 m a.s.l.), also on the 'Yuan', is located in the transitional zone between the Loess Plateau and the Tengger Desert. At present, the mean annual temperature and precipitation are 6.8 °C and 363 mm at Weiyuan, 8.3 °C and 332 mm at Huining, and 9.7 °C and 102 mm at Jingtai.

Fresh samples (~500 g each) were taken at 5–10 cm intervals. A total of 424 samples were collected. All sections consisted of soil unit S_0, loess unit L_{1-1} and the upper part of weakly developed soil L_{1-2}. Previous studies have shown that L_{1-2} was deposited in the late marine isotope state (MIS) 3 (~40–28 ka), L_{1-1} was deposited in the MIS 2 (~28–11 ka) which includes the LGM (~26.5–19 ka), and S_0 developed in the Holocene Optimum (~11–9–~3 ka) (Ding et al., 2002; Yang and Ding, 2004, 2014; Lu et al., 2007). For detailed stratigraphic information, please refer to Yang and Ding (2008, 2014).

3. Methods

Grain size was first measured for all samples using a SALD–3001 laser diffraction particle analyser. Ultrasonic pretreatment, with the addition of 20% $(NaPO_3)_6$ solution, was used to disperse the samples prior to particle size determination. The analytical procedures used were as detailed by Ding et al. (1999). Results showed that soil unit S_0 and the weakly developed soil L_{1-2} are consistently finer grained than loess unit L_{1-1} (Fig. 2). The correlation of the lithostratigraphy and grain size curves between sections indicates the continuity of the loess deposits.

A total of 68 samples were selected for pollen analysis (Fig. 2). Samples from the coarse–grained unit L_{1-1} represent deposition during a cold and dry glacial period, while those from the fine grained soil units (S_0 and L_{1-2}) represent deposition during relatively warm and humid interglacial intervals. Pollen grains were extracted using the heavy–liquid method (Li et al., 2006) and identified at ×400 magnification using a Nikon ECLIPSE 50i microscope. For each sample, ~150–300 pollen grains were counted (Figs. 3–5). Percentages of pollen, spores and algae were calculated relative to the sum of all land pollen counted. Pollen concentrations were calculated by adding *Lycopodium* spore tablets (Batch No. 483216) prior to chemical treatment (Berglund and Ralska-Jasiewiczowa, 1986). Pollen diagrams were drawn using the C2 program (Juggins, 2007; Wang et al., 2012).

4. Results

A total of 41 pollen types were identified in the three loess sections. The major pollen assemblages found in the loess and soil units in each loess section are detailed below.

4.1. Weiyuan section

L_{1-2}: Pollen concentration and types are low. Arboreal pollen (AP) (<5%) includes *Pinus*, *Betula* and Rhamnaceae (Fig. 3). Pollen of *Artemisia* (66%) and *Echinops*-type (21%) dominates the spectrum. Fern spores are low in abundance (~2%).

L_{1-1}: AP is as high as 18%, mainly derived from *Picea* (up to ~13%). Small amounts of *Pinus*, *Abies*, *Betula*, *Corylus*, *Carpinus*,

