The environmental signal of an early Holocene pollen record from the Shiyang River basin lake sediments, NW China

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Abstract **Pollen analyses of 85 samples from the Sanjiaocheng section well along the margin of a palaeolake at the end of the Shiyang River, NW China, show that *Picea* and *Sabina* dominate the pollen assemblage. Together they reach as high as 40%—60%, with the percentage of *Picea* varying inversely with that of *Sabina*. Similar results were obtained from another section in the Shiyang River drainage. Using modern ecological habitat relationship analogues, pollen transport characteristics, and the overall pollen assemblage, we propose that both *Picea* and *Sabina* pollen were transported by the river from the mountains at the upper reaches of the Shiyang River, and that the assemblage is more indicative of changes in upland vegetation than of local conditions near the section. This interpretation is supported by pollen data derived from surface samples, water samples, and riverbed samples. Using a moisture indicator (the *Picea* to *Sabina* ratio) and calculated pollen concentrations, we identify a series of palaeoenvironmental changes during the early Holocene (10—6.3 ^{14}C kaBP).**

Arid lands in northwest China are sensitive to climate change, and pollen records from lakes in the region are some of the best proxies on the Eurasian continent for vegetational history and environmental response to global climate change. However, most of lakes in the arid region of northwest China are open lakes supplied by rivers originating from high mountains. These rivers pass through multiple vegetation zones before terminating in the desert lakes[1]. The interpretation of pollen data from enclosed lakes (lakes supplied by rain and ground water) is complex[2—4], but pollen data from open lakes (lakes supplied by surface flow) are even harder to interpret than that from enclosed lakes because most pollen in the pollen assemblages is not local[3]. Furthermore, the interpretation of open lake pollen data from deserts is extremely difficult because strong winds and flash floods are very common and can carry pollen for long distance. Additionally, local vegetation in the desert lands is so sparse that the amount of local pollen is very small. When mixed with pollen from external sources, local pollen may be overwhelmed[5]. The question of how to interpret pollen data from open desert lakes is therefore important, not only to provide correct reconstructions of palaeoecological conditions in desert regions, but also to contribute to understanding the global climate change.

The palaeolake at the end of the Shiyang River is located at the northwest boundary of the summer monsoon and is therefore sensitive to environmental change. Together with previous research in the Shiyang River drainage[6—8], this study attempts to reveal vegetational history and environmental change in this drainage during the early Holocene.

1 Setting and method

The Shiyang River drainage lies on the northern side of the Qilian Mountains, on the eastern end of Hexi corridor. A flood plain and Gobi desert occur between the southern margin of the palaeolake and the northern margin of the Qilian Mountains. An alluvial plain and sandy desert are north of the palaeolake. The southern portion of the drainage is in a cool temperate semi-arid climate, while the middle and northern portions are in a temperate arid climate. From south to north, the distribution of modern vegetation is strongly related to elevation (see fig. 1): perennial snow and ice zone (>4500 m); cushion-like vegetation zone (4500—3800 m); meadow zone (3800—3500 m); alpine shrub zone (3500—3100 m); *Picea* and *Sabina* forest zone (3100—2500 m); mountainous grassland zone (2500—2350 m); desert grass zone (2350—2000 m) and Gobi-sand desert zone (<2000 m)[9,10]. The Shiyang River originates from the Qilian Mountains and disappears into the desert at the northern end of the drainage. During the late Pleistocene and Holocene there was a palaeolake at the end of the drainage, but by the 1950s, the paleaolake was dry because human use of river water increased [6].

The Sanjiaocheng (SJC) section, a 700-cm-deep well at an elevation of 1320 m, is located at the margin of the palaeolake, and is composed of continuous deposits consisting of clay, silty clay and silt. Ten adjusted ^{14}C age estimates from the section and bracketing strata from the last glacial to the present, include bulk sample estimates made with conventional techniques and AMS dates on charcoal and pollen concentrates. These dates have a near linear relationship with depth, and the ages of other depths were estimated by linear interpolation. The depth of 460 cm corresponds to the beginning of the Holocene[11]. This study focuses on the lower portion (292—460 cm, 10—

