ORIGINAL ARTICLE

Archaeobotanical evidence reveals the human–environment interactions during the 9th–13th centuries at Turpan, Xinjiang on the ancient Silk Road

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Abstract

The ancient Silk Road was a link of economic-cultural exchanges and religious communication between China and the West. Turpan in Xinjiang is an important site on this road and was once one of the areas where Buddhism flourished in the Western Regions. However, the relationship between environment, agricultural activity and Buddhism has received little attention. Here we analyzed the adobe samples from the Bezikelike Grottoes, Turpan for pollen, plant remains and charcoal, and reconstructed a desert steppe vegetation under warm-humid conditions during the period of 9th–13th centuries. In particular the climate of middle 9th–10th centuries was quite pleasant, with a mean annual temperature of 14.2 °C and mean annual precipitation of 880 mm. Ancient people planted economic crops such as grape (*Vitis vinifera*) and cultivated cereals, including broomcorn millet (*Panicum miliaceum*), wheat (*Triticum aestivum*) and barley (*Hordeum vulgare* var. *coeleste*), indicating agricultural production activities were well-developed at that time. Further comparison with the oasis environment of the 5th century suggested that the development of agriculture may have created favourable environmental conditions for the flourishing of Buddhism at that time. This finding provides a new perspective for understanding the interaction between environment and humans on the ancient Silk Road.

Keywords Agricultural production · Anthropocene · Buddhism · China · Environment · Human activity · Palaeoclimatology

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Introduction

Xinjiang is located in the arid region of continental Eurasia. As early as two thousand years ago, it was the gateway of the ancient Silk Road and played an important role in linking the economic and cultural exchanges between China and the West (Bi et al. 2014). As one of the key points on the Silk Road, Turpan once boasted a splendid ancient culture. Since ancient times, Turpan was not only a multi-ethnic area, but also a multi-religious gathering place with Buddhism, Manichaeism, Islam etc. Due to the extremely dry environment in this area, a large number of caves are well preserved, including the Bezikelike Grottoes, the Tuyoq Grottoes, and the Shengjinkou Grottoes (Fig. 1), which proves that Turpan (named Gaochang in ancient times) was once one of the most prosperous areas of Western Buddhism.

Although it is not exactly known when Buddhism was introduced to Turpan (Yao 1996; Wang 2014), it was considered to have spread into this region since around the 1st century BC based on textual research (Zhao 2013). Subsequently, the propagation of Buddhist culture in this

Fig. 1 Geographical map of the study area, **a** Xinjiang in China, **b** Turpan in Xinjiang, **c** Bezikelike Grottoes in Turpan
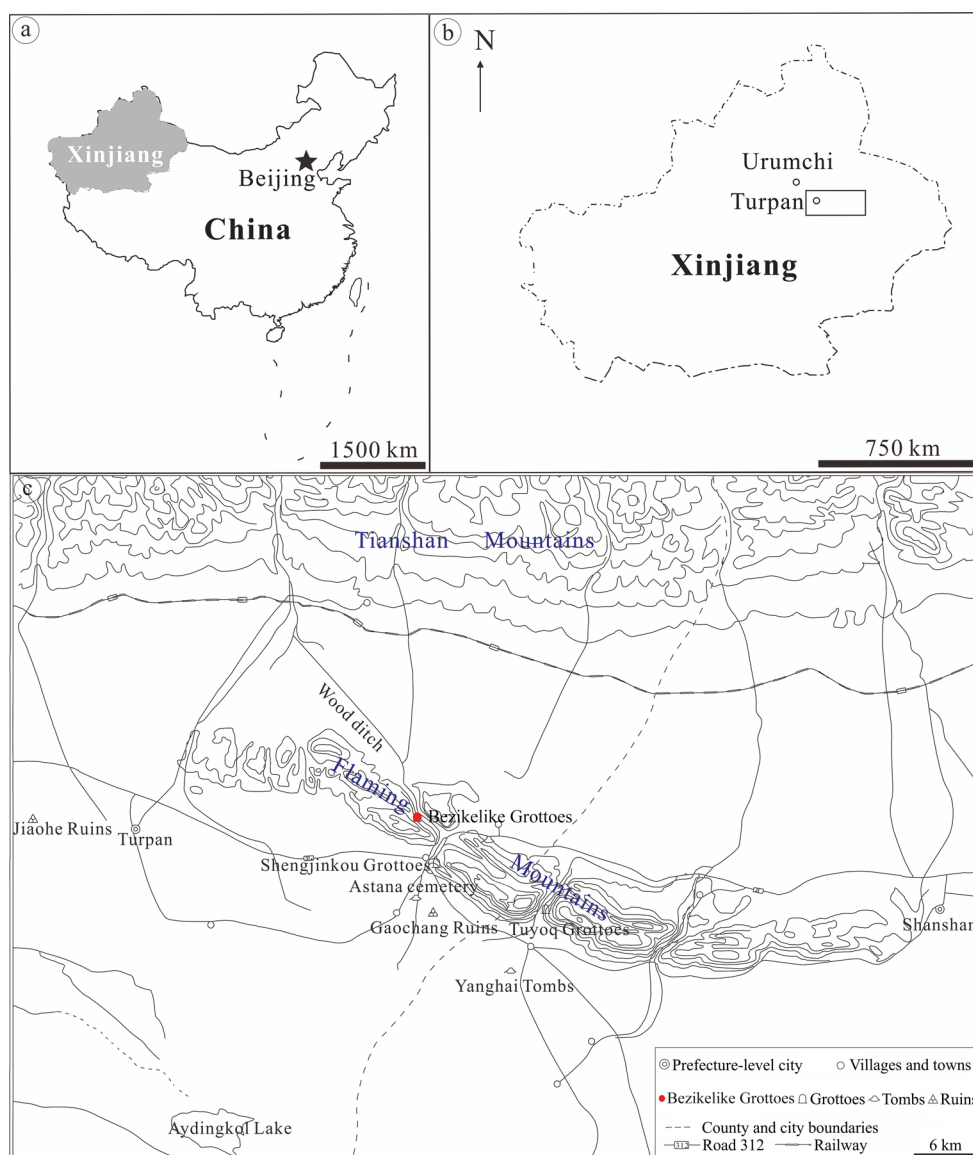
region was possibly related to the evolution of climate and environment, and the development of agricultural production. For example, Tang et al. (2014) investigated the environment of the Tuyoq Grottoes in the 5th century, and revealed that Tuyoq was a warm and humid oasis with a prosperous society and flourishing Buddhism.

However, why and how Buddhism flourished in some well-watered areas of the generally arid zone of Central Asia during the Uygur Gaochang period (middle of 9th–13th centuries) remains unclear. Here we provide a case study of Turpan to address this issue based on a multi-proxy analysis of micro- and macro-botanical remains (i.e. pollen, fruits, seeds and charcoal) extracted from adobe samples from the Bezikelike Grottoes, Xinjiang. This study provides new insight into the interaction between the environment and humans on the ancient Silk

Road, and expands our understanding of the multifarious impacts along the road.

