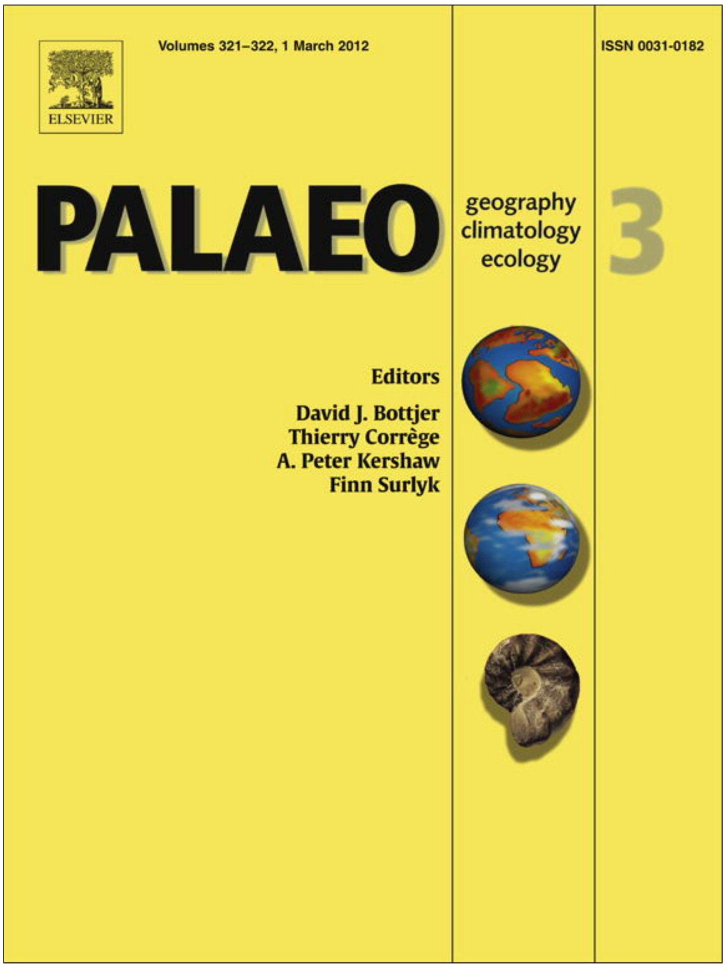

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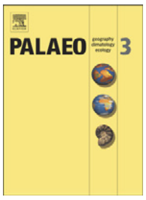

# Climatic variations over the last 4000 cal yr BP in the western margin of the Tarim Basin, Xinjiang, reconstructed from pollen data

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ABSTRACT

The nature of Holocene climate patterns and mechanisms in central Asia are open areas of inquiry. In this study, regional vegetation and climate dynamics over the last ca. 4000 years are reconstructed using a high resolution pollen record from the Kashgar oasis, on the western margin of the Tarim Basin, central Asia. *Ephedra*, Chenopodiaceae and Cannabaceae dominate the pollen assemblages, and Chenopodiaceae/*Ephedra* ratios and percentages of long-distance transported pollen taxa are used to infer regional variations in moisture and vegetation density. Three periods of increased humidity are identified, from ca. 4000–2620 cal yr BP, ca. 1750–1260 cal yr BP and ca. 550–390 cal yr BP and these periods coincide with the respective Holocene Bond Events 2, 1 and 0, which are reported in the North Atlantic. Any increase in strength, or southward migration, of the mid-latitude westerlies would result in more precipitation and meltwater on mountains surrounding the study site. Warm and dry conditions are detected between ca.1260 and 840 cal yr BP (AD 690–1110), and cool and wet conditions are detected between ca. 840 and 680 cal yr BP (AD 1110–1270), during the Medieval Warm Period (ca. AD 800–1200). The climate variations in the Kashgar region over the last 4000 years appear to have been dominated by changes to the westerly circulation system and glacier dynamics on surrounding mountains. However, the question of whether the Asian monsoon delivers precipitation to the western Tarim Basin, a region that is influenced by several climate systems, is still open to debate.

## 1. Introduction

Variability of the Asian monsoon and mid-latitude westerly systems has played a key role in driving Holocene climate changes in Asia, and is thus an important component of global change research programmes (Porter and An, 1995; Liu and Ding, 1998; An et al., 2000; Herzschuh, 2006a; Chen et al., 2008). The climate patterns and mechanisms of central Asia, where the mid-latitude westerlies are a dominant influence, are not as well understood as the monsoon-dominated areas of Asia (Chen et al., 2008; Li et al., 2011).

At present, theories about the nature of climatic patterns in central Asia are conflicting. One viewpoint is for an alternating warm–humid and cold–dry pattern (Yuan et al., 1998; Fang et al., 2002), while others argue for a warm–dry and cold–humid pattern (Li, 1990; Han and Qu, 1992). As for the main mechanisms influencing the climate of central Asia, some researchers argue that the mid-latitude westerlies dominated moisture changes during the Holocene (Chen et al., 2008; Liu et al., 2008), while others hold that the Asian monsoon was the most important factor affecting humidity, especially during the early and mid-Holocene (Mischke and Wünnemann, 2006; Rudaya et al., 2009; Zhong et al., 2010).

The Tarim Basin is a large inland basin in southern central Asia, which centres on the Taklimakan Desert. Oases occur along the margins of the basin and are fed by surface water and groundwater flowing from surrounding mountains (Xinjiang Expedition Team, Chinese Academy of Sciences, 1978a). The Tarim Basin, and surrounding mountains, are ideal areas for exploring past climatic changes in central Asia, as their fragile ecosystems are sensitive to climatic fluctuations, and they contain natural archives of past climate change, including glaciers, lakes, peat and loess deposits.