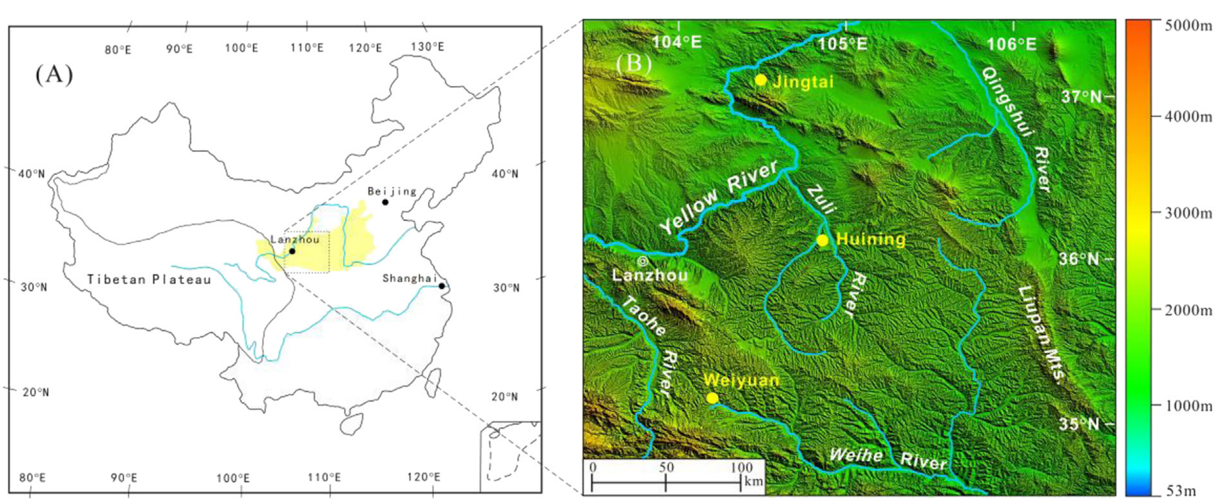

Fig. 1. Map showing location of the Loess Plateau (A) and the studied sites (circles) (B).

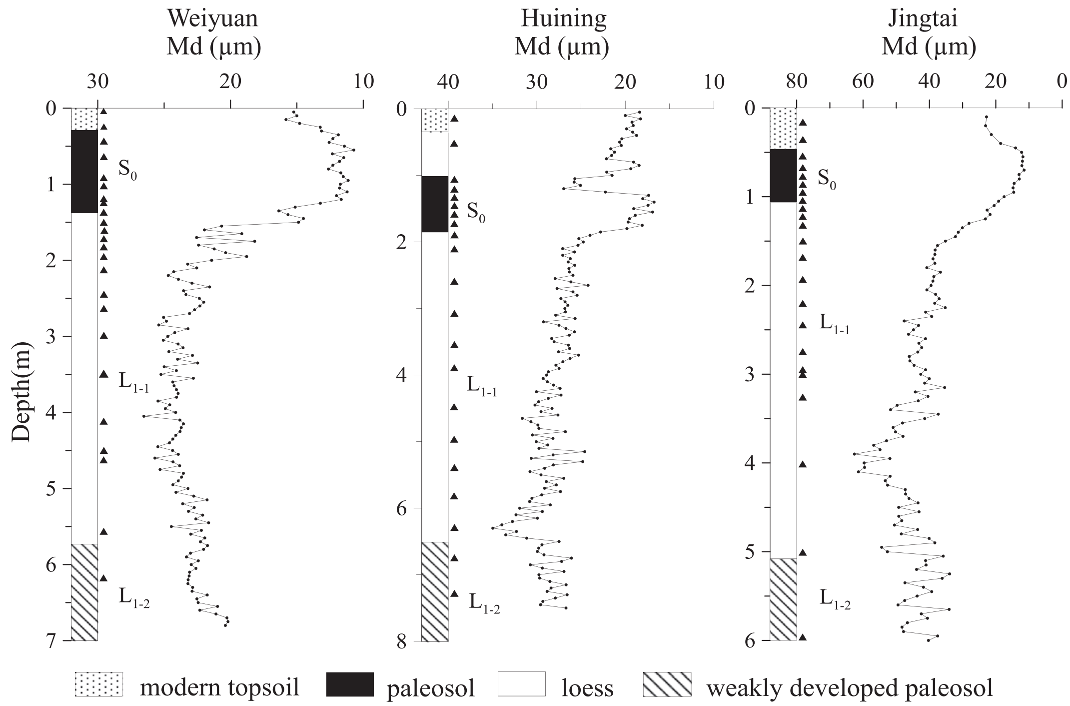

Fig. 2. Stratigraphic column and median grain size (Md) for the three loess sections. The stratigraphic positions used for pollen analyses are marked in triangles in each section.

Oleaceae and Rhamnaceae are also observed. Pollen of herbs and shrubs is dominant (84–99%), mainly consisting of *Artemisia*, *Echinops*-type, *Ephedra*, Gramineae, Chenopodiaceae, *Aster* and Leguminosae. There are a decrease in *Artemisia* pollen and an increase in pollen of *Ephedra* and *Echinops*-type around the depth of 4 m. Polypodium spores also emerge.