Material and methods

Study area

Turpan is located in the hinterland of Eurasia (41°12′–43°40′ N, 87°16′–91°55′ E). It is situated in a large intermontane basin in the eastern Tianshan Mountains (Fig. 1a, b). The area of the basin is approximately 50,000 km^2, of which the oasis area is 7.8 km^2. The three sides to the North, West and South are surrounded by mountains. To the north is the highest, Bogda Mountain, in the eastern part of the Tianshan Mountains (the average altitude is above 3,500 m, the

highest peak of 5,445 m). In the west is the Kelawucheng Mountain (3,500–4,000 m), while the southern side is bounded by Jueluotage Mountain. Turpan has a temperate continental climate with an average annual temperature of 13.3–13.9 °C, an extreme maximum temperature of 49.6 °C, and an average annual precipitation of 16.8 mm (Abdirahman et al. 2009). The water used for oasis agricultural irrigation comes mainly from snowmelt on the Bogda and Kelawucheng Mountains. Uygurs are the main ethnic groups in this area. In general they settle in oases and live on agriculture. They mainly plant *Gossypium hirsutum* L. (cotton), *Vitis vinifera* L. (grape), *Sorghum bicolor* (L.) Moench (broomcorn), *Citrullus lanatus* (Thunb.) Matsumura et Nakai (watermelon), *Cucumis melo* L. (sweet melon) and *Ziziphus jujuba* Mill. (Chinese jujube). The local natural vegetation is mainly composed of saline meadow, including xeromorphic grasses, *Alhagi sparsifolia* Shap. (camel thorn), *Tamarix* sp. (tamarisk), *Calligonum mongolicum* Turcz. (Mongolian calligonum), *Haloxylon ammodendron* (C.A. Meyer) Bunge (saxaul) etc. (CEXCAS and IBCAS 1978; Jiang et al. 2009; Yao et al. 2012).

The Bezikelike Grottoes (42°57′7.5″–42°57′34.26″N, 89°32′19.26″–89°32′26.1″E, elevation: 100–160 m), are located in the Flaming Mountain, about 3 km south of Murituke Village, Shengjin County. They are situated on the western cliff of the wooded gully and stretch nearly 1 km from north to south (Fig. 1c). The site is about 40 km west of Turpan, 5 km north of the Shengjinkou Grottoes, and about 10 km from the ancient city of Gaochang. There are vineyards and poplars growing in the valley below the grottoes (XICRA 2012).

Large-scale excavations and clearing of the Bezikelike Grottoes were carried out by the Turpan Cultural Relics Management Institute in 1978 and 1980, as well as the Xinjiang Uygur Autonomous Region Cultural and Archaeological Institute in 2009. A total of 83 caves with rich murals and various architectural forms were reported, which are considered as the most important and representative cultural relics of Uygur Buddhist art (TCRMI 1985). Based on the shape, content and painting styles of the caves, the Bezikelike Grottoes could be roughly divided into three periods, viz. Qu's Gaochang (AD 499–640), Xizhou of Tang Dynasty (AD 640-mid 9th century) and the Uygur Gaochang (the middle of 9th–13th centuries), thus spanning nearly eight centuries, including the Northern and Southern Dynasties

(AD 420–589), Tang (AD 618–907), Song (AD 960–1279) and Yuan (AD 1206–1402) Dynasties. The Bezikelike Grottoes were first constructed in the period of Qu's Gaochang, and referred to as the Ningrong Temple during the Tang Dynasty. It was an important centre of Buddhism in Xinjiang at that time. The Uygur Gaochang was the most prosperous period, during which Ningrong Temple became a royal monastery. At the end of the 13th century, the royal family of Gaochang moved to Yongchang, Gansu Province, and the Bezikelike Grottoes gradually turned into a people's temple. With the introduction of Islam to Turpan at the end of the 14th century, Buddhism gradually waned, and the Bezikelike Grottoes were finally abandoned in the middle of the 15th century (Liu 1986). Therefore, the history of the grottoes reflects the rise and decline of Buddhist culture in Turpan.

Sampling and dating

In 1982 China's State Council announced that the Bezikelike Grottoes are a national key cultural relic protection unit. With the permission of the Turpan Cultural Relics Administration, five adobe samples (No. BZ-1, 2, 3, 4, 5) were collected from the archaeological site in November 2011. Sample BZ-1 was a mural remnant from Cave 37, BZ-2 was taken from pagoda No. 1, while BZ-3, 4 and 5 came from the staircase passage connecting the cliff bottom with the cave temple (Supplementary Fig. 1). Abundant plant remains (including fruits, seeds, spikelets etc.) were sieved from sample BZ-1. Selected plant remains were dated in the Beta analytic radiocarbon dating laboratory, USA by accelerator mass spectrometry (AMS) ^{14}C dating. The ^{14}C age is quoted in conventional years BP; age calibration was achieved using the High Probability Density Range Method (Bronk Ramsey 2009) and database INTCAL13 (Reimer et al. 2013). Errors are expressed at the one sigma (68.2% probability) and two sigma (95.4% probability) levels of confidence, respectively, and dates are quoted in calibrated AD. Radiocarbon dating results are shown in Table 1.

The shape of pagoda No. 1 is exactly the same as that of the south-eastern Buddhist temple in the old city of Gaochang (e.g. Similar planes are convex diamonds, and the murals are similar in style) (XICRA 2012). It is considered that pagoda No. 1 is a relic of the Song and Yuan Dynasties, so sample BZ-2 dates from the 10th–13th centuries (TCRMI 1985). Samples BZ-3, 4 and 5 were taken from the staircase

Table 1 Radiocarbon dating of plant remains recovered from the Bezikelike Grottoes

Lab code	Dated material	δ^{13}C	^{14}C date (year BP)	Calibrated age (cal AD, 1σ)	Calibrated age (cal AD, 2σ)
Beta-497067	Plant remains from Cave No. 37	−23.3‰	1,140±30	880–970 (68.2%)	854–981 (78.6%) 802–848 (11.3%) 776–792 (5.5%)

passage, which, based on the archaeological data (TCRMI 1985), was supposed to have been built on the original foundation during the flourishing period of the grottoes in the 10th–11th centuries.

Pollen analysis

For pollen analysis, 30 g of each sample were treated by heavy liquid separation (density 1.95 g/ml) (Moore et al. 1991; Li and Du 1999). One tablet of *Lycopodium* spores (batch: 2013001; 27,560 ± 2,643 spores/tablet) was added to each sample before treatment, to enable us to calculate the pollen concentration. At least 300 spores and pollen grains were counted for each sample, together with the *Lycopodium* spores, under a Leica DM 2500 light microscope at a magnification of × 400. SEM imaging of single pollen grains (Liu et al. 2007) was conducted with a Hitachi S-4800 Field Emission Scanning Electron Microscope at the Institute of Botany, Chinese Academy of Sciences, Beijing. Identification of palynomorphs was performed by comparison with palynological monographs (IBCAS 1976; Xi and Ning 1994; Wang et al. 1995). Relative abundance (RA) of pollen and spores was calculated following the formula: RA = N/Nt (N: number of one type of pollen or spore, Nt: total pollen sum).

Plant remains

The remains of fruits, seeds and spikelets were found only in sample BZ-1, which were obtained by 100 µm mesh sieve. The length, width and thickness of the seeds were measured with a vernier caliper Pro'sKit PD-151. The weight was obtained with a Mettler Toledo AL104 electronic analytical balance. The plant remains were observed, identified and photographed under a Leica M165FC microscope. The descriptive terminology follows Hayward (1948), Li (1979), Guo (1987), Jacomet (1987) and Wang (1990). The modern plant samples used for comparison were provided by the National Herbarium (PE) of the Institute of Botany, Chinese Academy of Sciences.

Charcoal analysis

The extraction of charcoal was performed parallel to the process of pollen analysis. The 11 touch point-counts method and size-classes method were employed to count the charcoal and *Lycopodium* spores under an Olympus BH-2 light microscope at magnifications of × 200 and × 400. The area concentration of charcoal (AC, cm²/cm³) can be calculated by 11 touch point-counts method following the formula:

$$AC = S \times C \times L/(M \times l \times V)$$

where S is the area of the statistical field of view (= the area of a single field of view × the number of statistical fields); C is the number of pieces of charcoal; L is the number of exotic *Lycopodium* spores; M is the total number of micrometer scale calibration lines in the statistical field of view (= Number of fields of view × 11 scale lines); l is the number of *Lycopodium* spores counted; V is the volume or weight of sample (cm³ or g).