The main Holocene climate patterns in the Tarim Basin and surrounding areas are poorly understood, as are the dominant mechanisms that affect those climatic patterns. It is recognised that the mid-latitude westerlies and the Indian and East Asian monsoon system are the principle factors influencing the climate of the Tarim Basin. However, opinions differ about the relative importance of each of these factors. At Bangong and Sumxi basins, a moist period in the early Holocene has been attributed to a strengthened Indian and East Asian summer monsoon and more arid conditions in the

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middle to late-Holocene, to a weakened monsoon (Gasse et al., 1991, 1996). At Issyk-Kul, a humid period in the early to mid-Holocene is suggested to be due to either an increase in moisture brought by the mid-latitude westerlies or a strengthened Asian monsoon (Ricketts et al., 2001).

A change from dry conditions in the early Holocene to humid conditions in the mid-late Holocene at Bosten Lake is suggested to be connected to change in the westerly circulation and North Atlantic climate systems, rather than changes to the Asian monsoon (Chen et al., 2006). Glacier oscillations in the West Kunlun Mountains during the Late Glacial and Holocene are suggested to be affected by both conditions in the North Atlantic Ocean and changes to the mid-latitude westerlies, with only a minor influence from the south Asian monsoon (Seong et al., 2009).

Existing Holocene climate records in the Tarim Basin are few in number and sparsely distributed, and most lack sufficient sampling resolution and dating methods to allow regional climate patterns to be deduced. Holocene records of vegetation and climate change in the Kashgar area are few in number, and consequently understanding of past climate changes in this important region is limited. This study provides an AMS$^{14}$C dated, high resolution pollen record for a lacustrine sediment section near to Kashgar. The study aims to both reconstruct vegetation and climatic changes during the late Holocene in the western margin of the Tarim Basin, and improve understanding of the factors influencing climate in this region of central Asia.

## 2. Study area

The Tarim Basin is surrounded by high mountain ranges: the Tienshan Mountains (also referred to as Tianshan) to the north, the Pamir Mountains to the west, and the Kunlun Mountains to the south (Xinjiang Expedition Team, Chinese Academy of Sciences, 1978a). The climate of the Tarim Basin is characterised by extreme aridity. Mean annual precipitation is between 30 and 60 mm, and mean annual evaporation reaches 2536 mm. The climate of the Tarim Basin is influenced by Siberian high-pressure cells, the mid-latitude westerlies and the Indian Monsoon (Aizen et al., 2001). Moisture carried by the westerlies from the Atlantic Ocean, the Mediterranean, the Black Sea and the Caspian Sea, is the dominant source of precipitation on the Tienshan Mountains (Aizen et al., 2004). High mountain ranges to the basin's south prevent much of the precipitation associated with the Indian monsoon from reaching the Tarim Basin (Li, 1991).

Semi-desert and steppe vegetation dominate the southern slopes of the Tienshan and West Kunlun Mountains, in the western Tarim Basin. The vertical vegetation zones characterising the mountain slopes are classified with increasing elevation as: montane semi-shrubby desert, montane desert-steppe, montane steppe, alpine meadow and cushion-like vegetation. The montane desert zones are composed of *Sympegma*, *Iljinia*, *Ephedra*, *Zygophyllum*, *Gymnocarpos*, *Anabasis*, *Reaumuria* and *Artemisia*. The montane steppe zone is dominated by *Stipa*, *Agropyrum* and *Artemisia* (Xinjiang Expedition Team, Chinese Academy of Sciences, 1978b).

The alpine meadow and cushion-like vegetation zones are composed of *Kobresia*, *Sibbaldia* and *Androsace*. Patches of *Picea* forest occur in valleys on the shaded and humid southern slopes of the Tienshan Mountains, between 2300 and 3000 m a.s.l. *Picea* forest also occurs in wetter areas on the northern slopes of the West Kunlun Mountains, between 2800 and 3400 m a.s.l. (Xinjiang Expedition Team, Chinese Academy of Sciences, 1978b).

The Kashgar oasis is situated at the western margin of the Tarim Basin at an average altitude of 1300 m a.s.l. It is a huge alluvial–diluvial plain fed mainly by the Kealsu, Gaiz and Kushan rivers, which originated from Pamir and West Kunlun Mountains. The mean annual temperature is between 5 and 12 °C, mean annual precipitation ranges from 40 mm to 100 mm, and evaporation ranges from 1500 mm to 2500 mm depending on the terrain. Summers are hot but short, and winters are mild but prolonged. Natural vegetation in the oasis is characterised by shrubby species such as *Anabasis aphylla*, *Iljinia regelii*, *Kalidium schrenkianum* and *Ephedra przewalskii*. Small *Populus* forests occur along riverbanks (Xinjiang Expedition Team, Chinese Academy of Sciences, 1978b).

## 3. Study materials and methods

### 3.1. Sediment and dating

The Wupaer section (39°16′53.6″N, 75°35′43.6″E) is located near Wupaer Town, approximately 45 km southeast of Kashgar City, at an elevation of 1402 m a.s.l. (Fig. 1). The 855 cm deep section was exposed by erosive action of a small river. The sediments are composed of silts, sandy silts and silty sands and show considerable variation through the section (Table 1). The varied lithology is likely to be due to the sediment's duel origins: from melt-water deposits associated with spring floods, and from aeolian sand deposits derived from the Taklimakan Desert.

