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Land degradation during the Bronze Age in Hexi Corridor (Gansu, China)

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ABSTRACT

Pollen and charcoal analysis, with high resolution AMS ^{14}C dating, on two sediment sections in the Hexi Corridor track the process of settlement development and abandonment during the Bronze Age. The evidence shows that agricultural activity during the Bronze Age caused an increase in farmland and a decrease in the abundance of *Artemisia* grassland in the Hexi Corridor. Land degradation is probably the main cause for decreased agricultural activity and settlement abandonment. Agriculture- induced soil fertility loss and land salinization contributed to the process of land degradation. However, increasing climate aridity around 4000–3500 cal BP is probably the main initiating cause for the contraction of arable land and vegetation degradation in the Hexi Corridor.

1. Introduction

The connection between the rise and fall of ancient societies and variations in past environmental conditions is a topic of interest in recent studies (Cullen et al., 2000; Gasse, 2000; Weiss and Bradley, 2001; Drysdale et al., 2006; Migowskia et al., 2006). An understanding of this connection is important for understanding the potential effects of environment change on modern societies and developing optimal adaptation strategies for future climate changes. Systematic studies, which include archeological, geological and botanical methods, can help to better understand the nature of ancient agriculture and the effect that past climate changes had on prehistoric human activities in a particular area (Kirch, 2005).

The Hexi Corridor is well known for lying on the main path of the ancient Silk Road, which was an important east-west communicated route. A large amount of cultural remains from the Neolithic period to Bronze Age have survived in the Hexi Corridor, and these provide a detailed picture of prehistoric cultures and past environmental changes. Recent archeological studies show that oases in the Hexi Corridor were already occupied by Neolithic agricultural people who were probably derived from the Majiayao culture, which occurred after 5000 cal BP and was centred in south Gansu and east Qinghai (Xie, 2002). After 4200 cal BP, the Qijia and Siba Cultures, which had copper smelting technology, prevailed in this region (Li, 1993; Shui, 2001; Dodson et al., 2009). Prosperous Bronze Age agriculture in the Hexi Corridor appears to have terminated suddenly around 3500-3400 cal BP. The subsequent Shajing cultures show evidence of cultural retrogression and site numbers are low until the rise of nomadic tribes after 3000 cal BP (Shui, 2001; Xie, 2002). These previous studies provide a picture of emerging and declining agricultural societies during the Bronze Age in the Hexi Corridor. However, systematic study on the relationship of these cultural changes to paleo-environments and agricultural activities has barely commenced.

Pollen and charcoal analysis of ancient sedimentary sequences can provide important information about vegetation change and human activity (e.g. slash and burn agriculture) in an area (Goldberg et al., 2001; Kirch, 2005). The present paper provides new evidence based on pollen and charcoal analysis, along with high resolution AMS ^{14}C dating, for two sediment sections from Huangniangniangtai and Donghuishan sites (Fig. 1). Early agricultural development and vegetation changes during different stages in the Bronze Age in this area of the Hexi Corridor are described.

2. Environmental setting

The Hexi Corridor is located in west Gansu Province between the Mahanshan Mountains and the desert of East Xinjiang (35°15′–37°10′N, 106°20′–108°45′E). It passed through oases scattered along the narrow desert belt between the Qilian Mountains and Mongolian highlands.

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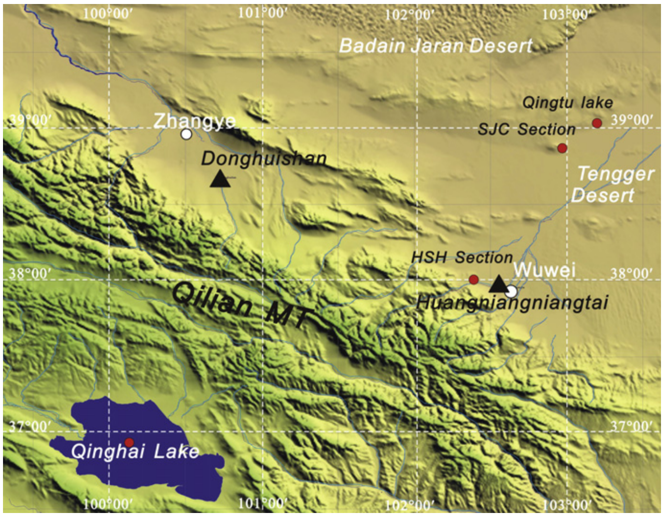

Fig. 1. Study area and sample sites and the location of the records mentioned in the context.