S_0: Pollen concentrations increase. AP (<4%) is low. Conifers almost disappear, while deciduous broadleaved trees such as *Quercus* and Oleaceae slightly increase. Pollen of herbs and shrubs increases due to rises in *Artemisia*, *Taraxacum*-type, and Cruciferae. Ferns are rare (<3%).

Modern topsoil: pollen concentrations increase significantly. AP remains low (~4%). Pollen of herbs and shrubs dominates the spectrum. *Artemisia* pollen decreases and Chenopodiaceae pollen increases. Ferns are still rare.

4.2. Huining section

L_{1-2}: Pollen concentrations and types are low (Fig. 4). AP (4–9%) includes *Picea*, *Tsuga*, *Corylus*, *Betula*, *Abies* and *Juglans*. *Artemisia* is predominant (87–95%). Gramineae, *Ephedra*, Chenopodiaceae, *Aster* and Cruciferae occur in very small amounts.

L_{1-1}: AP (2–28%) is mainly derived from *Picea* (as high as 24%). Other AP types include *Pinus*, *Abies*, *Tsuga*, *Betula*, *Corylus* and Rosaceae. *Artemisia* pollen (64–93%) dominates the spectrum. There are three peaks in Chenopodiaceae pollen content. Other pollen types of herbs and shrubs, such as Gramineae, *Ephedra*, *Aster*, *Echinops*-type, Solanaceae, Leguminosae, *Nitraria*, Polygonaceae and Umbelliferae, also appear.

S_0: Pollen concentrations increase. AP decreases to <2%, mainly because of decreases in conifers. Herbs and shrubs increases in both abundance and diversity. *Artemisia* pollen decreases from 92% to 74%. Pollen of Chenopodiaceae, *Aster*, *Echinops*-type, *Taraxacum*-type, *Ephedra*, *Nitraria* and Cruciferae increases.

Modern topsoil: AP (1–7%) slightly increases, mainly *Pinus*, *Picea* and *Ulmus*. *Artemisia* pollen decreases to ~70%. Pollen of *Ephedra*, *Echinops*-type and *Nitraria* increases. Other herbs and shrubs, such as *Aster*, *Taraxacum*-type, Cruciferae, Gramineae and Polygonaceae, also occur.

4.3. Jingtai section

L_{1-2} and L_{1-1}: The AP, as high as 23%, is mainly derived from *Picea*, *Pinus*, *Abies* and *Tsuga* (Fig. 5). Pollen of deciduous broadleaved trees such as *Betula*, *Corylus*, *Juglans*, Oleaceae and *Ulmus* is present in very low incidence. Pollen of herbs and shrubs consists of *Artemisia*, *Echinops*-type, Chenopodiaceae, Gramineae, *Ephedra* and *Aster*. Ferns are rare.

S_0: Pollen concentrations increase. The AP, including *Betula* and *Corylus*, drops to <1%. *Artemisia* pollen ranges from 81% to 93%. Other herbs and shrubs include *Taraxacum*-type, *Ephedra*, *Aster*, *Nitraria* and *Thalictrum*.

Modern topsoil: The AP is rare (<1%). *Artemisia* pollen shows a reverse variation trend with Chenopodiaceae pollen. The former drops to ~71% and the latter increases to ~20%. Pollen of *Ephedra*, *Taraxacum*-type, Polygonaceae, *Aster*, *Echinops*-type, *Nitraria* and *Sparganium* is also observed.

5. Discussion and conclusions

5.1. Vegetation and climate in the loess area west of the Liupan Mountains since the LGM

Pollen results show that steppe vegetation, characterized mainly by *Artemisia*, prevailed on the loess area west of the Liupan Mountains during the LGM and the Holocene Optimum. However, compositions of the floras changed significantly from the cold to the warm period.