A total of four AMS$^{14}$C dates were obtained for the Wupaer section (Table 2). Three of the dated samples were composed of charcoal fragments, retrieved from the section at depths of 420–421 cm, 380 cm and 40 cm. The fourth date comes from a pollen residue sample, which was prepared separately from sediment taken at 840–845 cm depth. AMS$^{14}$C dating was conducted at the Australian Nuclear Science and Technology Organisation in Sydney. Dates were calibrated according to Reimer et al. (2004). We used a linear interpolation method to estimate ages through the section (Fig. 2). The Wupaer section has a calibrated age range of ca. 3950 to ca. 390 cal yr BP.

Accumulation rates through the section are relatively high. Average accumulation rates are calculated to be 0.189 cm/a, 0.102 cm/a, and 0.437 cm/a for the depths of 850–420 cm, 420–380 cm, and 380–0 cm respectively. Pollen preservation is generally expected to be better in sediments that are composed of clays and poorer in sediments composed sands. The relative fast accumulation rates of the sand- and silt-rich sediments of the Wupaer section would be expected to have resulted in lower proportions of pollen being preserved in the sediments. In addition to this, the sparse vegetation cover and low pollen productivity typical of arid ecosystems are also expected to contribute to low pollen concentrations.

### 3.2. Pollen analysis

A total of 105 samples were collected from the exposed sediment section for pollen analysis. Samples were taken at 10 cm intervals through the section, except between the depths of 100–200 cm and 350–450 cm where they were taken at 5 cm intervals. Pollen samples were processed using heavy liquid separation (Moore and Webb, 1978; Li and Du, 1999) and acetolysis (Erdtman, 1960). *Lycopodium* tablets were added to the samples to allow for estimation of pollen concentrations (Peck, 1974).

Samples sizes of 100 g were used to prepare pollen residues for the upper 160 cm depth, while samples sizes of 150 g were required for lower depths. At least 300 pollen grains were counted for each sample, except samples with extremely low concentrations, such as those between the depths of 435 and 600 cm (corresponding to pollen zone II in Fig. 3). Pollen morphological keys were used to identify pollen taxa (e.g., Xi and Ning, 1994; Wang et al., 1997). Pollen percentages are calculated from the total sum of arboreal and non-arboreal taxa identified in each pollen spectrum.

### 3.3. Interpretation methods

Previous publications on the vegetation and surface pollen of western China (Editorial Committee for Vegetation of China, 1980; Weng et al., 1993; Cour et al., 1999; Luo et al., 2009) were used to

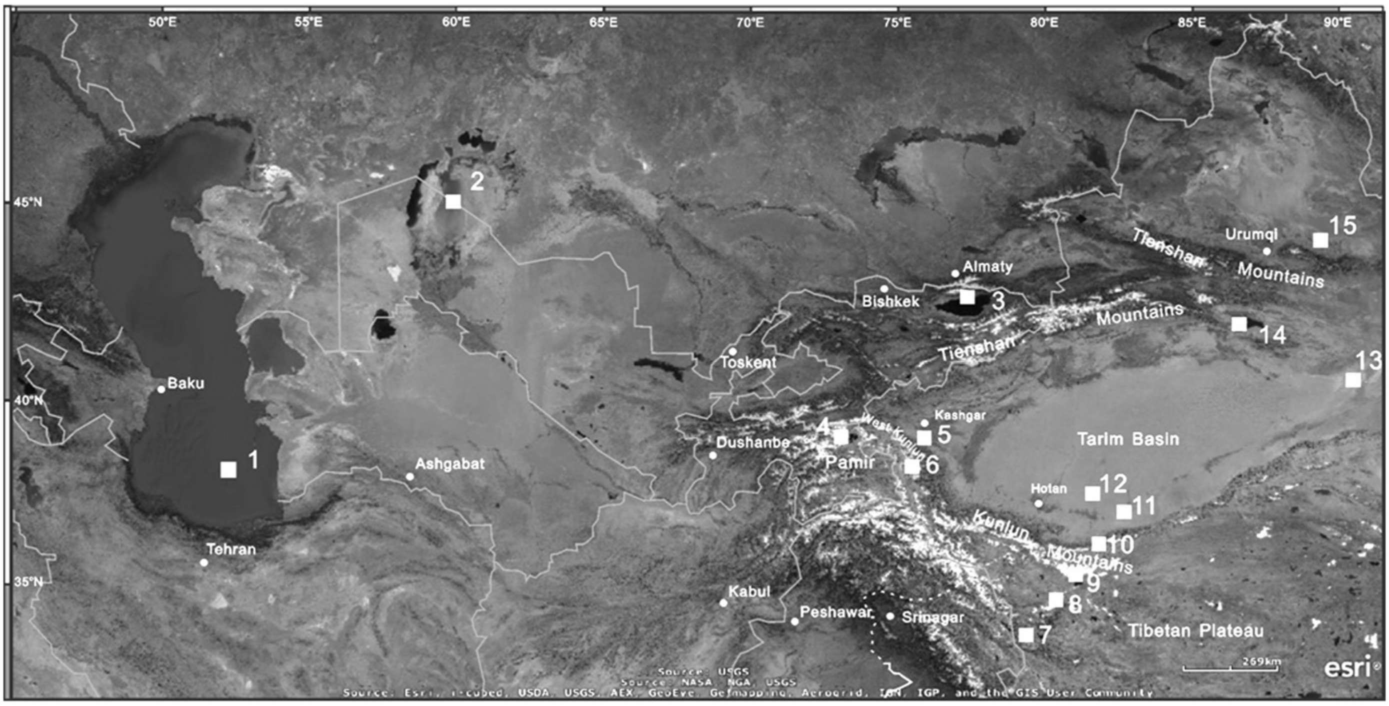

**Fig. 1.** The study site—Wupaer section and other sites mentioned in the paper:1, Caspian Sea (Leroy et al., 2007); 2, Aral Sea (Boomer et al., 2009); 3, Issyk-Kul Lake (Ricketts et al., 2001); 4, Kalakul Lake (Mischke et al., 2010); 5. Wupaer section (this study); 6, Muztag Ata and Kongur Shan (Seong et al., 2009); 7, Bangong Co (Gasse et al., 1996); 8, Sumxi Co (Fontes et al., 1993); 9, Guliya ice core (Shi et al., 1999) ; 10, KMA section (Tang et al., 2009); 11, Niya River section (Zhong et al., 2007); 12, Keriya River (Yang et al., 2002); 13, Lop Nur (Ma et al., 2008); 14, Bosten Lake (Chen et al., 2006); 15, Sichanghu section (Zhang et al., 2009).