The average annual precipitation over most of the Hexi Corridor is only about 200 mm, while the annual evaporation is between 2000 and 3000 mm (Li and Liu, 2000). The biological environment of the Hexi Corridor is sensitive to changes in hydrological regimes as water supply to oases and desert rivers is mostly limited to that flowing northwards from the Qilian Mountains. The Asian summer monsoon delivers moisture to this region and is the main controlling factor governing water available in this area (Li and Liu, 2000).

The modern vegetation of the Hexi Corridor is dominated by low shrubs and perennial herbs including *Tamarix*, *Reaumuria*, *Hexinia*, *Hippophae*, *Nitraria*, *Alhagi*, *Calligonum* and *Chenopodiaceae*. Vegetation in oasis areas and areas in the south-east of the corridor is mainly steppe, which is dominated by *Stipa*, *Artemisia*, *Cleistogenes*, *Allium* and *Achnatherum*. *Populus euphratica* and *Elaeagnus oxcarpa* forest occur along the Heihe, Sule and Beidahe Rivers, where there is a better water supply (Huang, 1996). The pollen results of the two sections describe a similar mix of xeric grassland with some shrub vegetation, and with trees probably occurring along rivers or in wetlands near to the site. This is probably similar to the present environment.

3. Materials and methods

3.1. Huangniangniangtai site

Huangniangniangtai site (37°56′N, 102°36′E) is located in Songjiayuan village, 2.5 km northwest of Wuwei city. The archaeological site covers an area of about 125,000 m^2, and spans about 500 m from east to west and about 250 m from north to south. The cultural layer ranges from 0.6 to 2.3 m deep. Earlier work conducted at the site, between 1957 and 1975 by archaeologists from Gansu Museum, reported the culture remains to belong to the Qijia culture (4200–3600 cal BP), which was a culture widely distributed in Gansu and Qinghai provinces. The unearthed cultural relics included pottery and tools made of stone, bone and copper (Gansu Museum, 1960).

An exposed sediment section (Fig. 2) located on the edge of a loess terrace in the east of the site was sampled for this study. The 2.5 m deep section can be subdivided into four layers, according to colour and structure: (1) 0–10 cm, a modern cultivated layer; (2) 10–50 cm, a loess layer, containing fine sand; (3) 50–200 cm, a layer containing Qijia cultural remains, grey sandy loess, large charcoal fragments, red mud formed pottery and calcium concretions; (4) 200–250 cm, a light brown sandy loess layer.

3.2. Donghuishan site

Donghuishan site (38°40′N, 100°44′E) is located in the Zhangye oasis, 27 km north of Minle. It was discovered in 1958 and initially

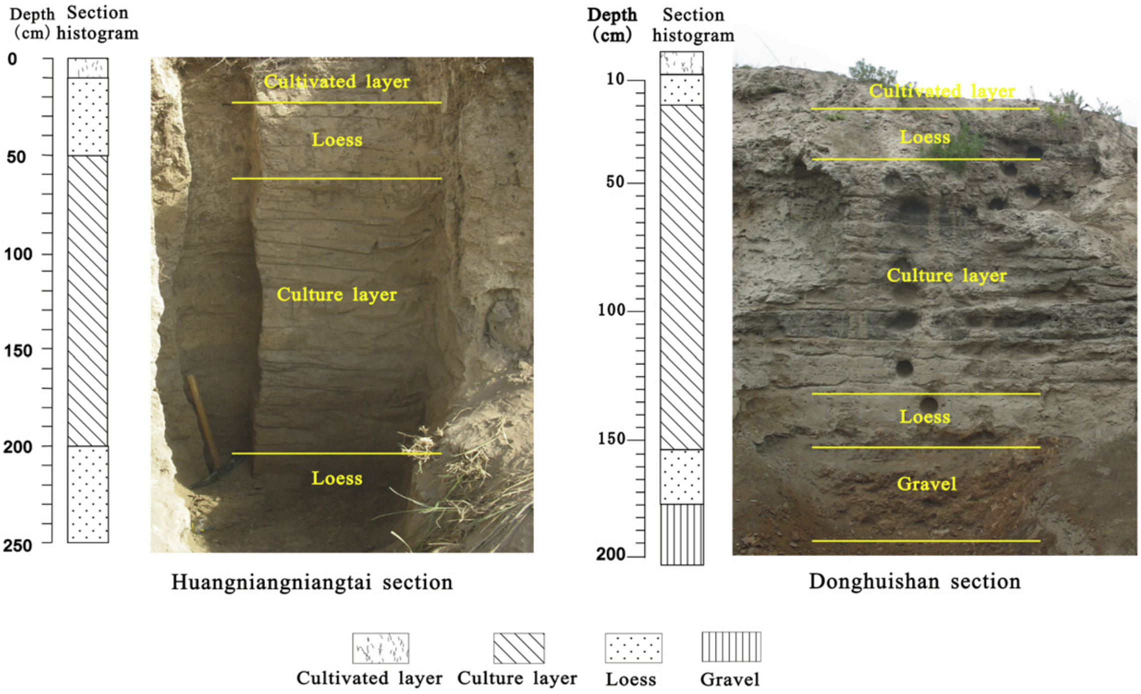

Fig. 2. The layer sequence and section Lithology of Huangniangniangtai and Donghuishan sections.