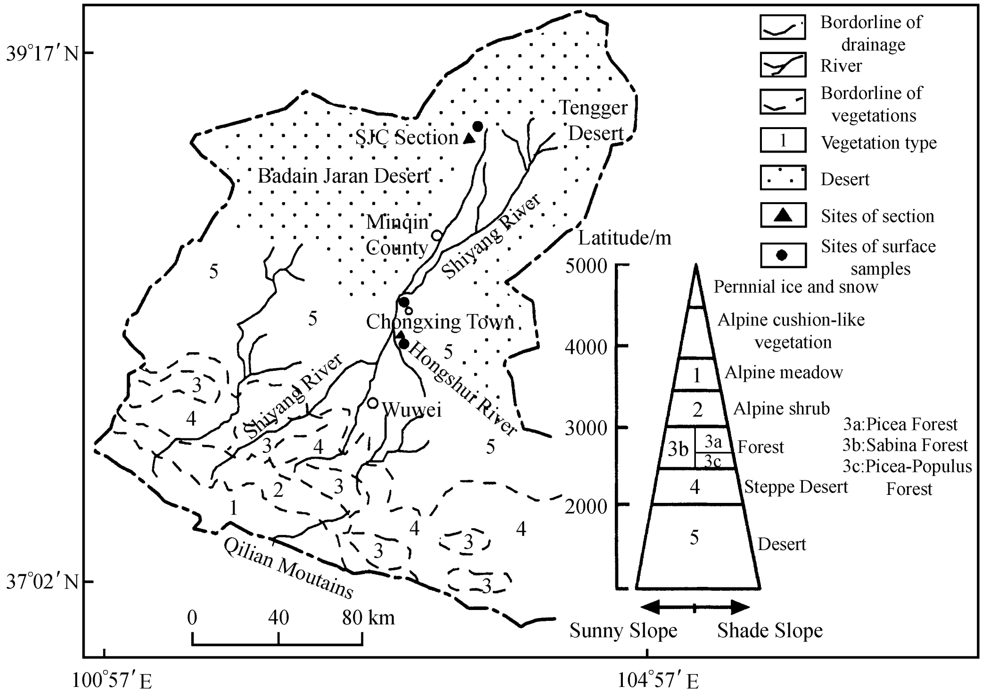

Fig. 1. Location of the Shiyang River drainage.

6.3 ^{14}C kaBP) of the Sanjiaocheng section. Samples were taken at 2 cm intervals. Standard techniques were employed for pollen extraction and analysis, including washes in HCl, and HF, and filtration through 6 μ mesh. Over 300 pollen grains and spores per sample were counted, with the maximum count reaching 1789 grains per sample. Redeposited pollen, with buff color and broken fragment, were excluded by counting.

2 Results

Over 50 taxa were identified, of which about 20 were common. Conifer pollen exceeds 50%—60% through the section and dominates the assemblage (fig. 2). *Picea* and *Sabina* are the primary conifer taxa; *Pinus* and other conifers are secondary. Deciduous trees are dominated by *Betula*, *Ulmus*, *Quercus*, *Salix*, and a variety of other types, and the combined percentages range from 5% to 25%. Rosaceae, Leguminosae, *Corylus*, Rhamnaceae, and Tamaricaceae are the main types of shrub pollen, with a combined percentage of 1%—10%. The percentage of herb pollen is 5%—20%, and the herb sum consists mainly of Gramineae, Compositae, Chenopodiaceae, *Artemisia*, *Polygonum* and Cyperaceae. Xerophytic plants living in extreme arid conditions have a special environmental signal. In this study, xerophytes such as *Nitraria* and *Calligonum*, which thrive in extremely dry habitats, reach a maximum percentage in the pollen assemblage of up to 7%. Aquatic plants, such as *Typha*, appear in some portions of the section, with a total percentage of 1%—3%. *Selaginella* and *Polypodium*, are the primary fern taxa, and reach around 10% in most of the pollen assemblage and up to 20%—40% in some samples.