interpret pollen data for the Wupaer section. In addition, some important pollen assemblages and indicator taxa were selected to interpret palaeoenvironmental and palaeoclimatic information.

Generally the ratio of *Artemisia* to Chenopodiaceae pollen (A/C) is used to reconstruct variations in effective moisture in arid areas (EL-Moslimany, 1990; Zheng et al., 2008). It is considered necessarily for Chenopodiaceae and *Artemisia* to compose at least 50% of a total pollen count before a reliable representation of moisture changes can be made (Sun et al., 1994). However, as the average percentage of Chenopodiaceae and *Artemisia* in the Wupaer section is relatively low (27.7%), it is not applied here. The climate of Tarim Basin is extremely dry, and the assemblages of surface pollen are dominated by Chenopodiaceae and *Ephedra*. As *Ephedra* tolerates drier conditions than Chenopodiaceae does, the ratio of Chenopodiaceae to *Ephedra* pollen (C/E) can be used as a proxy to indicate the moisture levels in the Tarim Basin (Cour et al., 1999; Luo et al., 2009). High C/E ratios indicate more humid conditions.

**Table 1**
A simplified description of the Wupaer section.

| Depth (cm) | Sediment description |
|---|---|
| 0–75 | Grey silt layer including plant roots |
| 75–120 | Grey sandy silt layer |
| 120–295 | Green-grey silt layer with two interbedded silt layers at 155–165 cm and 235–250 cm |
| 295–320 | Grey sandy silt layer |
| 320–380 | Grey silt layer |
| 380–435 | Brownish red silt layer including charcoal |
| 435–465 | Grey silty sand layer |
| 465–550 | Brownish yellow sandy silt layer with an interbedded silt layer at 490–505 cm and silty sand layer at 530–540 cm |
| 550–600 | Brownish grey silt |
| 600–625 | Brownish yellow silty sand |
| 625–725 | Brownish yellow silt with an interbedded silty sand layer at 675–685 cm |
| 725–855 | Brownish grey sandy silt with an interbedded silt layer at 750–785 cm and silty sand layer at 800–810 cm |

The component of long-distance transported pollen in the pollen assemblage is generally low when regional pollen production is high. But it is greater when the regional vegetation is sparse and its pollen production is low (Herzschuh et al, 2006b). Previous work in the Tibetan Plateau, Alashan Plateau, Former Soviet Union and Mongolia (Tarasov et al, 1998; Herzschuh et al, 2004; Herzschuh et al, 2006b) has confirmed that high percentages of long-distance transported pollen can be interpreted as an indicator of sparse vegetation, due to cold and/or dry climate conditions. Long-distance transported components such as *Pinus*, *Abies*, *Tsuga*, *Betula*, *Quercus*, *Castanea*, *Juglans*, *Platycarya*, Anacardiaceae, Meliaceae, and *Tilia* appear in the Wupaer section in periods of low pollen concentrations, and this is likely to reflect sparse vegetation cover at these times. It is likely that these tree pollen grains originated from distant sources outside the region and were transported to the site by wind.

## 4. Results

In total, 16 arboreal and 29 non-arboreal pollen types were identified in the Wupaer section (Table 3). The pollen of herbs and shrubs dominates the section (averaging 88.5%) and of those plant types, *Ephedra*, Chenopodiaceae and Cannabaceae dominate the pollen sum. Tree pollen has an average value of 11.5% throughout the section, of which *Picea* pollen occurs in highest proportions, contributing up to 70.8% of the terrestrial pollen sum.

**Table 2**
AMS$^{14}$C dating of the Wupaer section.

| Lab code | Depth (cm) | Sample type | $^{14}$C yr BP | $^{14}$C cal yr BP (1σ) |
|---|---|---|---|---|
| OZL461 | 40 | Charcoal | 400 ± 30 | 482 ± 24 |
| OZL464 | 380 | Charcoal | 1300 ± 35 | 1261 ± 23 |
| OZL461 | 420–421 | Charcoal | 1755 ± 50 | 1664 ± 61 |
| OZM252 | 840–845 | Pollen residue | 3570 ± 90 | 3897 ± 83 |

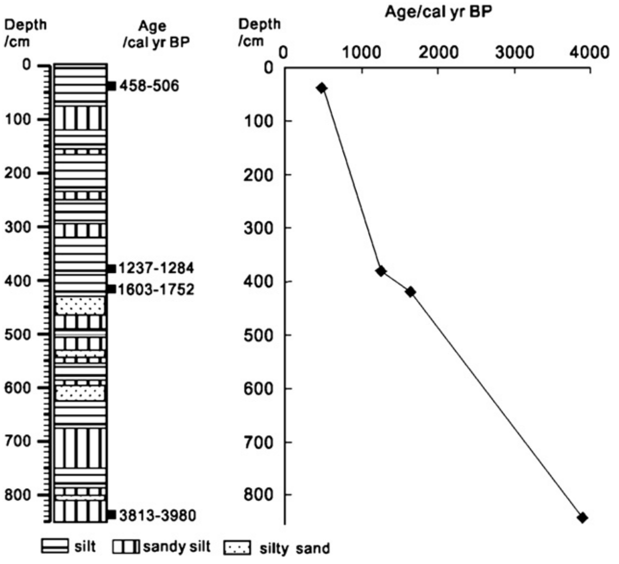

**Fig. 2.** Depth-age model for the Wupaer section.

The pollen assemblage was divided into seven pollen zones (PZ) that were chosen to reflect the main changes in pollen abundance and C/E ratios (Fig. 3).