Table 1
The Neolithic and Bronze Age culture in Hexi Corridor.

Culture type	Age (cal BP)	Distribution in Hexi Corridor	Sites
Majiayao culture (Majiayao and Banshan type)	5000–4300	Wuwei-Jinchang	Mozuizi, Dongping, Yuanyangci
Majiayao culture (Machang type)	4300–4000	Wuwei-Jinchang and Zhangye-Jiuquan	Mozuizi, Yuanyangci, Xihetan
Qijia culture	4200–3600	Wuwei-Jinchang	Huangniangniangtai, Haizangsi
Siba culture	3900–3400	Zhangye and Jiuquan	Donghuishan, Yingshuwo, Siba, Huoshiliang, Ganggangwa
Shajing culture	3000–2500	Wuwei-Jinchang	Shajingzi, Nuanquan

excavated by an archeological team from the Gansu Archeological Institute and Jilin University in 1987. The archeological study showed the remains at Donghuishan to belong to the Siba culture, which was a middle-late Bronze Age culture of the Hexi Corridor. Pottery, tools made of stone, bone, wood, gold and copper, and 249 graves were unearthed during the excavation (Gansu Provincial Institute of Cultural Relics and Archaeology and Research Center for Chinese Frontier Archaeology of Jilin University, 1998).

Donghuishan is well known for its early evidence of wheat and barley agriculture, but opinion about the age of these remains has changed. Remains of wheat seeds from the site were originally reported to date to as early as 5000 cal BP (Li, 1989), but they were later reported to date to about 4500 cal BP (Li and Mo, 2004). Recent work has Recent work has reported the age of the Donghuishan wheat remains to between 3700 and 3450 cal BP, within the Siba culture (Flad et al., 2010). Further study of agricultural remains at the site, using AMS dating methods, is needed to understand the timing of commencement of agriculture at Donghuishan (Table 1).

Samples were taken from the wall of a trench, dug for irrigation works in 1973, in the east of the site. The 2 m deep section (Fig. 2) can be subdivided into five layers: (1) 0–10 cm, a modern cultivated layer, composed of yellow sandy soil and low amounts of charcoal and burnt soil; (2) 10–100 cm, a culture layer, containing grey sandy loess, small amounts of gravel and large amounts of charcoal and pottery; (3) 100–150 cm, a cultural layer, containing a light brown palaeosol with calcium concretions, and large amounts of charcoal, pottery and gravel; (4) 150–170 cm, a yellow sandy loess layer with low amounts of charcoal; (5) 170–200 cm, a reddish brown gravel layer.

The two sections studied were chosen to include cultural deposits and avoid likely stratigraphic disturbances, from ash-pits or burials for example. Thirty two samples from both sections were analysed for pollen and charcoal content. These samples consisted of about 200 g of sediment and were taken in 5 cm thick slices at intervals of 10 and 20 cm in the Donghuishan and Huangniangniangtai sections respectively. Due to the expected low concentration of pollen in the loess sediments of this area, an integrated method of sieving and heavy liquid flotation was used to prepare samples for pollen analyses (Li et al., 2006a). Pollen and charcoal abundance was quantified in 11 samples from the Huangniangnangta section and 21 samples from the Donghuishan section. The total pollen count exceeded 250 grains in most samples, although four samples from Huangniangniangtai and two samples from Donghuishan failed to yield 250 pollen grains. Charcoal concentrations were quantified using the point count method (Clark, 1982; Li et al., 2006b).