During the LGM, low pollen concentrations indicate low vegetation coverage. Although a certain amount of pollen of coniferous and broadleaved trees emerge, the pollen assemblages are mainly dominated by *Artemisia*, together with other significant pollen

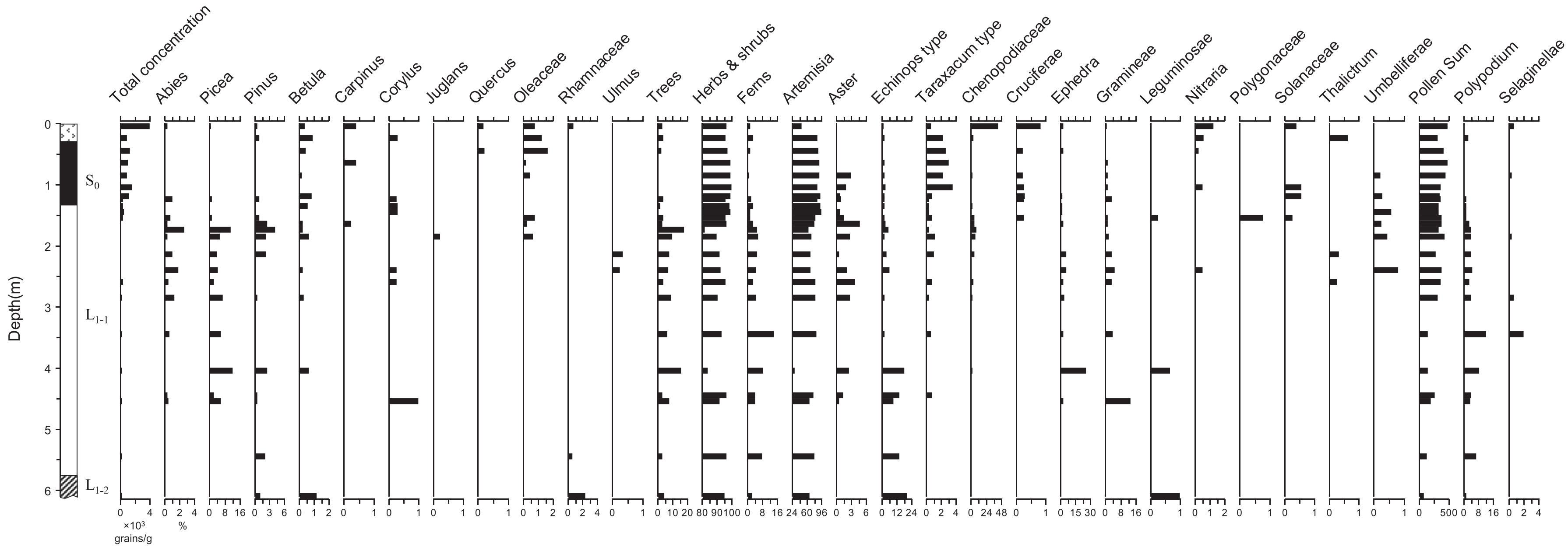

Fig. 3. Pollen percentage diagram and stratigraphic column at Weiyuan (Please note independent scales are used).