PZ I (855–600 cm, ca. 3950–2620 cal yr BP): This zone is characterised by a high content of Cannabaceae (2.5–50.3%) which averages 21.5%. *Artemisia* and Chenopodiaceae compose 20.1% of the total pollen sum. *Ephedra* pollen accounts for, on average, 15.9% of the total pollen sum, but its contribution fluctuates considerably in this zone. Poaceae percentages reach 30.9% in the upper part of the zone but have an average for this zone of 8.0%. Long-distance transported pollen occurs in low percentages. *Tsuga* appears at 3200 cal yr BP and has a maximum percentage of 6.2% around 2800 cal yr BP. The C/E ratio ranges from 0 to 41 and has an average value of 5.7. Overall, the pollen assemblage and C/E ratios point to a relatively humid climate for this zone.

PZ II (600–435 cm, ca. 2620–1750 cal yr BP) is characterised by low pollen concentrations (around 1 grain/g). Cannabaceae pollen percentages are markedly lower than PZ I, while the percentages of long-distance transported pollen are higher (up to 58.8%) and dominated by *Pinus* (0–34.4%), *Quercus* (0–17.6%) and *Tsuga* (0–33.3%), which is a consequence of the sparse nature or absence of vegetation near the sampling site. The average C/E value is low in this zone (around 1). The high values of long-distance transported pollen and low values of C/E all indicate a drier climate in PZ II compared with PZ I.

**Table 3**
Pollen types in the Wupaer section.

| | |
|---|---|
| Trees | *Picea*, *Pinus*, *Abies*, *Tsuga*, *Salix*, *Ulmus*, *Betula*, *Corylus*, *Carpinus*, *Quercus*, *Castanea*, *Juglans*, *Platycarya*, Anacardiaceae, Meliaceae, *Tilia* |
| Shrubs and Herbs | *Artemisia*, Cannabaceae, Caprifoliaceae, Caryophyllaceae, Chenopodiaceae, Compositae, Cruciferae, Elaeagnaceae, *Hippophae*, *Ephedra*, Gentianaceae, Geraniaceae, Leguminosae, Liliaceae, Malvaceae, Oleaceae, Poaceae, Polygonaceae, Rhamnaceae, Ranunculaceae, Rosaceae, *Tamarix*, *Thalictrum*, Thymelaeaceae, Zygophyllaceae, *Nitraria*, Umbelliferae |
| Hydrophytes | *Sparganium*, *Typha* |

PZ III (435–380 cm, ca. 1750–1260 cal yr BP) has increased pollen concentrations compared with the underlying zone. Compositae dominates the pollen assemblages and has an average of 32.6% in this zone. *Tamarix*, *Artemisia* and Poaceae occur to a lesser extent. Percentages of long-distance transported pollen are markedly less than in PZ II, and *Tsuga* pollen disappears entirely. C/E ratios range from 0.5 to 16.7 and have an average value of 5.4, indicating a relatively humid climate.

PZ IV (380–195 cm, ca. 1260–840 cal yr BP) is characterised by high percentages of *Ephedra* (16.8–90.8%); the average is 47.5%. *Tamarix* content ranges between 0 and 62.8% and has an average of 8.5%. Compositae, Chenopodiaceae, *Artemisia*, and Poaceae percentages are lower than in the underlying zone, while the percentages of long-distance transported pollen are higher (especially *Pinus*, *Betula*, *Quercus*, *Castanea* and *Carpinus*). Overall the pollen assemblage indicates sparse vegetation cover. C/E ratios range between 0 and 0.6 with an average of 0.2, indicating a dry climate.

PZ V (195–125 cm, ca. 840–680 cal yr BP) is characterised by markedly higher *Picea* percentages (42.1% on average), which coincide with low percentages of *Ephedra*. *Picea* has strict precipitation and moisture requirements, in addition to temperatures requirements. Generally, *Picea* cannot grow well where precipitation is less than 500 mm/yr (Editorial Committee for Vegetation of China, 1980). Therefore *Picea* pollen in the Wupaer section is unlikely to have originated from forests growing near the site during late Holocene. The high percentages of *Picea* pollen suggest an expanded *Picea* forests on the West Kunlun and south Tienshan mountains, under moisture conditions.