3 Discussion

The percentage of conifer pollen in the sample is high, reaching over 50%. Normally, this would suggest that a coniferous forest was present near the SJC section, an environment very different from the modern desert vegetation. Pollen analyses of the Hongshuihe (HSH) section, located at an elevation of 1460 m at the end of the Hongshui River, a middle reaches tributary of the Shiyang River (fig. 1), also produced the same results (fig. 3)[7]. Chenopodiaceae and *Artemisia* dominate the pollen assemblage from the alluvial and fluvial sediments of strata 1—2. However, the pollen assemblages from strata 3—5, which are lake sediments, are dominated by conifer pollen at ratios of over 50%. Radiocarbon age estimates bracketing the HSH section indicate that the pollen sequence represents the period from 8—3 ^{14}C kaBP[7].

If the high percentage of conifer pollen from both of the SJC and HSH sections indicates that there were coniferous forests at the lower and middle reaches of the Shiyang River drainage from 10—6.3 and 8—3 ^{14}C kaBP, respectively, it raises a major question. The deserts of northwest China, of which the middle and lower reaches of the Shiyang River basin are a part, have been controlled by arid conditions for periods well beyond the Holocene. The modern lower coniferous forest tree line is around

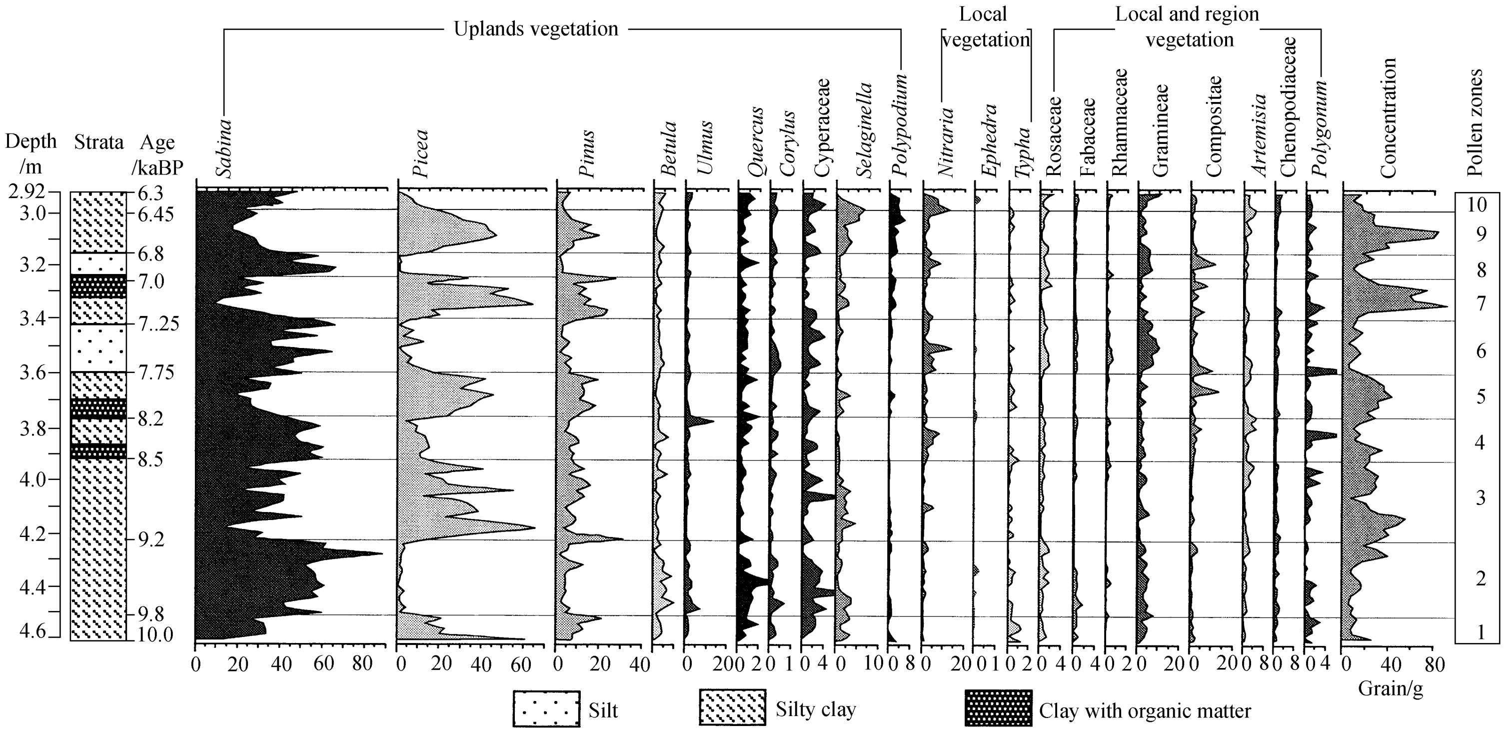

Fig. 2. Pollen diagram of the Sanjiaocheng section. The division of the pollen sum is based on modern vegetation in the drainage. Percentages were calculated by total taxa, as the percentage of aquatic plants is too low to influence the results.