The size-classes method divides the charcoal into three classes, i.e. < 50 µm, 50–100 µm and > 100 µm. The particle concentration (GC, grains/cm³ or grains/g) of different charcoal in size-classes can be calculated by the following formula:

$$GC = G \times L/(l \times V)$$

where G is the total number of charcoal particles (grains) (= total number of charcoal in multiple fields of view) (Li et al. 2010).

Ancient climate analysis

The Coexistence Approach method (Mosbrugger and Utescher 1997) has been employed to evaluate the climatic parameters of the middle of 9th–13th centuries in Turpan, including the annual mean temperature (MAT), the mean temperature of the warmest month (WMT), the mean temperature of the coldest month (CMT), the difference of temperature between the warmest and coldest months (DT), and the annual mean precipitation (MAP). The method is based on the assumption that the climatic tolerance of a fossil taxon is similar to that of its Nearest Living Relative (NLR). The procedure for obtaining the climatic tolerance of a NLR is as follows. First, the climatic parameters of all NLRs (seed plants) in a palynoflora are obtained from the climatic records within their modern distributional area (Wu and Ding 1999). Second, the maximum and minimum of each parameter for each NLR are established. Third, the climatic interval of each parameter of all NLRs is overlapped and the coexistence interval of all NLRs is obtained. The modern climatic data recorded by the meteorological stations of China were extracted from the publications of the Information Department of Beijing Meteorological Center (IDBMC 1983a, b; 1984a, b, c, d). The 3D reconstruction of the Bezikelik Grottoes landscape in the 9th–13th centuries was completed using software of '3D Studio Max' and 'Adobe Photoshop'.

Results

Radiocarbon dating

Records document the absolute age of the Bezikelik Grottoes at ca. 5th–13th centuries AD. The AMS date obtained

from the plant remains (sample BZ-1) recovered form Cave No. 37 was ca. 1,140 years BP, and was calibrated to calendar years AD 880–970 cal (68.2% probability), i.e. the middle of the 9th–10th centuries, which is consistent with the documented age (Table 1). Based on the archaeological data, sample BZ-2 dates from the 10th–13th centuries, and samples BZ-3, 4 and 5 date from the 10th–11th centuries, but the radiocarbon dates of these samples likely may not be consistent with the historical records. In this regard, Liu et al. (2018) indicated that the radiocarbon dates of ancient cities in the Heihe River Basin did not correspond well to those from historical documents.

Pollen assemblage

A total of 33 types of palynomorphs were identified from the samples, including 20 families and 13 genera (Table 2). The selected palynomorphs are shown in Figs. 2, 3, and 4. The pollen assemblage is dominated by angiosperm pollen (RA: 83.5%), mainly comprising woody plants *Juglans* (18.2%) and Elaeagnaceae (8.0%), and herbaceous plants Poaceae (16.6%), Chenopodiaceae (13.6%) and *Artemisia* (10.4%). The relative abundance of gymnosperm pollen is 14.2%, mainly consisting of *Ephedra* (13.4%). Fern spores are represented by Polypodiaceae with a low percentage value (0.6%) (Fig. 5).

The 9th–10th centuries (sample BZ-1)

The angiosperm pollen (91.0%) dominates in this period, among which Poaceae is the dominant element (34.3%). Other important taxa include *Juglans* (14.2%), Apiaceae (9.6%), Chenopodiaceae (8.4%), Elaeagnaceae (7.5%), Zygophyllaceae (7.2%) and *Artemisia* (3.6%). *Vitis* pollen occurs sporadically (0.3%). The gymnosperm *Ephedra* pollen is fairly well represented (7.2%) (Fig. 6).

The 10th–11th centuries (samples BZ-3, 4, 5)

The relative abundance of angiosperm pollen decreases to 77.8%, in particular Poaceae pollen decreases sharply to 1.1%. At the same time the relative abundance of Chenopodiaceae (19.3%), *Juglans* (18.8%), *Artemisia* (16.1%), *Tamarix* (9.9%) and *Ephedra* (17.9%) pollen increase considerably (Fig. 6). Fern spores, viz. Polypodiaceae occur in small numbers (1.7%).

The 10th–13th centuries (sample BZ-2)

In this interval, the angiosperm pollen increases up to 81.6%. Specifically Poaceae (14.2%), Elaeagnaceae (12.1%) and *Juglans* (21.6%) increase rapidly, while Chenopodiaceae

Table 2 Extracted palynomorphs and their relative abundance (%)

Age (century AD)	9–10th	10–11th	10–13th
Adobe samples	BZ-1	BZ-3, 4, 5	BZ-2
Pteridophytes			
Polypodiaceae	–	1.7	–
Gymnosperm			
Ephedra	7.2	17.9	15.1
Picea	0.6	0.6	0.5
Pinus	–	0.4	0.3
Angiosperm			
Corylus	–	0.1	–
Juglans	14.2	18.8	21.6
Ulmus	0.9	0.3	1.6
Salix	0.6	0.5	0.3
Castanea	0.3	1.2	1.1
Olacaceae	–	0.1	–
Fabaceae	0.3	0.9	0.3
Poaceae	34.3	1.1	14.2
Tamarix	0.3	9.9	1.9
Elaeagnaceae	7.5	4.4	12.1
Thymelaeaceae	–	0.1	–
Zygophyllaceae	7.2	2.7	0.5
Caprifoliaceae	–	0.4	–
Chenopodiaceae	8.4	19.3	13.2
Convolvulaceae	1.2	0.1	0.5
Malvaceae	0.3	0.1	0.3
Solanaceae	0.3	–	–
Ranunculaceae	–	–	1.1
Rosaceae	0.3	0.1	–
Vitis	0.3	–	–
Boraginaceae	–	0.1	–
Onagraceae	–	0.1	–
Apiaceae	9.6	0.3	–
Artemisia	3.6	16.1	11.5
Asteraceae	0.6	1.1	1.1
Lamiaceae	0.6	–	–
Brassicaceae	–	–	0.3
Cyperaceae	–	0.1	0.1
Typha	–	0.1	–
Unknown	1.2	1.7	2.5

(13.2%), *Artemisia* (11.5%), *Tamarix* (1.9%) and *Ephedra* (15.1%) pollen decrease (Fig. 6). Fern spores are absent.