*Tamarix* percentages rise in the upper part of this zone, reaching 36.2%. Poaceae, *Artemisia*, and Compositae respectively average 4.4%,

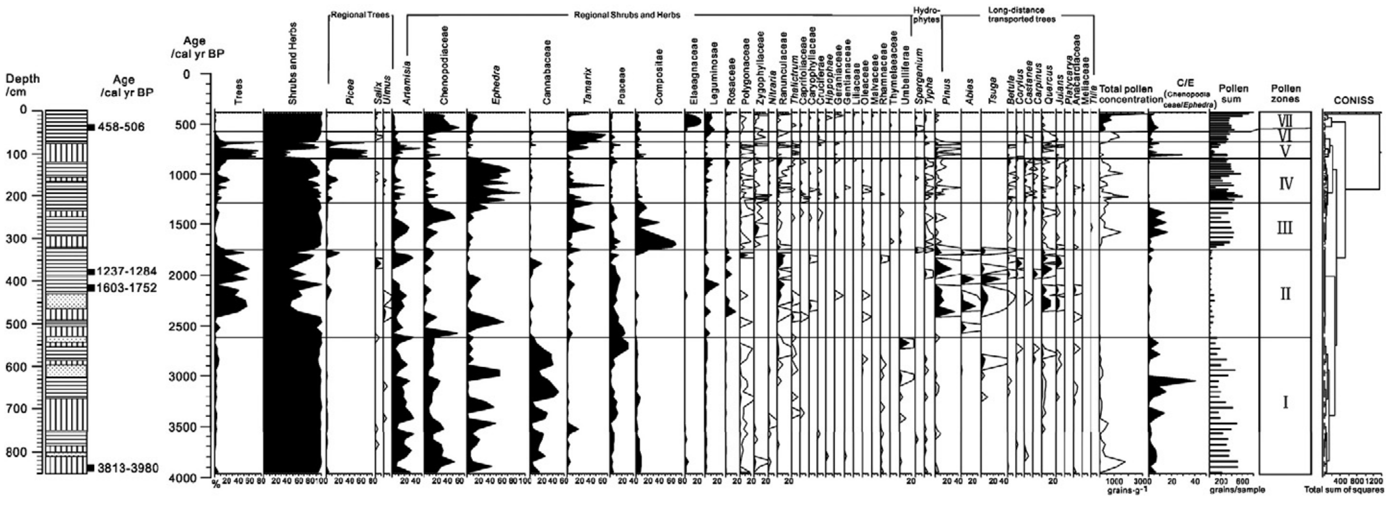

**Fig. 3.** Pollen percentages diagram of Wupaer section. 10× exaggeration for the less abundant taxa, 30× exaggeration for the total pollen concentration.

14.1% and 5.1% of the total pollen sum. Long-distance transported pollen occurs in low percentages. C/E ratios range between 0 and 29 and have an average of 4.5. Overall, the pollen assemblage and C/E ratios indicate a relatively moist climate.

PZ VI (125–75 cm, ca. 680–550 cal yr BP): *Tamarix* pollen dominates this pollen zone and contributes up to 49.2% of the total pollen sum. Associated taxa are Chenopodiaceae, *Artemisia*, and Poaceae. The lower boundary of this pollen zone is marked by a distinct decline of *Picea* pollen. C/E ratios range between 0.9 and 3.2 and have an average of 2.1, indicating a relatively dry climate. Higher temperatures and higher aridity characterise this period.

PZ VII (75–0 cm, ca. 550–400 cal yr BP) is characterised by having high percentages of Chenopodiaceae (39.1%) and Elaeagnaceae (15.6%). Leguminosae content is higher than in other parts of the section. Total pollen concentrations are high, up to 835 grains/g, and C/E ratios are between 2 and 8.1 and have an average of 4.3. The pollen assemblage and C/E ratios for this zone indicate a relatively humid climate.

## 5. Discussion

The western Tarim Basin lies in a climatic transition zone under the influence of the mid-latitude westerlies and Asian monsoon (Mischke et al., 2010). The glaciers on the Kunlun, Pamir and Tienshan Mountains also influence environments in the Tarim Basin, especially at the margins of the basin (Benn and Owen, 1998; Yang et al., 2002; Mischke et al., 2010).

The Wupaer pollen record presented here provides an opportunity to study vegetation and climate changes over the last 4000 years in the Kashgar area of the western Tarim Basin. The record also allows for comparison with paleoclimate records from other parts of central Asia, the North Atlantic Ocean and monsoon Asia. This study provides information about the nature of, and influencing factors on, climate changes in the western Tarim Basin during the late Holocene and contributes to understanding of climates during time periods of broad significance, such as the Medieval Warm Period (MWP) (around AD 800–1200) (Lamb, 1965; Broecker, 2001).

The pollen record, and particularly the high abundance of Cannabaceae, indicates that humid conditions prevailed in the region between ca. 4000 and 2620 cal yr BP. Punctuating this humid period were three drier periods occurring around 3500 cal yr BP, 3300 cal yr BP and 3000 cal yr BP. Humid conditions have been detected in other paleoclimate records in central Asia at this time. High meltwater inflow and high lake levels are reported from 4200 to 3500 cal yr BP at Lake Karakul in the Pamir Mountains (Mischke et al., 2010). Higher lake levels around 4000–3700 cal yr BP, 3400–3300 cal yr BP and 3000–2400 cal yr BP are reported at Bosten Lake in the northern Tarim Basin (Mischke and Wünnemann, 2006). Also, slightly wetter conditions are reported at sites in western Tibet from ca. 3400 to 2100 cal yr BP at Bangong Co and from ca. 3800 to 2600 cal yr BP at Sumxi Co (Fontes et al., 1993; Gasse et al., 1996).

The relatively humid period detected in the Wupaer record between ca. 4000 and 2620 cal yr BP coincides with the Holocene Bond Event 2 in North Atlantic deep-sea records (Fig. 4, Zone I) (Bond et al., 2001). Seong et al. (2009) suggested that the glacier advance around 3.3 ± 0.6 kyr BP in the Muztag Ata–Kongur Shan region was affected by a southward migration and increased strength of the mid-latitude westerly system, which are directly linked to conditions in the North Atlantic Ocean. A southward migration and increased strength of the mid-latitude westerlies would have increased the amount of winter snowfall on the mountains surrounding the Tarim Basin (Seong et al., 2009), and these conditions would have brought more meltwater to the Kashgar Oasis. The humid conditions detected at Wupaer between ca. 4000 and 2620 cal yr BP may have been caused by increasing meltwater from the Kunlun Mountains.