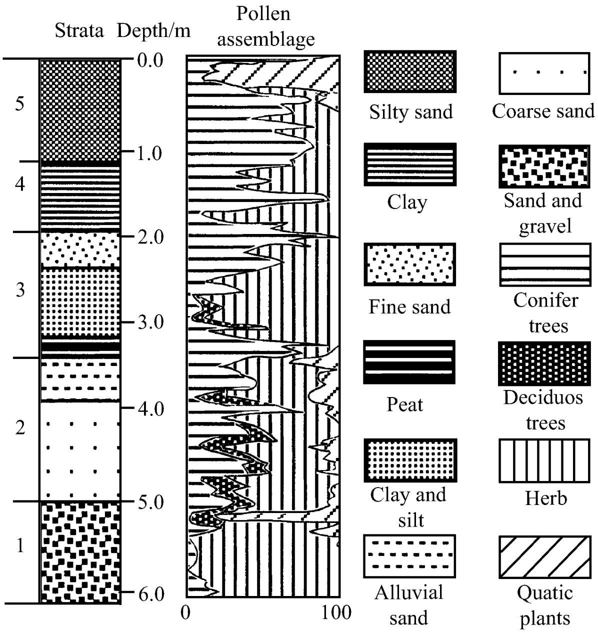

Fig. 3. Strata and pollen assemblages of the Hongshuihe section (after ref. [7]).

2500 m a.s.l., and no environmental change event of a magnitude large enough to cause a 1000 m decline of the tree line has yet been reported. Why then do the lacustrine sediments from both sections contain so high a percentage conifer pollen if there was no coniferous forest at the middle and lower reaches of the Shiyang River basin during the Holocene? The main elements of the pollen assemblage from the SJC section are *Picea* and *Sabina*, with the combined percentage of *Picea* and *Sabina* reaching 40%—60%, and in some samples up to 80%. The percentage of *Picea* also varies inversely with that of *Sabina*. As a result, a study focusing on environmental signals of *Picea* and *Sabina* pollen should provide a reasonable interpretation of the relationship between the pollen assemblage from the SJC section and palaeoenvironmental conditions during the early Holocene.

(ⅰ) Environmental signals of *Picea* pollen. *Picea* pollen is poorly dispersed, relative to other conifer pollen, with most *Picea* pollen deposited near the point of origin[12,13]. The high percentage of *Picea* pollen should therefore indicate that a *Picea* forest existed near the section. However, it seems unreasonable to conclude the lower *Picea* forest tree line dropped from 2500 to 1300 m a.s.l. That would mean that temperatures declined by 6—7℃ during the early Holocene. While a decrease in temperature may be partially countered by an increase in moisture, a decrease in temperature of such magnitude during the Holocene seems impossible. We prefer another interpretation.