Plant remains

Four species of gramineous plant remains were identified in sample BZ-1, including *Aeluropus pungens* var. *pungens* and three cereals, viz. *Panicum miliaceum*, *Triticum aestivum* and *Hordeum vulgare* var. *coeleste* (Fig. 7). The characteristics of each plant remain are described as follows.
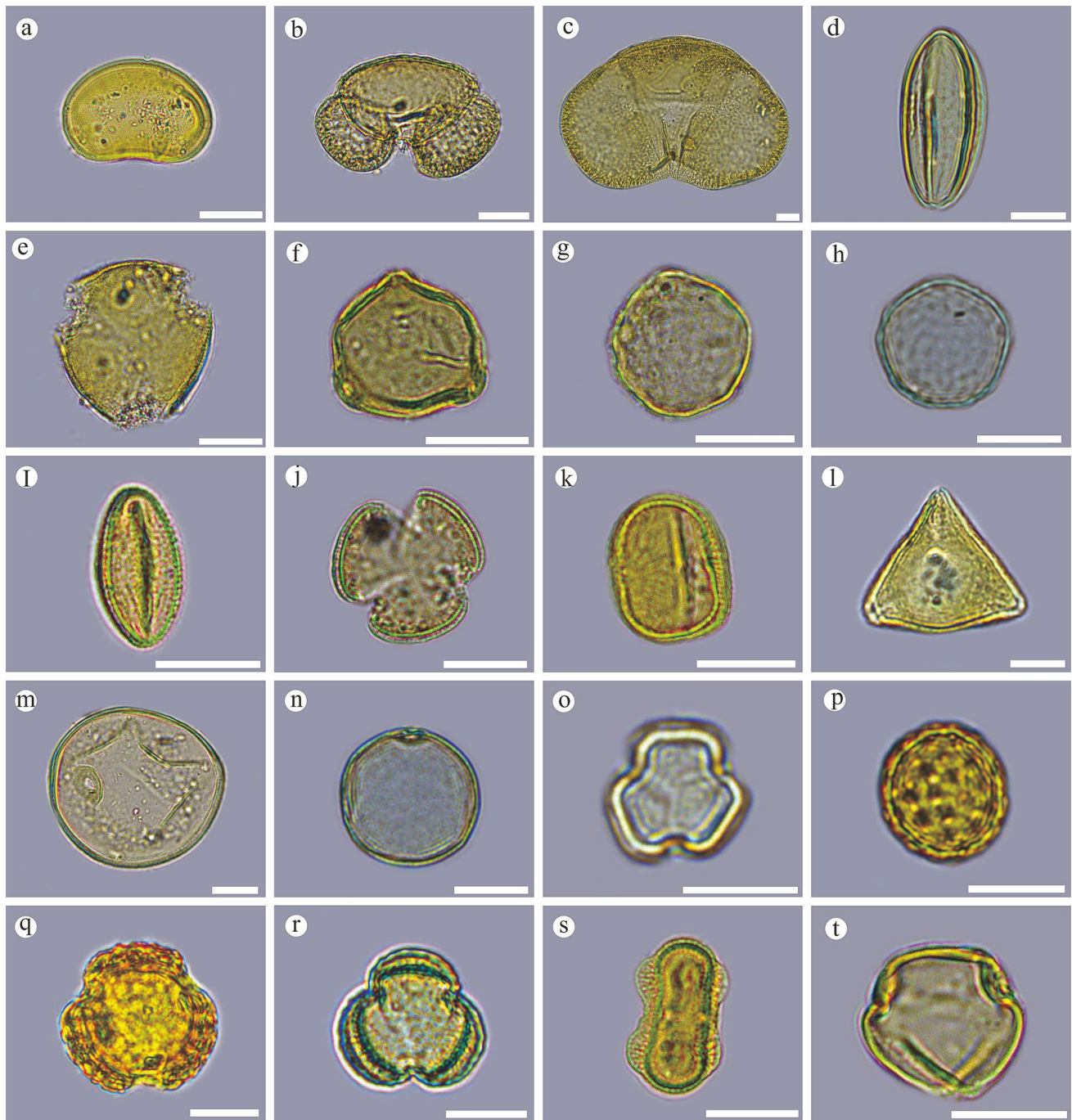
Fig. 2 Selected palynomorphs (LM) recovered from the samples of Bezikelike Grottoes, **a** Polypodiaceae, **b** *Pinus,* **c** *Picea,* **d** *Ephedra*, **e** Rosaceae, **f** *Corylus,* **g** *Juglans*, **h** *Ulmus,* **i**. *Salix*, **j**, **k** Fabaceae, **l** Elaeagnaceae, **m**, **n** Poaceae, **o** *Vitis*, **p** Chenopodiaceae, **q** Asteraceae, **r** *Artemisia*, **s** Apiaceae, **t** Solanaceae; scale bar = 20 μm

Aeluropus pungens var. *pungens*

The unearthed specimen is a spikelet (Fig. 7c) (specimen No. BZKLK-1). The spikelet is 6.5–9.4 mm in length and 2.3–4.6 mm in width, comprising 8–12 florets.

Panicum miliaceum

The unearthed specimens are four caryopses with lemma and palea (Fig. 7f) (specimen No. BZKLK-2). The lemma is smooth and hard on the back, and is involute and clings

Fig. 3 Selected palynomorphs (LM, SEM) recovered from the samples of Bezikelike Grottoes, **a–c** Polypodiaceae, **d–f** *Picea*, **g–i** *Tamarix,* **j–l** *Juglans*, **m–o** Convolvulaceae; scale bar (white) = 20 µm, (red) = 5 µm
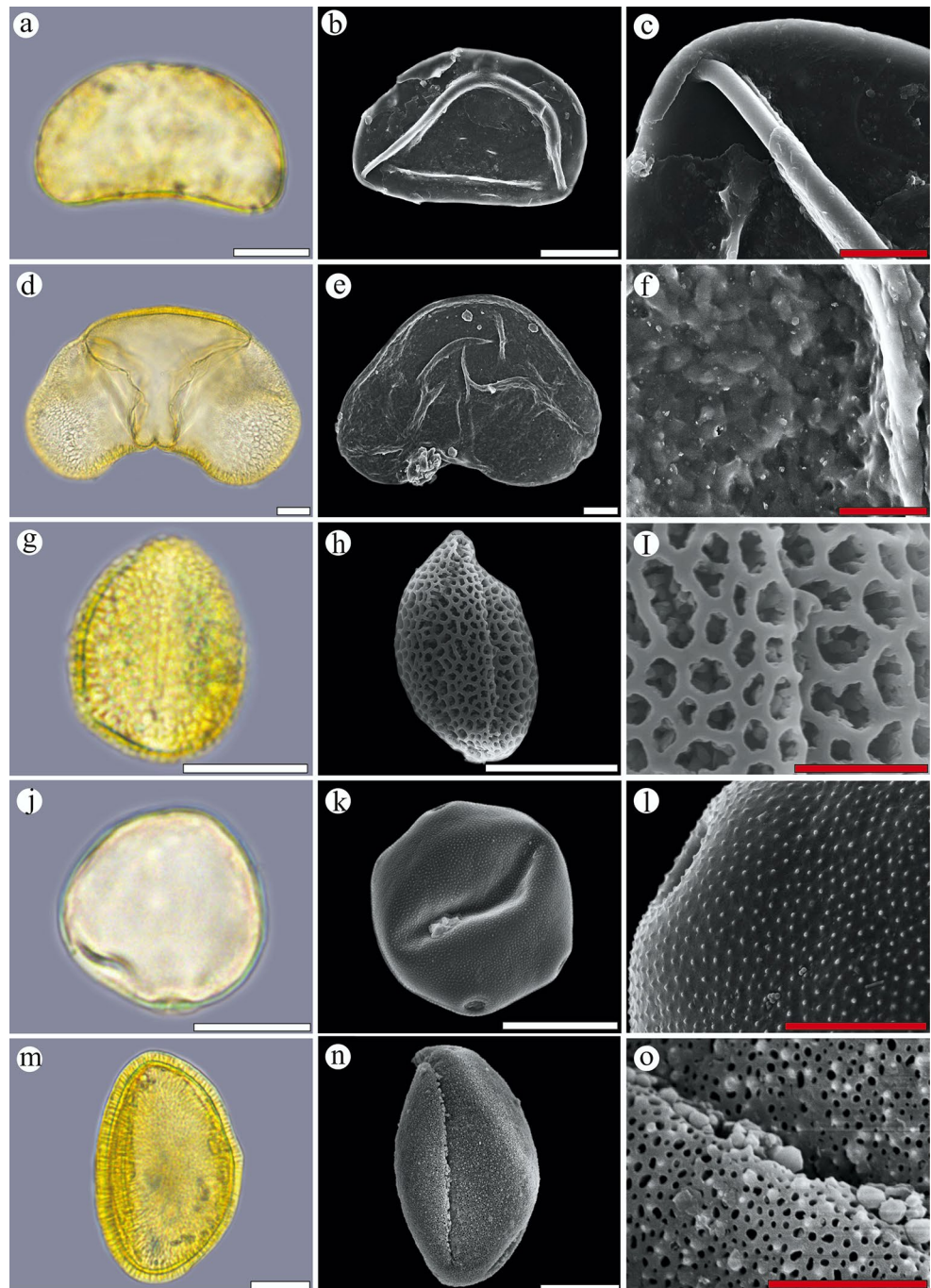
to the homogeneous palea. Palea's apex is protruding from the lemma. Lemma and palea combined are 2.5–3.3 mm in length, 1.4–1.9 mm in width and 0.9–1.1 mm in thickness.