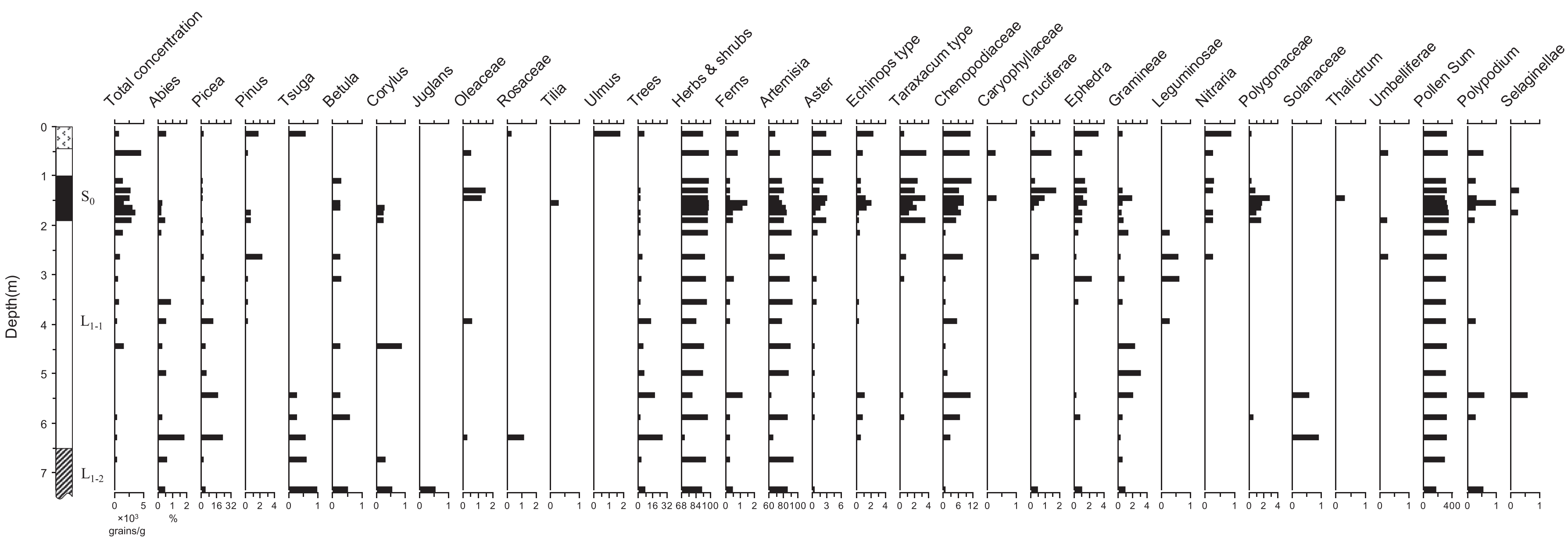

Fig. 4. Pollen percentage diagram and stratigraphic column at Huining (Please note independent scales are used).