Percentages of *Picea* pollen in the SJC section are directly proportional to pollen concentration, plant diversity, and percentages of aquatic plants and fern, but are inversely proportional to pollen from xerophytic plants. The geographical distribution of modern *Picea* forest indicates that *Picea* favors wet, cool conditions [10]. Results of *Picea* pollen-climate surface response analyses suggest that increases in *Picea* pollen percentages are caused by increased effective moisture in the Shiyang River basin climatic conditions[14]. Analyses of the relationship between pollen data and other proxies from the SJC section indicate that the relative amount of *Picea* pollen is directly proportional to carbonate content and loss on ignition (LOI), and inversely proportional to grain size (that is, high *Picea* pollen ratios are associated with periods of palaeolake expansion and increasing river flow). All this suggests that there is a direct correlation between the percentage of *Picea* pollen in the section and the amount of effective moisture. Additionally, the SJC section is located at the margin of an open palaeolake supplied by a drainage system originating in the Qilian Mountains where *Picea* forests are prevalent. In the Shiyang River drainage, modern surface runoff comes mainly from this conifer zone. We propose that this runoff carried *Picea* pollen to the end of the Shiyang River and deposited *Picea* pollen in the palaeolake. Previous studies of pollen transport have shown that river water has enough capacity to transport pollen for long distance[12,15—17]. However, deposition of pollen generally requires slowly moving or still water[16]. The horizontal and vertical distance from the lower conifer tree line to the palaeolake is ca. 250 km and 1200 m, respectively, and the fall rate is so sharp that there are almost no areas of reduced flow along the Shiyang River drainage except for where it flows into the palaeolake at its end. The palaeolake was apparently the depositional locus of pollen in the river.

To test this hypothesis we collected 30 water samples, 30 samples of riverbed mud and 64 surface soil samples along the Shiyang River drainage on April 5—9, and July 12—19, 2000. Pollen analyses of these samples show that the *Picea* percentages in the riverbed mud and water samples are much higher than that of the surface samples at the same sites (see table 1).

Additionally, this hypothesis helps explain why high percentages of conifer pollen in the HSH section do not indicate that a coniferous forest has existed in the middle reaches of the Shiyang River drainage, or that temperatures did not decline by around 5℃ during the middle Holocene[7]. The Hongshui River originates from an alluvial fan at the foot of the Qilian Mountains. Surface runoff apparently brings pollen from mountain vegetation to the alluvial fan and then to the end of the Hongshui River (see table 2).The lower portion of the HSH section consists of fluvial and alluvial sediments, which indicates that there was a large stream or river passing the HSH section when

Table 1 Percentage of *Picea* pollen from different samples at the same site in the lower reaches of the Shiyang River drainage

Site (see fig. 1)	Latitude and longitude	Distance to lower conifer tree line/km	Water samples (%)	Mud from the riverbed (%)	Surface soil sample (%)
North side of the Hongshui River at the Hongshui River bridge	38°12′06″—102°46′20″	135	21.8	49.5	5.1
River margin of the Shiyang River west of Chongxing Town	38°21′30″—102°48′54″	145	8.9	37.1	2.0
End of the Shiyang River near the SJC section	39°00′38″—103°20′25″	250	No river, no samples		1.6

Table 2 Percentages of principal taxa in pollen assemblages from samples at the Hongshui River bridge

Sample	*Picea*	*Pinus*	*Sabina*	Elaeagnaceae	Gramineae	Compositae	*Artemisia*	Chenopodiaceae	Cyperaceae	*Polygonum*	*Nitraria*	Zygoghyllaceae
River water	21.4	13.4	2.2	0.0	18.8	13.4	6.5	5.1	4.0	2.2	2.2	1.4
Mud from riverbed	49.5	22.3	1.1	0.3	3.2	10.5	0.5	1.9	0.3	1.0	1.9	1.6
Surface soil	5.1	8.1	0.3	19.1	5.5	5.2	0.1	3.0	0.1	9.1	24.6	15.7

strata 1 and 2 were deposited. During this period, the site of the HSH section was in an open basin where river water flowed in and out, taking a portion of the pollen influx, including both local and mountain pollen, to the Shiyang River. Previous studies of pollen sorting have shown that Compositae and Chenopodiaceae pollen are the first types to be deposited in alluvial and fluvial sediments[18—21]. This matches the pollen record from the HSH section, in that high percentages of Compositae and Chenopodiaceae pollen are associated with alluvial and fluvial sediments. The previous watercourse at the end of the Hongshui River became a pond or small lake when the sediments comprising the three upper strata of the HSH section were deposited as stream flow was greatly reduced. All upstream sediments, including pollen, accumulated in the pond rather than flowing on to the Shiyang River, so the percentage of upper elevation pollen was high in the lacustrine sediments of the HSH section.

In sum, large amounts of *Picea* pollen in the SJC section came from the Qilian Mountains and were transported primarily by the Shiyang River water. This pollen does not indicate the nature of local vegetation, but rather that of the uplands, and is associated with effective moisture in the upper Shiyang River drainage.