Vegetation cover was sparse from 2620 to 1750 cal yr BP, which is interpreted to reflect a relatively dry climate in the Kashgar area (Fig. 4, Zone II). The lowest meltwater inflow for the last 4000 years occurred between 2600 and 1900 cal yr BP at Lake Karakul in the Pamir Mountains (Mischke et al., 2010). However, in the south Caspian basin a later phase of water inflow has been observed from 2.1 to 1.7 cal. ka BP (Leroy et al., 2007). A low level phase has been recognised from ca. AD 0–400 in Aral Sea (Boomer et al., 2009). On the northern slopes of the Kunlun Mountains, conditions between 2600 and 1750 cal yr BP are reported to have been dry (Tang et al., 2009). Also coinciding with this period is a clear decrease in ice-rafted debris in North Atlantic Ocean deep-sea records (Bond et al., 2001) (Fig. 4, Zone II). A decrease in strength and northward migration of the westerlies is there for the probable cause for the dry climate between ca. 2620 and 1750 cal yr BP in Kashgar.

A return to more humid conditions at Wupaer is detected after 1750 cal yr BP, and this persisted until ca. 1260 cal yr BP (Fig. 4, Zone III). This humidity corresponds with the onset of wetter conditions on the northern slopes of the Kunlun Mountains around

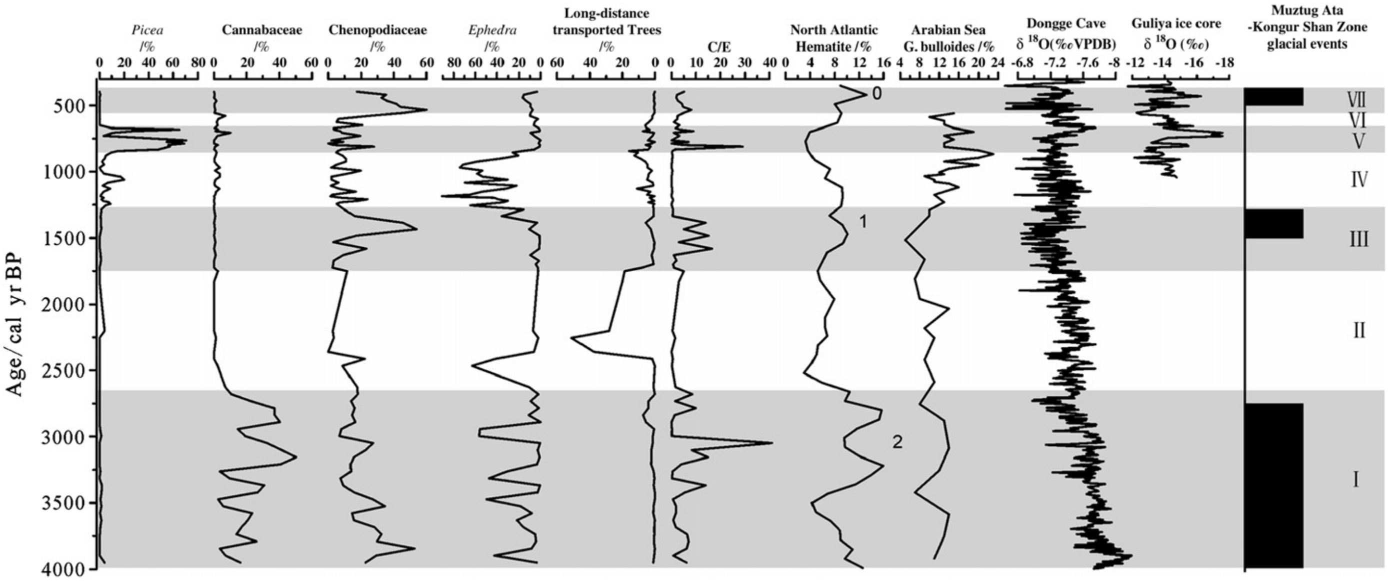

**Fig. 4.** Comparison of moisture changes in Kashgar with other selected proxy records from the North Atlantic (Bond et al., 2001), the Arabian Sea (Gupta et al., 2003), Dongge Cave (Wang et al., 2005), the Guliya ice core (Thompson et al., 2003) and Muztug Ata–Kongur Shan (Seong et al., 2009). Light-grey bands indicate relatively humid periods in the Kashgar area.

1750 cal yr BP (Tang et al., 2009). Also, a wet period in the Niya River area is reported from 1500 to 1400 cal yr BP (Zhong et al., 2007), greater fresh water inflows are detected at Karakul Lake between 1750 and 1250 cal yr BP (Mischke et al., 2010), and in the Muztag Ata–Kongur Shan region, glacier advances are reported around 1.4 ± 0.1 kyr BP (Seong et al., 2009). The Holocene Bond Event 1 of the North Atlantic Ocean also coincides with humid conditions at Kashgar (Bond et al., 2001) (Fig. 4, Zone III). An increased strength and southward migration of the mid-latitude westerlies, which could lead to more precipitation and meltwater on surrounding mountains, are the likely cause for the greater humidity between ca. 1750 and 1260 cal yr BP in the western Tarim Basin.

A dominance of *Ephedra* between ca. 1260 and 840 cal yr BP (AD 690–1110) in the study area indicates that the climate was drier at this time (Fig. 4, Zone IV). This period corresponds approximately to the MWP that is recognised in other parts of the world (Broecker, 2001). A tree ring record from the Dulan area of Qinghai shows a warm period from AD 819–1086, this was the most prolonged warm period detected in the 2000-year-long record (Kang et al., 1997). Tree ring records from the Karakrum Kunlun and Tienshan Mountains support evidence of higher temperatures from AD 618–1139 (Esper et al., 2002). Meanwhile, the regional environmental setting at Issyk-Kul Lake was characterised by a progressive decrease of the moisture from AD 1000 to AD1180 (Giralt et al., 2004).