AMS ^{14}C dating was conducted on three charcoal fragments and one charred wheat seed from the Huangniangniangtai section, and four charred wheat seeds from the Donghuishan section (Table 2). AMS ^{14}C dating was performed at the Australian Nuclear Science and Technology Organization (ANSTO), and calibrated ages were calculated using Calib Rev 6.0.1 software (Stuiver and Reimer, 1993) and the INTCAL09 dataset (Reimer et al., 2009). Age-depth models were produced with the clam. R and R (version 1.12.1) statistical packages (Blaauw, 2010; R Development Core Team, 2010)

4. Results

4.1. Chronology of the sections

Calibrated ages for all but the uppermost date in the Huangniangniangtai section range from ca. 3992–3679 BP, which corresponds with the Qijia culture (4200–3600 cal BP) and previous estimates of the site's occupation. This narrow age range suggests that much of the sediment section accumulated in only two to three hundred years. The uppermost AMS ^{14}C date of 210 ± 45 BP lies just below sediments clearly disturbed by cultivation and is likely to reflect the re-worked nature of the upper layers. Calibrated ages from Donghuishan section range from ca. 3830-3389 BP, and correspond with the Siba culture (3800–3500 cal. A BP) (Shui, 2001; Xie, 2002).

Age-depth models for the two sections are based on linear interpolation between the calibrated ages (Fig. 3) (see Blaauw, 2010). As the uppermost date in the Huangniangniangtai section is suspected to have been affected by sediment reworking, it has been excluded from model calculations. An extrapolated sediment accumulation rate is tentatively adopted for the Huangniangniangtai section from 135 cm depth to the stratigraphic change at 10 cm depth.

4.2. Pollen analysis

A total of 2138 pollen grains belonging to 29 taxa were identified in the 11 samples from Huangniangniangtai, and 5278 pollen grains belonging to 31 taxa in the 21 samples from Donghuishan. Pollen taxa in the two sections are similar, indicating similarity in the vegetation surrounding the two sites. The dominant tree taxa were

Table 2
AMS data for Huangniangniangtai and Donghuishan.

Site	Depth (cm)	Sample type	Lab code	AMS ^{14}C age (BP)	Calibrated age range (BP, 2σ)
Huangniangniangtai	15 cm	Charcoal	OZK415	210 ± 45	423–0
Huangniangniangtai	135 cm	Charcoal	OZK417	3510 ± 50	3910–3641
Huangniangniangtai	155 cm	Wheat seed	OZK418	3570 ± 60	4074–3695
Huangniangniangtai	210 cm	Charcoal	OZK419	3560 ± 50	3977–3704
Donghuishan	30 cm	Wheat seed	OZK653	3260 ± 45	3584–3382
Donghuishan	90 cm	Wheat seed	OZK654	3405 ± 50	3828–3487
Donghuishan	130 cm	Wheat seed	OZK655	3425 ± 40	3827–3576
Donghuishan	170 cm	Wheat seed	OZK656	3410 ± 50	3830–3490

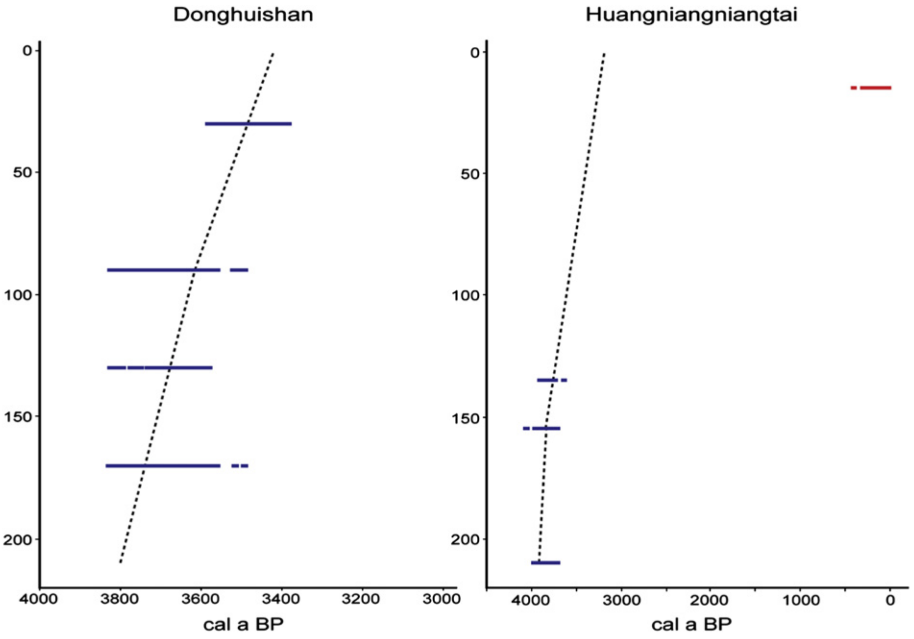

Fig. 3. Age-depth models for Huangniangniangtai and Donghuishan sections based on linear interpolation between calibrated radiocarbon dates (Blaauw, 2010). The blue lines represent calibrated age distributions of the radiocarbon dates, the uppermost date in the Huangniangniangtai section (red line) has been excluded from the model calculations. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

Pinus, *Picea*, *Sabina*, *Quercus*, *Juglans*, *Corylus*, *Salix* and Fagaceae. The herb taxa were dominated by *Artemisia*, Chenopodiaceae, Compositae, Leguminosae, Polygonaceae, *Zygophyllum*, *Ephedra*, *Peganum*, *Stellera*, Poaceae, *Fagopyrum* and Caryophyllaceae.