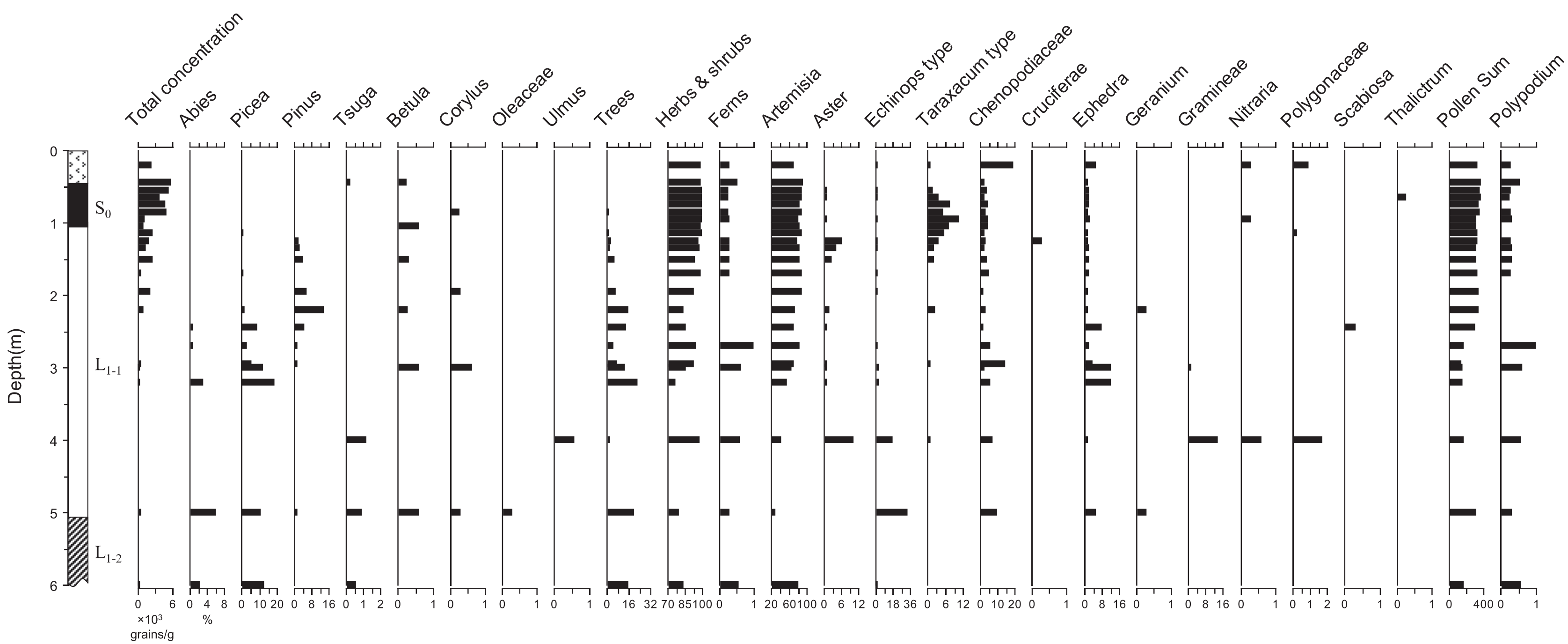

Fig. 5. Pollen percentage diagram and stratigraphic column at Jingtai (Please note independent scales are used).

types including *Echinops*-type, Chenopodiaceae, Gramineae, *Ephedra* and *Nitraria*. The significant incident of desert species, such as *Echinops*-type, Chenopodiaceae, *Ephedra*, and *Nitraria* (Figs. 3–5) imply that desert shrub and desert steppe prevailed, and the climate was dry and cold (Xu et al., 1980; Sun et al., 1996; Chen et al., 2004).

During the Holocene Optimum, pollen concentrations are significantly elevated, indicating an increase in vegetation coverage. Trees reduced significantly, mainly because of a decrease in *Picea*. *Artemisia* still dominated. The incidence of *Taraxacum*-type, Polygonaceae, Leguminosae, Solanaceae and Cruciferae that favor relatively humid conditions (Ma et al., 2009) increased, while dry species prevalent during the LGM, such as *Echinops*-type, Chenopodiaceae, *Nitraria* and *Ephedra*, decreased in the Holocene Optimum. It is thus inferred that vegetation was characterized by desert steppe and dry steppe, and the climate was relatively warm and humid.

During the late Holocene, vegetation in the study area mainly consisted of *Artemisia*, Chenopodiaceae, Cruciferae and Solanaceae. Previous studies have shown that soil nitrogen, which facilitates the growth of Chenopodiaceae, increases due to human activities (Luo et al., 2006). Chenopodiaceae can be considered as an "anthropogenic indicator" (Li et al., 2008). Although Chenopodiaceae pollen content reached the highest levels in all the three sections, the incidence of other desert species was rather low. It follows that the increase of Chenopodiaceae during the late Holocene is more likely to be caused by increased human activity rather than by climate change. This phenomenon merits further investigation.

5.2. Differences in specific plant types between the loess areas east and west of the Liupan Mountains since the LGM

5.2.1. Vegetation and climate during the LGM

In the loess area east of the Liupan Mountains, trees (mainly *Pinus*) only appeared sporadically in the north and central part during the LGM (Jiang et al., 2013, 2014). Vegetation was mainly composed of *Artemisia*, Asteraceae and *Echinops*-type (Jiang and Ding, 2005; Jiang et al., 2013, 2014). On the southeastern Loess Plateau, although both the incidence and types of trees increased, including *Pinus*, *Quercus*, *Juglans*, and *Corylus*, vegetation was still characterized by dry steppe and meadow steppe (Shi, 2000; Jiang et al., 2014). In the loess area west of the Liupan Mountains, the incident of *Picea* pollen reached as high as 24% (Figs. 3–5), while nearly no *Picea* was present in the loess area east of the mountains.

At present, *Picea* is not present near the study sites, while there are two species of *Picea* (*Picea wilsonii* and *Picea crassifolia*) in mountainous areas (2400–2800 m a.s.l.) of south Gansu Province (Fu et al., 2000; Ma et al., 2006), ~1000 km away from the study area. *Picea* favors cold, wet conditions. Previous studies have shown that humidity and temperature of the warm season are the most important factors controlling the distribution of *Picea* forest, and the favorable conditions for *Picea* are a relative humidity of 70–80% and mean temperatures of ~10–19 °C during the warmest month (Chinese Vegetation Editorial Committee, 1980).