A recent review of central Asian palaeoclimate records, covering the last 1000 years, concludes that the climate was warm and dry during the MWP (Chen et al., 2010). However, considerable variation in the climate of Xinjiang is evident over this time period. A record from Sichanghu, located at the southeastern margin of the Gurbantunggut Desert, indicates humid conditions as well as high plant diversity and biomass during this period (Zhang et al., 2009). A climate reconstruction at Lop Nur shows a reduction in storminess and generally favourable conditions during this period (Ma et al., 2008).

Ice-rafted debris decreased in the North Atlantic during the MWP (Bond et al., 2001) (Fig. 4, Zone IV), reflecting a warming of the North Atlantic Ocean. However, the intensity of the Indian and Asian monsoon was enhanced at this time (Gupta et al., 2003; Wang et al., 2005). Based on above analyses, the climate of the western Tarim Basin during the MWP appears to have differed from the climate of the eastern monsoon area and northern Xinjiang. Possible causes for the dry climate in the western Tarim Basin during the MWP are: (1) a decrease in intensity and northward migration of the mid-latitude westerlies; (2) a slightly stronger Indian and Asian monsoon, which failed to bring effective precipitation to the Kashgar area but strengthened the subsidence of air masses over the region; and (3) greater evaporation caused by higher temperatures.

A cool and wet climate between 840 and 680 cal yr BP (AD 1110–1270) is indicated by high *Picea* abundance in the Wupaer pollen record (Fig. 4, Zone V). The period corresponds to the later MWP. In the North Atlantic Ocean, the content of ice-rafted debris in deep-sea records was still low at this time (Bond et al., 2001). Diatom flora and the dinoflagellate cyst assemblages from the Aral Sea indicate low water levels from ca. AD 1100 to 1300 (Boomer et al., 2009). No glacier advances are reported for the Muztag Ata–Kongur Mountain region at this time. However, the oxygen isotope records of a Guliya ice core show that the climate was cold during the 11th and 12th centuries (Shi et al., 1999) (Fig. 4, Zone V). Tree ring records in the northwest Karakorum mountains of Pakistan and the southern Tienshan mountains of Kirghizia show that temperature was below the average of the last 1400 years between AD 1140 and AD1874 (Esper et al., 2002). Low temperatures coupled with low evaporation is likely to be linked to the wetter climate and expanded spruce forest on the west Kunlun and south Tienshan mountains at this time.

The relatively dry climate shown in the Wupaer record between 680 and 550 cal yr BP (AD 1270–1400) (Fig. 4, Zone VI) is also reflected in sediment records from the Kunlun Mountains and Niya Oasis (Tang et al., 2007; Zhong et al., 2007). The relatively humid climate between 550 and 390 cal yr BP (AD1400–1560) in the western Tarim Basin corresponds approximately with the Little Ice Age (LIA, ca. AD 1500–1800), which affected much of the Northern Hemisphere (Bradley and Jones, 1993). A higher sea level, resulting from increased rainfall, has been found in the drainage basin of Caspian Sea during the LIA (Leroy et al., 2011). At Keriya River, the climate was more humid during the LIA (Yang et al., 2002). The last Holocene Bond event in the North Atlantic occurred during this period (Bond et al., 2001) (Fig. 4, Zone VII). Our finding for a humid climate in the Kashgar area supports the idea that climates were wetter in central Asia during the LIA due to increased strength and southward migration of the mid-latitude westerlies (Chen et al., 2010).

The climate variations over the last 4000 years in the Kashgar region are explained by the combined effects of the westerly circulation system and glacier movement on surrounding mountains. However, the western Tarim Basin is located at the boundaries of several climate systems. The Asian summer and winter monsoon may also be an important influence in this region. The *Tsuga* pollen identified in this study is likely to have been transported by the Asian summer monsoon from the southern flanks of the Tibetan Plateau (Cour et al., 1999). We are however, unable to confirm whether the monsoon delivers precipitation to the western Tarim Basin. This is a topic to challenge future researchers.

## 6. Conclusions

The pollen data presented here indicate that four humid periods (ca. 4000–2620 cal yr BP, ca. 1750–1260 cal yr BP, ca. 840–680 cal yr BP and ca. 550–390 cal yr BP) and three dry periods (ca. 2620–1750 cal yr BP, ca. 1260–840 cal yr BP and ca. 680–550 cal yr BP) occurred over the last 4000 yr BP in the Kashgar area of western Tarim Basin. This is a region where very few palaeoclimate records currently exist.

Three of the humid periods (ca. 4000–2620 cal yr BP, ca. 1750–1260 cal yr BP and ca. 550–390 cal yr BP) are synchronous with the Holocene Bond Events 2, 1 and 0 of the North Atlantic respectively. These events are suggested to have been caused by an increase in the strength and southward migration of the mid-latitude westerlies, which would also have resulted in more precipitation and meltwater on the mountains surrounding the Kashgar area.

The climate of the western Tarim Basin was warm and dry between ca.1260 and 840 cal yr BP (AD 690–1110), and cool and wet between ca. 840 and 680 cal yr BP (AD 1110–1270) during the MWP. The evidence for humid conditions in the western Tarim Basin between ca. 550 and 390 cal yr BP (AD 1400–1560) supports an argument for wetter conditions in central Asia during the LIA.

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