The pollen spectrum of the Huangniangniangtai section can be subdivided into three zones (Fig. 4). Zone I, dating to ca. 3910–3820 cal BP (210–150 cm depth), is dominated by pollen of *Artemisia* (mean = 43.4%) and Poaceae (mean = 20.7%). Chenopodiaceae is very low in this layer.

Zone II, dating to ca. 3820–3480 cal BP (150–70 cm depth), contained high proportions of Poaceae pollen. Charcoal concentrations were less than Zone I, and the proportion of Chenopodiaceae was higher.

Zone III, dating to after ca. 3480 cal BP and including recently cultivated soil (70–0 cm depth), had lower proportions of *Artemisia* and Poaceae compared to Zones I and II. Proportions of Chenopodiaceae are markedly higher in this zone. The pollen from desert shrubs (*Zygophyllum*, *Ephedra* and *Nitralia*) occur in this zone.

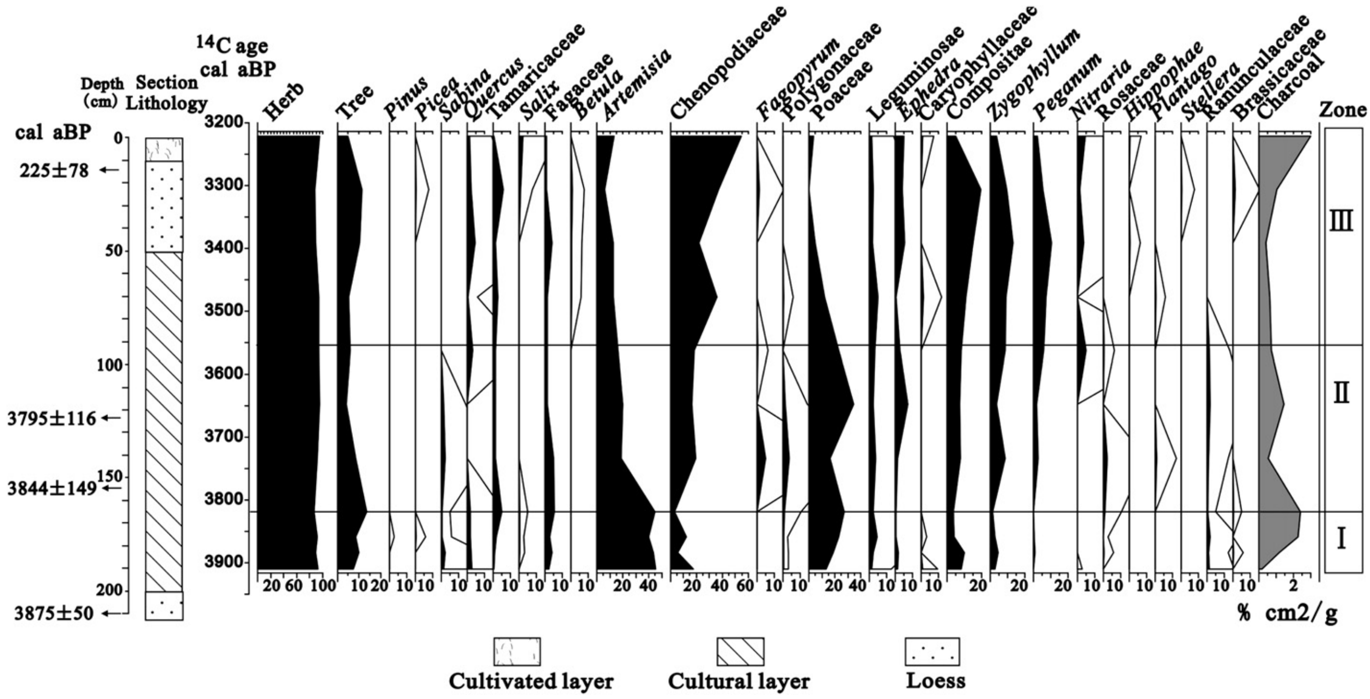

Fig. 4. Pollen percentage spectrum in the Huangniangniangtai section.