Triticum aestivum

The unearthed specimens are three caryopses (Fig. 7i) (specimen No. BZKLK-3). The caryopsis is shriveled, ellipsoid, apex hairy, and has an abdominal longitudinal furrow. The average length of the caryopsis is 4.4–5.6 mm, average width 1.7–2.5 mm and average thickness 1.1–1.7 mm.

Hordeum vulgare **var.** *celeste*

The unearthed specimen is a spikelet (Fig. 7l) (specimen No. BZKLK-4). The spikes are yellow brown, and spikelets arranged tightly with an average length of 27.6 mm, 14 mm wide and 3 mm thick. The rachis is usually composed of 15 to 20 segments, each of which contains three

Fig. 4 Selected palynomorphs (LM, SEM) recovered from the samples of Bezikelike Grottoes, **a–c** Chenopodiaceae, **d–f** Asteraceae, **g–i** Elaeagnaceae, **j–l** Apiaceae, **m–o** Poaceae; scale bar (white)=20 µm, (red)=5 µm
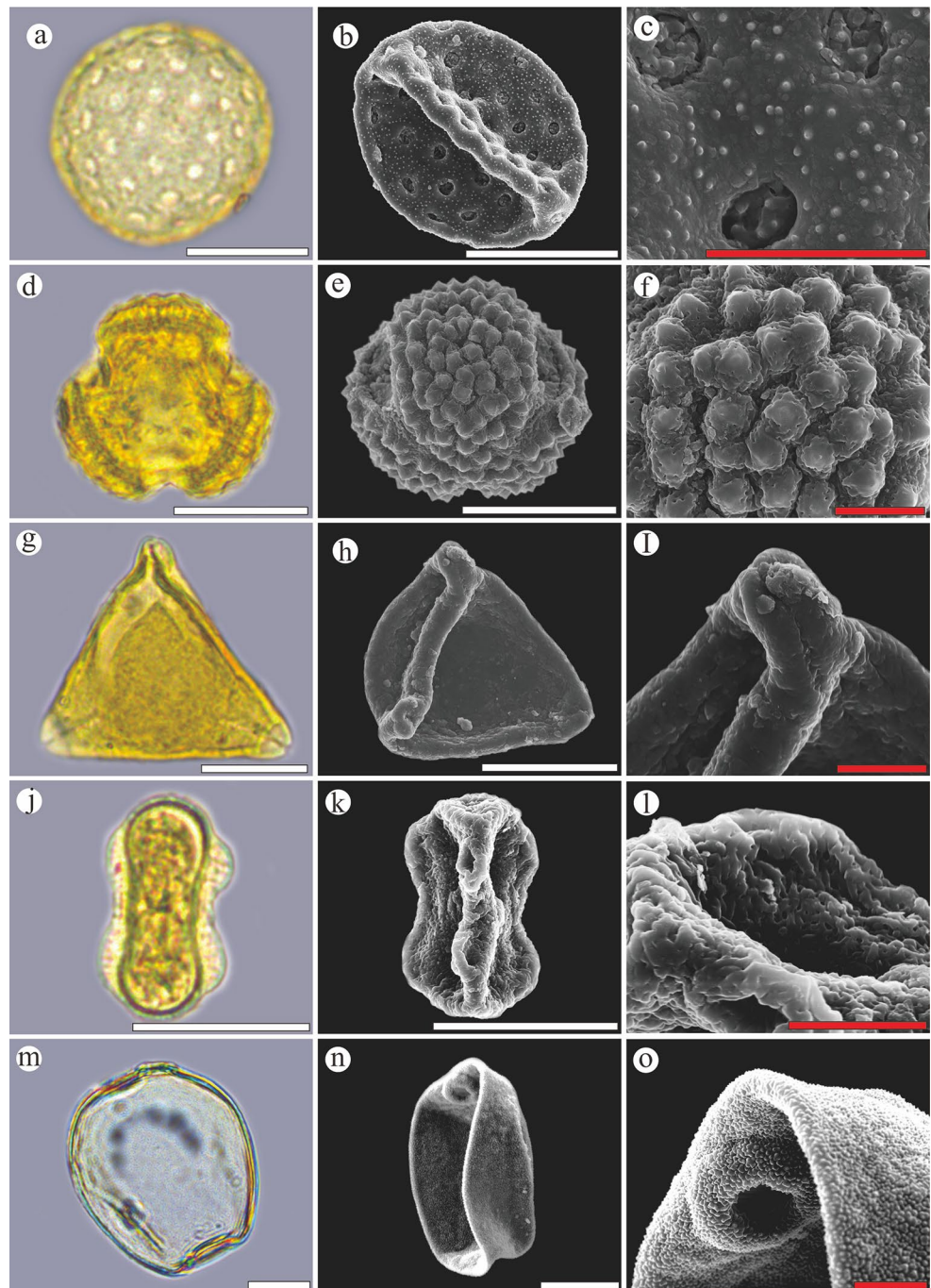
spikelets, which form a triple spikelet. The triple spikelet is alternate on the rachis, and each spikelet consists of two glumes and one fertile small flower. The glumes are lanceolate, apex extending into awn. The spikelet is conical, densely spreading villous, with an average length of 11.6 mm. Lemma and palea are on a small spike, papery, margin membranous.

Charcoal

The area concentration and particle concentration of the charcoal (Fig. 8) in the samples are shown in Table 3. The area concentration of the charcoal in sample BZ-1 is distinctly higher than that of the other samples. In all the samples, the particle concentrations of 0–50 µm
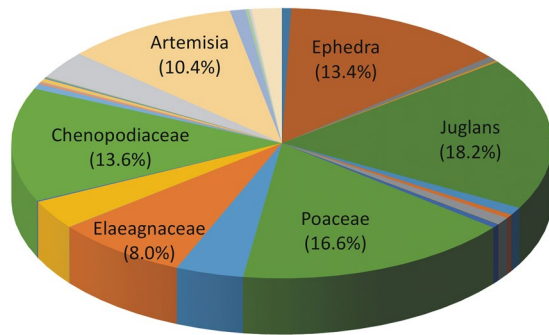
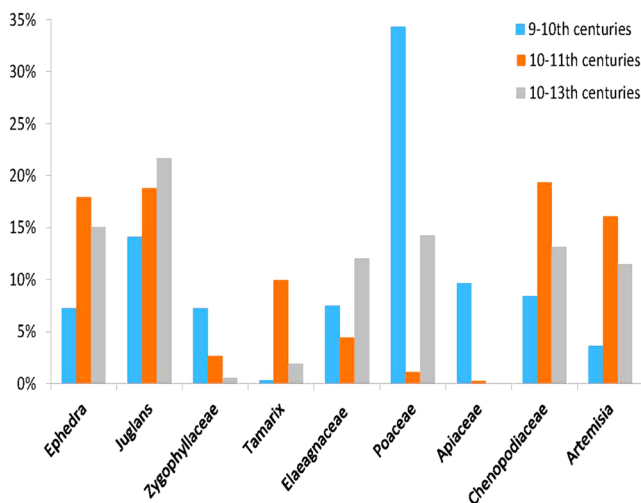Fig. 5 Dominant palynomorphs in samples and their relative abundance

Fig. 6 Major palynomorphs and their relative abundance in the samples of different periods

charcoal are significantly higher than those of 50–100 µm and > 100 µm.