Pollen grains of *Picea* have two sacs and are transported by wind. Compared with pollen of *Pinus*, *Betula* and *Alnus*, *Picea* pollen is low in production, large in size and heavy in weight (Stephen, 1991; Faegri et al., 2000). Its fall speed is about 2 times higher than *Pinus* pollen (Eisenhut, 1961). Therefore, it is generally considered that *Picea* pollen has low dispersal ability, with most pollen grains falling within hundreds of meters from their parent trees (Jackson, 1990; Bittencourt and Sebbenn, 2007). Modern surveys have also confirmed that *Picea* pollen percentages can reach more than 30% in surface samples collected 30 m away from the *Picea* forests, while they decreases to 9–30% and 3–5% with the distance increasing to 15 km and 50–110 km, respectively (Li, 1991; Zhu et al., 2004; Pan et al., 2013.).

Pollen assemblages and concentrations from our sites show that desert shrub and desert steppe prevailed during the LGM. However, *Picea* pollen contents reached 12–24% in this period, indicating the presence of *Picea* forest nearby. In the Loess Plateau, the land surface is dissected by deep gullies. Previous studies have shown that *Picea* forests thrived in many river valleys of the western Loess Plateau during the late Pleistocene (Tang et al., 2007; Wu et al., 2009). Due to the weak dispersal ability of *Picea* pollen, we suggest that the *Picea* pollen originated from *Picea* forests growing in adjacent river valleys rather than from in–situ vegetation. As shown in Fig. 1, the three sections are all located within ~10 km away from the nearest deep valleys. Specifically, the Jingtai section is located nearby the Yellow River valley, the Huining section is adjacent to the valleys of the Zuli and Guanchuan Rivers, and the Weiyuan section is close to the Weihe River valley.

During the LGM, the winter monsoon strengthened while summer monsoon weakened (Xiao et al., 1995; Yang and Ding, 2003, 2004, 2010), leading to a cold and dry climate. As a result, the treeline retreated downward substantially (Xu et al., 1980; Zhang et al., 2006). In river valleys, the groundwater table is relatively high (Cai, 2013), thus the moisture conditions were suitable for *Picea*. In areas with thick loess such as "Yuan", rainwater infiltrated quickly (Chen et al., 2008; Yang et al., 2012), and the water in the surface soil thus is insufficient to maintain trees. This explains why the in–situ vegetation was dominated by drought–tolerant herbs and shrubs, such as *Echinops*-type, Chenopodiaceae, *Ephedra* and *Nitraria*.

5.2.2. Vegetation and climate during the Holocene Optimum

During the Holocene Optimum, the loess area east of the Liupan Mountains was dominated by steppe vegetation. Compared with the loess area in the west, *Pinus* and some broadleaved trees increased in the east. For example, *Corylus* is the dominant component of trees in the central Loess Plateau (Jiang et al., 2013, 2014), while *Pinus* contents are relatively high in the southeast (Li et al., 2003b; Jiang et al., 2013, 2014), and *Quercus*, *Corylus*, *Ulmus*, *Carpinus* and other arboreal species flourished in the southern Plateau (Shi, 2000; Li, 2010). Thus, there were different specific plant types between the loess areas west and east of the Liupan Mountains. Relatively high abundance and diversity of trees in the east indicate a warmer and wetter climate than that in the west.

In the Holocene Optimum, summer monsoon strengthened (Jiang et al., 2006, 2010; Cai et al., 2010), causing an increase in temperature and an upward shift of the treeline. Thus the river valleys adjacent to the study sites were no longer suitable for the growth of *Picea* and other dark coniferous trees. As a result, conifers decreased dramatically, and herb species and vegetation density increased dramatically. In this context, temperature is the major factor controlling the growth of *Picea* in the Loess Plateau. During glacial periods, relatively low temperature and high relative humidity in river valleys in the western Loess Plateau favored the growth of *Picea*. Although precipitation increased during interglacials (Cai et al., 2010; Seki et al., 2011), temperatures exceeded the limits of *Picea* growth, and *Picea* forest withdrew from the river valleys.

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