The pollen spectrum of the Donghuishan section (Fig. 5) can also be subdivided into three zones (Fig. 4). Zone I, dating to ca. 3790-3740 cal BP (200–170 cm depth), is dominated by pollen of the herbs *Artemisia* (mean = 41.4%), Chenopodiaceae (mean = 13.8%), and has high percentages of the desert shrubs *Ephedra* and *Tamarix*. Pollen of arboreal taxa includes *Picea*, *Sabina*, and *Quercus*. Fagaceae pollen occurs in very low percentages. Charcoal concentrations are very low in this layer. The pollen results indicate mixed grassland and desert shrub vegetation dominated land surrounding the site at this time.

Zone II dates to ca. 3740-3590 cal BP (170–80 cm depth) and is characterized by a gradual decrease in the proportion of *Artemisia* towards the top of the zone (mean = 25.1%). High percentages of Poaceae occur in this zone (mean = 30.0%) and charcoal concentrations are high (mean = 2.75 cm^2/g).

Zone III dates to ca. 3590–3420 cal BP (80–0 cm depth) and is characterized by having lower proportions of Poaceae (mean = 10.0%) and *Artemisia* (mean = 8.9%) pollen compared with the underlying zones. Proportions of Chenopodiaceae pollen are markedly higher (mean = 50.4% and maximum = 77.0%) and concentrations of charcoal are markedly lower than the underlying zones.

5. Discussion and conclusions

Chenopodiaceae is a desert shrub with comparatively high pollen production. Chenopodiaceae normally composes about 10–30% of pollen in surface samples from desert areas in this region, but in some extremely dry or salt-affected areas, the proportion can reach 50% (Surface Pollen Database of East Asia, http://eapd.sysu.edu.cn/database/). High proportions of *Artemisia* pollen occur in surface samples from areas where steppe or grassland vegetation occurs. Thus the ratio of *Artemisia* to Chenopodiaceae pollen is often used as an index of aridity in studies located in Central Asia (El-Moslimany, 1987; Davies and Fall, 2001). At Huangniangniangtai and Donghuishan there is a shift towards higher proportions of Chenopodiaceae and lower proportions of *Artemisia* pollen in the upper layers and this can be regarded as signalling a shift from grassland to desert shrubland vegetation.

The percentage of Poaceae in loess sediments is usually less than 10%, even where grasses dominate (Xu et al., 2005). The high Poaceae pollen percentages in the Huangniangniangtai and Donghuishan sections probably resulted from cultivated cereals in the area. Charcoal concentrations appear to mimic the Poaceae pollen percentages through the sections, and reflect an expansion and subsequent decline of agriculture and human activity near to the sites. The increase of Chenopodiaceae pollen in the upper layers of both Huangniangniangtai and Donghuishan sections is contemporaneous with a decrease of Poaceae pollen and charcoal concentrations, and is likely to represent land degradation and a decline of agriculture.

The changes in vegetation and fire activity recorded in the Huangniangniangtai and Donghuishan sections reflect a widespread pattern of development and abandonment of Bronze Age settlements in the arid Hexi Corridor. The lowest zones of both Huangniangniangtai and Donghuishan sections are dominated by *Artemisia*, pollen proportion average around 40%, and this indicates that the regional vegetation of the study site was dominated by grassland or steppe vegetation before humans settled the area. The subsequent increase of Poaceae and decrease of *Artemisia* indicates the establishment of farmland and intensive agricultural activities. Intensive agriculture appears to have lasted for only one to two centuries, as is shown by sustained high percentages of Poaceae in Zone II of both pollen spectrums. The subsequent decline in agricultural activities in the upper zones corresponds with increasing aridity.

Agricultural activities probably also contributed to the process of the land degradation. The prosperity of Bronze Age agricultural societies in the Hexi Corridor persisted from ca. 4200 to 3500 cal BP, and was characterised by agro-pastoralist societies that kept