Ancient vegetation

The A/C ratio (A: *Artemisia*, C: Chenopodiaceae) has been widely used in distinguishing the different vegetation of arid areas (Yan 1991; Weng et al. 1993; Zhao et al. 2012). Based on Luo et al.'s (2007) study on surface soil pollen of Xinjiang, the A/C ratio (median value) of desert was 0.57, steppe 1.26, desert-steppe 0.57–1.26, thus an A/C ratio of 0.88 in sample BZ-2 and 0.84 in samples BZ-3, 4 and 5 at the Bezikelike Grottoes is indicative of desert-steppe during the 10th–11th centuries and 10th–13th centuries, respectively. The main components of vegetation include herbaceous plants such as Poaceae, Chenopodiaceae, *Artemisia* and Apiaceae, woody plants comprising Zygophyllaceae, Elaeagnaceae, *Ephedra*, *Tamarix* and *Juglans*. An A/C ratio

of 0.43 in sample BZ-1 suggests desert vegetation during the middle of the 9th–10th centuries, however, large quantities of Poaceae pollen, high concentrations of charcoal and cereal remains in the samples indicate that human activities were frequent during this period, and when steppe vegetation was disturbed by human activities, it would lead to a low A/C ratio. Therefore, at least desert-steppe occurred during this period.

Ancient climate

Based on pollen data (Table 2), the climate from the 9th century to the 13th century at the Bezikelike Grottoes was quantitatively estimated by the coexistence approach (Table 4).

The mid-9th–10th centuries

The MAT was 8.5–19.8 °C (mean value: 14.2 °C) with the two boundary taxa of *Vitis* and *Ephedra*. The mean temperature of the warmest month was 20.5–28 °C (mean value: 24.3 °C) with the bordering taxa of *Juglans* and Chenopodiaceae. For the mean temperature of the coldest month, the interval of 0.2–11.9 °C (mean value: 6.1 °C) is determined by lower boundary taxon *Vitis* and upper one *Ephedra*. The difference between the warmest and coldest months was 13.6–26.1 °C (mean value: 19.9 °C) with the lower and upper taxa being *Vitis*. The MAP is 654.1–1,113.3 mm (mean value: 883.7 mm) delimited by the bordering taxa of *Vitis* and *Ephedra*.

The 10th–11th centuries and 10th–13th centuries

The MAT was 5.7–19.8 °C (mean value: 12.8 °C) with the two boundary taxa of *Castanea* and *Ephedra*. The mean temperature of the warmest month was 20.5–28 °C (mean value: 24.3 °C) with the bordering taxa of *Juglans* and Chenopodiaceae. For the mean temperature of the coldest month, the interval of -10.2–11.9 °C (mean value: 0.9 °C) is determined by lower boundary taxon *Castanea* and upper one *Ephedra*. The difference between the warmest and coldest months was 12.8–35 °C (mean value: 23.9 °C) with the lower and upper taxa of *Picea* and *Castanea* respectively. The MAP was 549.9–1,113.3 mm (mean value: 831.6 mm) delimited by the bordering taxa of *Castanea* and *Ephedra*.

3D reconstruction of ancient environment

The environment of Turpan in the 9th–13th centuries was reconstructed and visualized in a 3D presentation based on the investigation of ancient vegetation and climate at the Bezikelike Grottoes (Supplementary Fig. 2). In the 9th–13th centuries, the landscape of the Bezikelike region was composed of valley, village and mountains. Temperate
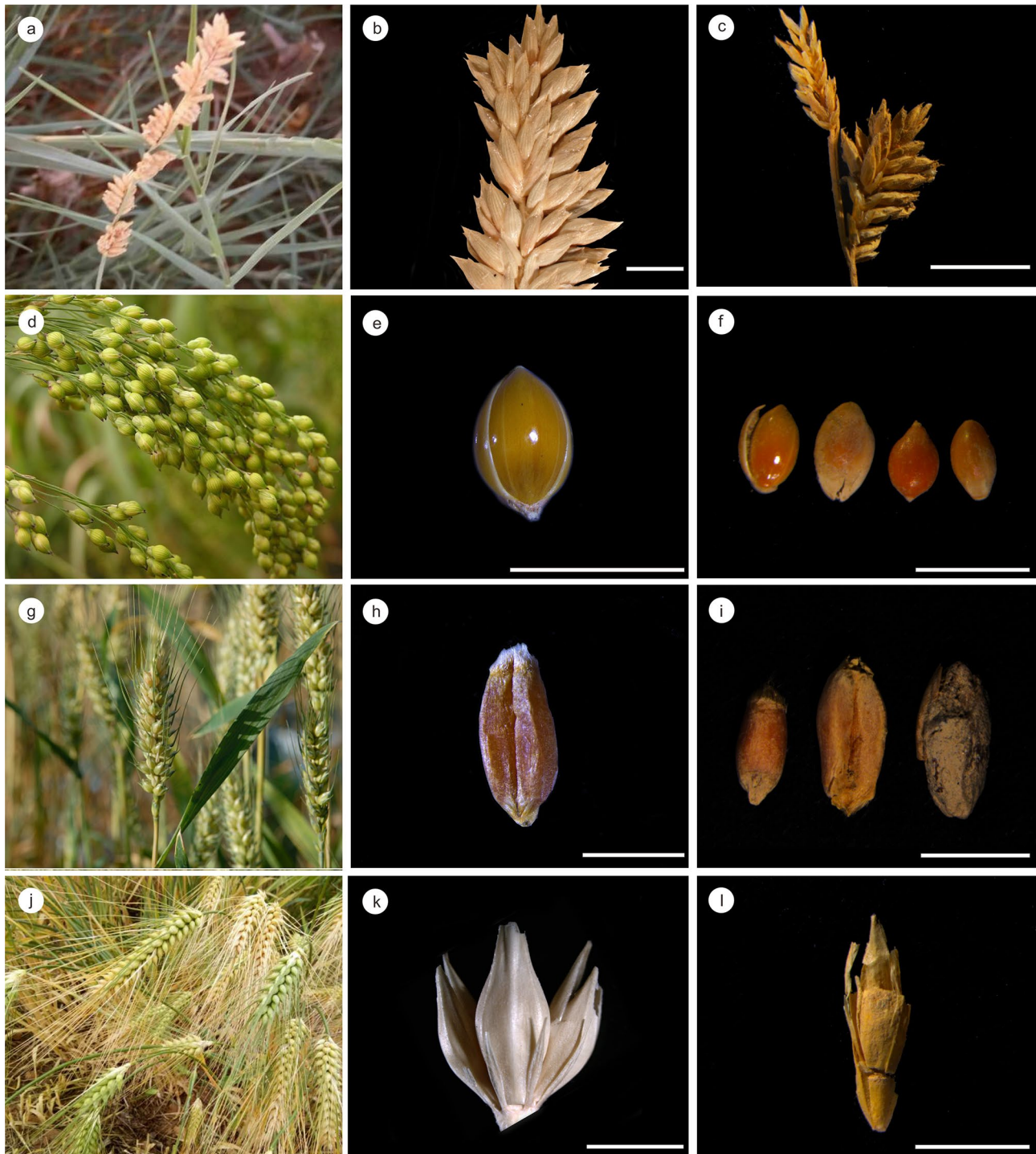
Fig. 7 Plant remains unearthed from the ruins and their modern counterparts, **a** *Aeluropus pungens* var. *pungens*, **b** Modern spikelet of *A. pungens* var. *pungens*, **c** Spikelet remain of *A. pungens* var. *pungens*, **d** *Panicum miliaceum*, **e** Modern caryopsis of *P. miliaceum*, **f** Caryopsis remain of *P. miliaceum*, **g** *Triticum aestivum*, **h** Modern caryopsis of *T. aestivum*, **i**. Caryopsis remain of *T. aestivum*, **j** *Hordeum vulgare* var. *coeleste*, **k** Modern spike of *H. vulgare* var. *coeleste*, **l** Spikelet remain of *H. vulgare* var. *coeleste*; scale bar = 5 mm (b, c, e, f, h, i, l)