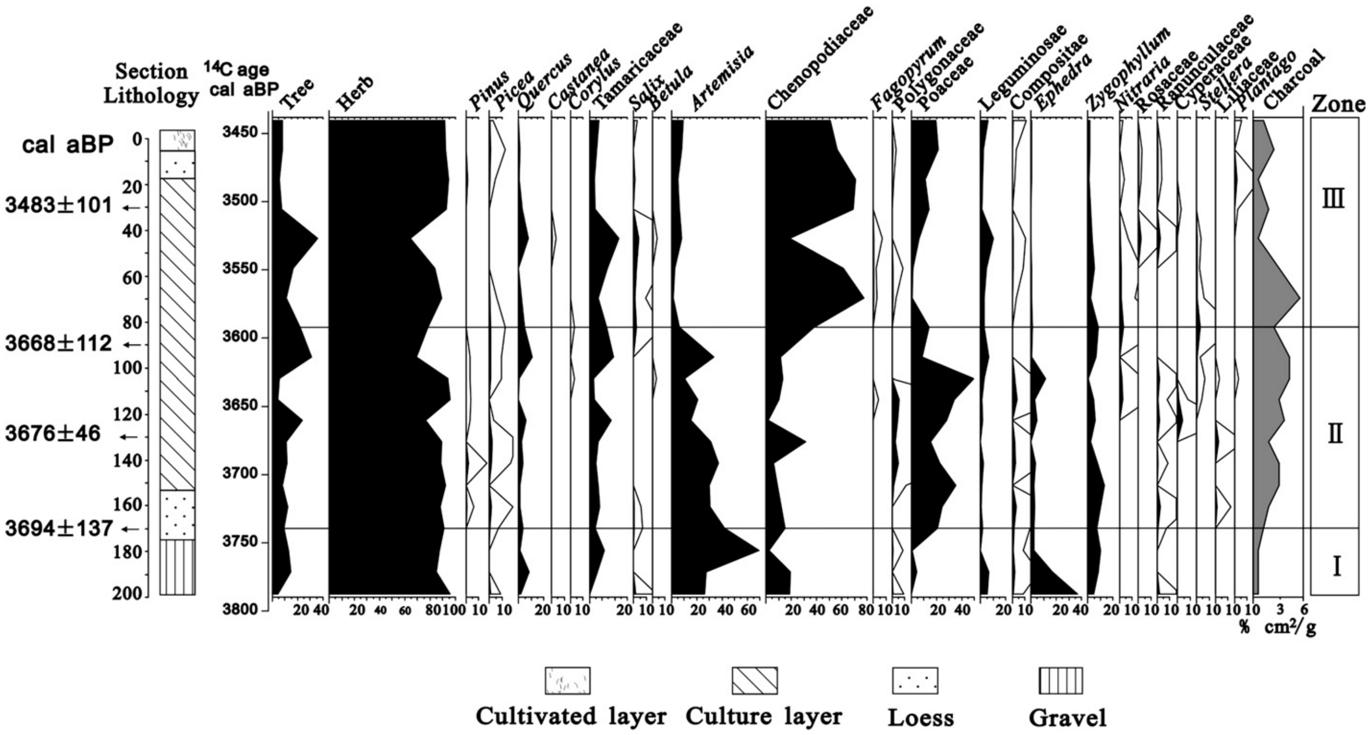

Fig. 5. Pollen percentage spectrum in the Donghuishan section.

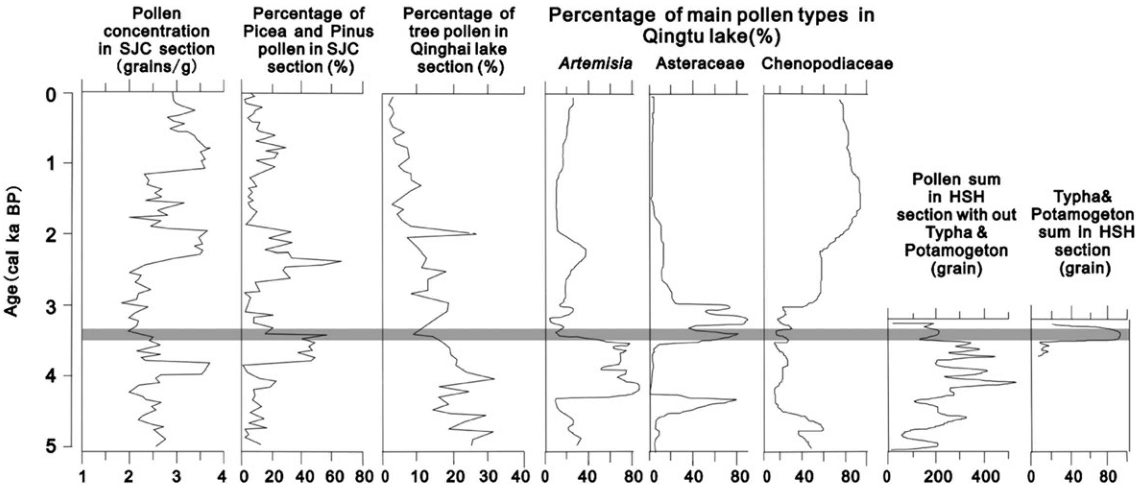

Fig. 6. Abrupt climate change around 3500 cal a BP recorded in the SJC section (Chen et al., 2006), Qinghai lake (Shen et al., 2005), Qingtu lake (Zhao et al., 2008) and HSH section (Zhang et al., 2000).