vegetation of desert-steppe predominated in this area with widespread herbs—Poaceae, Chenopodiaceae, *Artemisia*, and numerous shrubs – *Ephedra*, *Tamarix*, Elaeagnaceae and Zygophyllaceae. The Bezikelike Grottoes were constructed in the western cliff of the valley. A river flowed through the valley and village, and the aquatic plant *Typha*
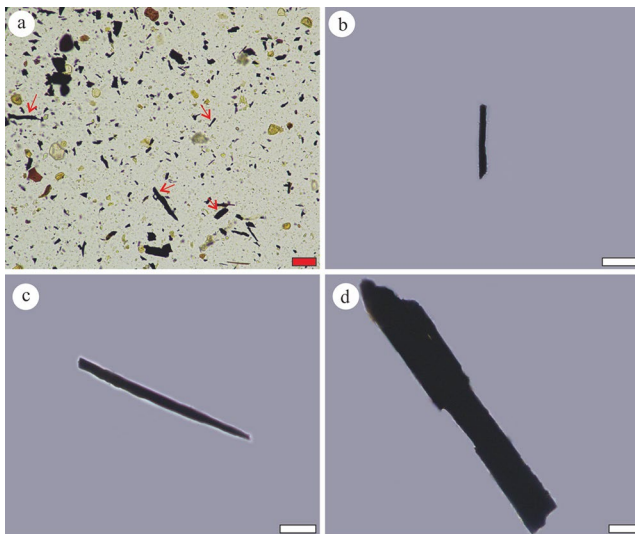
Fig. 8 Different size-class of charcoal in the samples, **a** Charcoal under 100×light microscope, **b** 0–50 μm charcoal, **c** 50–100 μm charcoal, **d** >100 μm charcoal; scale bar (red)=80 μm, (white)=20 μm

Table 3 The area concentration and particle concentration of the charcoal in the samples

Sample No	11 touch point-counts method	Size-classes method		
	Area concentration (cm²/g)	0–50 μm (grains/g)	50–100 μm (grains/g)	>100 μm (grains/g)
BZ-1	0.91	104,045	4,009	364
BZ-2	0.03	3,865	168	42
BZ-3	0.02	1,298	16	0
BZ-4	0.06	6,255	83	28
BZ-5	0.03	2,281	22	22

grew on its banks. Arable fields and vineyards were visible around the village, along with a few deciduous trees such as *Juglans*, *Ulmus* and *Salix*.

Discussion and conclusions

Vegetation, climate and human activities in the 9th–13th centuries at Turpan

The pollen assemblages revealed that the vegetation around the Bezikelike Grottoes was dominated by herbaceous plants such as Poaceae, Chenopodiaceae and *Artemisia* in the 9th–13th centuries, accompanied by shrubby plants such as *Ephedra*, *Tamarix*, Elaeagnaceae and Zygophyllaceae, and arboreal *Juglans*, which generally reflected the vegetation landscape dominated by desert steppe. Although the A/C ratio in the sample from the mid-9th to 10th centuries suggests that the vegetation was desert vegetation at that time, the A/C ratio may be lower because of the influence of human activities on steppe vegetation. For example, when ancient people reclaimed parts of the steppe to plant crops, large quantities of Poaceae pollen may be found in the sediments alongside *Artemisia*, *Ephedra* and Chenopodiaceae. It may reduce the total sum of *Artemisia* and Chenopodiaceae pollen, finally resulting in a lower A/C ratio. Therefore, in this case only judging the vegetation type according to the A/C ratio will lead to a false conclusion.

The climate of the 9th–13th centuries in Turpan is recorded in historical documents. For example, Turpan experienced droughts in AD 840 and 843, consistent with the unusual warmth of Japan in the 9th century, and this period was 0.5–1 °C warmer than at present (Li 1985). Our quantitative estimation based on pollen data shows that the MAT in Turpan during the mid-9th–10th centuries was about 0.3 °C higher than today, while the annual precipitation was about 880 mm at that time (Table 4).

In the 10th century, the climate changed from warm to cold, and became more humid. This lasted until the end of the 13th century. The temperature was 1 °C lower than the present value, and then gradually recovered until it was about 1 °C higher than today (Li 1985). For example, in AD 939, a blizzard caused the death of sheep and horses. Several consecutive years of snow disasters and epidemics seriously destroyed the social economy of the Uygur, which accelerated the collapse of the Uygur regime, and a gradual decline in the Uygur culture. In AD 970, the rainfall on one occasion

Table 4 Comparison of climate in Turpan at present, in the 5th century and 9th–13th centuries (the modern climate data are cited from Abdirahman et al. 2009)

| Climatic parameters	5th century	9–10th centuries	10–11th 10–13th centuries	Modern
MAT (°C)	15.3	14.2	12.8	13.3–13.9
WMT (°C)	25.4	24.3	24.3	32.7
CMT (°C)	−1.8	6.1	0.9	−9.5
DT (°C)	24.0	19.9	23.9	42.2
MAP (mm)	1004.2	883.7	831.6	16.8

in Turpan reached 16–17 mm, and houses were destroyed. The present study shows that the MAT in the 10th–11th centuries and 10th–13th centuries was about 1.1 °C lower than that of today, and the annual mean precipitation was about 830 mm (Table 4).

Previously, Tang et al. (2014) quantified the climate of the Tuyoq Grottoes in the 5th century, so we are able to make a comparison between the 5th and 9th–13th centuries. The Turpan area experienced a warm period in the 5th century, with a MAT about 1.4 °C higher than today (Tang et al. 2014), while the MATs for the mid-9th–10th, 10th–11th and 10th–13th centuries were about 1.1–2.5 °C lower than that in the 5th century. The comparison indicates that the climate in Turpan underwent a cooling trend from the 5th century to 9th–13th centuries. The variations of MAT during the 5th, mid-9th–10th, 10th–11th and 10th–13th centuries are basically consistent with the qualitative curves of the temperature variations in Xinjiang, western China during the last 3,000 years (Fig. 9a). However, the warm climate in Turpan in the 5th century contrasts with the cold climate in eastern China, while the climate in the 9th–13th centuries in Turpan is consistent with the trend and amplitude in eastern China

(Fig. 9a). The MAPs in the 9th–13th centuries were about 120–170 mm lower than that of the 5th century (Table 4). Although the MAP reconstructed in each period is as high as 800–1,000 mm, it is not really local precipitation. It represents ice and snow meltwater from the Tianshan Mountains, which was introduced to Turpan through rivers or springs to meet the water requirement of plant growth.