livestock including pig, sheep, cattle and horse, while also producing bronze objects of alloyed copper, arsenic and tin (Mei, 2004; Dodson et al., 2009) Isotope analysis of skeletal remains from Bronze Age sites shows human and domestic omnivore diets to have been dominated by millet, with animal protein contributing minimally to diets at that time (Atahan et al., 2011). The effect of soil fertility loss due to sustained cultivation is particularly significant in ecologically fragile regions. In prehistoric agricultural societies, swiddening and fallowing was widely used as a strategy to help maintain land fertility, but during periods when arable land was scarcer, due to aridity and reduced water availability for example, the remaining arable land was probably farmed more continuously until it was abandoned.

Besides soil fertility loss and desertification, land salinization induced by irrigation is another form of land degradation that probably occurred in the Hexi Corridor. The evaporation of Hexi, as high as 2000–3000 mm, is far more than the precipitation around the area, causing salt to accumulate in the surface soil. The soil types in Hexi Corridor include brown calcic soil, grey desert soil, sierozem and brown desert soil. Surface water from the Qilian Mountains infiltrates into the soil and forms unconfined water with soluble salts. The underground water of Heihe basin, for instance, contains $NaHCO_3$ with high-grade mineralization ($M = 15–110$ g/L, pH = 7.15–8.11) (Liu et al., 2005). The deep confined water also contains high levels of soda. The depth of the water table is normally as shallow as 1.1–3.1 m as a result of the subdued landforms of the upper Heihe basin (Liu et al., 2005). Flood irrigation with overflowing water and/or insufficient drainage will accelerate salt accumulation in the surface land of this area. The water table containing soluble salt will rise due to flood irrigation. As a result, saline-alkali patches will develop on the surface and expand rapidly under continuous flood irrigation.

The main agricultural crops at Donghuishan site during the Bronze Age were not only foxtail millet and common millet, which originate in eastern Asia, but also wheat and barley, which originate in south-western Asia (Li, 1989; Li, 1993; Li and Mo, 2004; Flad et al., 2010). The high content of xeric species, such as *Nitraria*, *Tamarix*, *Hippophae*, *Ephedra*, and *Zygophyllum*, in the Bronze Age deposits at Huangniangniangtai and Donghuishan suggest annual precipitation at the time did not exceed 200 mm. Wheat agriculture requires irrigation in such low rainfall areas. Soil salinization in Mesopotamian (2400–1700BC) has been attributed to irrigation practices (Jacobsen and Adams, 1958; Gelbund, 1963). Irrigation associated with wheat agriculture may have also led to increased soil salinity and land degradation in the Bronze Age Hexi Corridor.

A weakening of the Asian summer monsoon after 5000 cal BP caused the climate to become more arid in northern China, and a second marked shift towards greater aridity is reported to have occurred after ca. 3500 cal a BP (Zhang et al., 2000; Shen et al., 2005; Chen et al., 2006; Feng et al., 2006; Wang et al., 2006; Zhao et al., 2009) (Fig. 6). The collapse of the Qijia culture around 4000 cal a BP is attributed to increased aridity (An et al., 2005). It is likely that changes to hydrological regimes at this time caused oasis contraction and desert expansion.

Historically, most human activity in the region has been restricted to areas where water is available, and settlement sites have shifted in response to changing hydrological regimes and water management practices (Hou, 1985; Wang et al., 2006; Zhang, 2006). Shifts from arable farming to herding appear to have coincided with periods when water availability and the extent of arable land were reduced (Madsen and Elston, 2007; Zhao et al., 2008). It appears that the development and decline of Bronze Age agricultural societies in the Hexi Corridor (from ca. 4200–3500 cal BP) responded to climate variations, and thus it is likely that the climate aridity from ca. 4000–3500 cal BP was the main reason for the observed land degradation and decreased agricultural activities at Huangniangniangtai and Donghuishan.

In summary, Huangniangniangtai and Donghuishan Bronze Age settlements in the Hexi Corridor appear to have persisted for one to two centuries. Land degradation is the likely cause for the decrease of agricultural activities and the abandonment of these settlements. Soil fertility loss induced by sustained farming and land salinization induced by over-irrigation probably contributed to the process of the land degradation. But the increasing climate aridity between ca. 4000 and 3500 cal BP, which was induced by a weakening of the Asian monsoon, is the underlying cause for the shrinking of arable land and vegetation degradation in Hexi Corridor, and this is the likely cause for the decrease of the agricultural activities and collapse of the Bronze Age societies in Hexi Corridor.

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