In the 9th–13th centuries, Turpan was climatically favourable for relatively abundant production of agricultural crops as shown by the discovery of cereals such as millet, common wheat and highland barley, the presence of a large number of gramineous pollen grains (up to 34.3% relative abundance), and a small amount of grape pollen. Similarly, wheat and grape were also cultivated in this region in the 5th century under a warmer and wetter environment than today (Tang et al. 2014). In addition, we found a high concentration of micro-charcoal (up to 104,000 grains/g of 0–50 μm charcoal particles) in the samples, indicating an increase in human activities during a period of agricultural productivity (Xu et al. 2002). All this evidence demonstrates that human activities were intense and agricultural production was moderately well-developed during this period.

Fig. 9 a Comparison of climate change in East China (red line) and West China (blue line) during the past 3,000 years (modified from Zhu 1973; Li 1985). Green box: 5th century in Turpan, Grey box: 9th–13th centuries in Turpan; b Schematic diagram showing the spread of Buddhism in Turpan
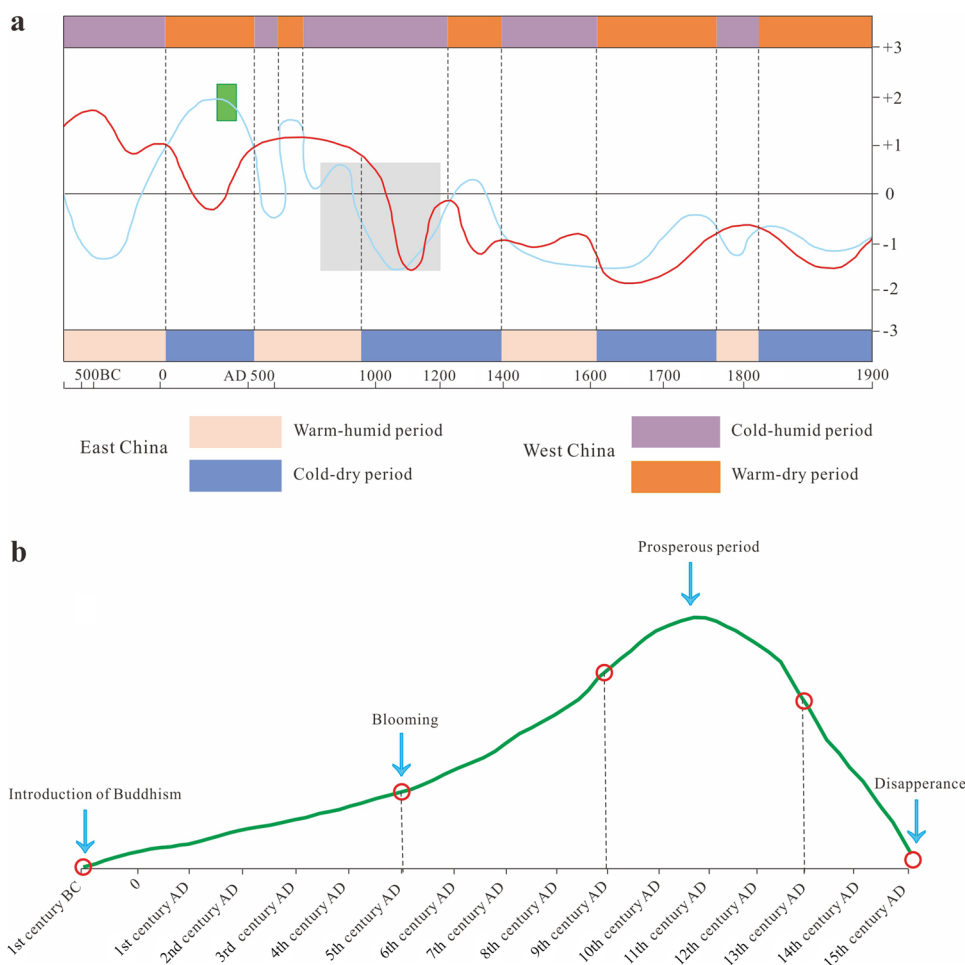
Buddhism in Turpan and its relationship with environment and human activity

Turpan is located at the eastern gateway of the ancient Western Regions, and is situated at the crossroads and transportation hub between China and the West. The opening of the Silk Road led to the development of a splendid ancient culture and civilization in this region, which became the hub of a multi-cultural society. In particular the Buddhist culture, which had a great influence on China, can be seen in the numerous grottoes and monastery ruins.

From the 6th century BC to the 5th century BC, early Buddhism spread mainly in northern India and along the Ganges River, then gradually prevailed in the entire Indian region and spread to the outside world, with its northern branch entering the central plains through Xinjiang (Zhao 2013). The Western Regions played an important role in the process of eastward spreading of Buddhism in ancient China. According to textual research, Buddhism was introduced into Turpan about the 1st century BC (Zhao 2013). In the 4th–5th centuries, a large number of caves were dug in the area of Gaochang. In the period of Qu's Gaochang, there were more than 130 Buddhist temples in Turpan. Some Buddhist temples reached nearly 10,000 m² in ancient Gaochang (Zhao 2013).

During the period of Uygur Gaochang (9th–13th centuries AD), the Bezikelike Grottoes were highly valued by the Gaochang Kingdom and became a monastery for the royal family. There were more than 50 Buddhist temples in Gaochang alone. Buddhism continued to flourish after it was introduced into Turpan. By the 10th century, Gaochang Uygur Buddhism began to be threatened and harassed by Islamic forces from Central Asia. In the late 13th century, the Turpan area became the scene of serious warfare, and the royal family of Gaochang was forced to move eastwards. As a result of successive years of war and plunder, the Turpan region's economy was seriously damaged, which was a heavy blow to Buddhism, which relied on the agricultural economy. By the late 15th century, Islam eventually replaced Buddhism as a popular religion in Turpan (Fig. 9b).

Buddhism left rich cultural relics in Turpan, including the Tuyoq, Shengjinkou and Bezikelike grottoes. From the existing Buddhist sites in Turpan, we can clearly see that Buddhism once flourished here. However, which factors drove the development of Buddhism in Turpan during the 5th and 9th–13th centuries? The influencing factors may include favourable climate, agricultural activity, expanding population etc., which were possibly related to the spread of Buddhist culture. Here we concentrate on how climate change and human activities promoted the development of Buddhism during the periods of the 5th and 9th–13th centuries. Generally, the favourable climate may have facilitated the development of agricultural production, which provides a good external environment for promoting the development of Buddhism. For example, in the 5th century the Tuyoq Caves in Turpan were occupied during a relatively warm period with abundant water. Ancient people engaged in agricultural activities such as wheat and grape cultivation, which provided an oasis environment for the prosperity of Buddhism (Tang et al. 2014). During the middle of the 9th century to the 10th century, the MAT at Bezikelike in Turpan was slightly cooler (about 1.1 °C lower) and the MAP was slightly lower (about 120 mm less) than those of the 5th century at Tuyoq. However, the climatic conditions could meet the needs of human beings in cultivating cereals such as millet, highland barley and wheat, suggesting that the agricultural economy at that time was fairly well-developed and created a suitable environment for the Buddhist culture of the Uygur Gaochang period. In summary, the climate in the 5th century seems to have been more favourable than that of 9th–13th centuries, but the acme of Buddhism was in the latter period (Figs. 9a, b). Apart from the favourable climate and agricultural activity, this prosperity can be explained by the great importance attached to Buddhism by the Gaochang Kingdom, so Buddhism flourished and Buddhist temples spread throughout the country at that time.

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