(ii) Environmental signal of *Sabina* pollen. High percentages of *Sabina* pollen in the SJC section also came from the Qilian Mountains. *Sabina* favors drier and cooler habitats than *Picea* and can endure arid conditions. Modern pure *Sabina* forests presently grow on sunny slopes of the Qilian Mountains[10]. The percentages of *Sabina* pollen in the SJC section are inversely proportional to the percentages of *Picea* pollen, the percentages of the pollen and spores of aquatic plants and ferns, pollen concentrations, and plant diversity are directly proportional to percentages of xerophytic plant pollen. Moreover, high percentages of *Sabina* pollen correspond to coarse grain sizes, which indicate dry conditions and stronger winds. This suggests that high percentages of *Sabina* pollen indicate a dry period with decreased plant diversity and biomass. During such dry periods, decreasing effective moisture reduces the pollen productivity of all plants and pollen concentrations in the SJC section decline. Those plant taxa favoring cooler and wetter habitats, such as *Picea*, were most affected by dry conditions, with both biomass and pollen production decreasing dramatically. Some such taxa could not tolerate such dry conditions and disappeared. *Sabina* was also influenced by these dry conditions, but relatively less so since it is more tolerant of decreased moisture; percentages of *Sabina* increase even as absolute amounts decrease, since the amounts of pollen of other taxa declined more than that of *Sabina*.

(iii) A model for reconstructing palaeoenvironments in the Shiyang River drainage. The principal taxa of the pollen assemblage from the SJC section indicate the nature of upland rather than local vegetation, and the ratio of *Sabina* to *Picea* pollen can be used as a moisture indicator. During periods with a high percentage of *Picea* pollen, high effective moisture promotes growth of most plants, and both plant diversity and absolute amounts of pollen increase. The amount and intensity of surface runoff also increase as effective moisture increases, strengthening runoff supplying the palaeolake at the end of the Shiyang River and carrying increased amounts of mountain pollen to the palaeolake. During periods with high percentages of *Sabina* pollen, on the other hand, effective moisture declines, species diversity and absolute pollen amounts decline, some taxa adapted to wet conditions disappear, runoff decreases, and the paleaolake shrinks. *Sabina* is also affected by drier conditions, but the degree of influence on *Sabina* is less than that on *Picea*, so that its pollen percentages increase.

4 Reconstruction of early Holocene environments

Based on the ratio of *Picea* to *Sabina* pollen and variation in other taxa with environmental signals, the pollen assemblage of the SJC section was divided into 10 zones (fig. 2) and early Holocene palaeoenvironments were reconstructed using the model described above.

11.6—11.4 cal. kaBP (zone 1): The amount of *Picea* pollen equals that of *Sabina*. Aquatic plants appeared. Moisture in the drainage increased. A stable lake developed at the end of the Shiyang River.

11.4—10.7 cal. kaBP (zone 2): *Sabina* pollen dominates the pollen assemblage. The percentage of xerophytes increases. It was a variably dry period. The forest zone in higher elevations was covered by *Sabina* forest, *Picea* and deciduous tree forests almost disappeared. Area of steppe desert and desert vegetation expanded at the lower elevations.

10.7—9.95 cal. kaBP (zone 3): The percentage of *Picea* pollen increases variably and varies inversely with *Sabina* and xerophytic plant pollen percentages. It was a relatively wet period.

9.95—9.55 cal. kaBP (zone 4): *Sabina* pollen dominates the pollen assemblage and percentages of xerphytic plant pollen increase. This was a moderately wet period with some dry intervals. During this period, uplands were covered by *Sabina-Picea* forest, and the area of xerophytes expanded at lower elevations.

9.55—9.05 cal. kaBP (zone 5): The percentage of *Picea* pollen increases. The palaeolake expanded during this long wet period. Vegetation coverage in the entire drainage increased, and conifers, deciduous trees, and ferns grew well in the uplands.

9.05—8.45 cal. kaBP (zone 6): *Sabina* pollen dominates the pollen assemblage. Gramineae becomes a principal taxa and the percentage of *Nitraria* pollen reaches its maximum value. Effective moisture decreased rapidly. This was one of the driest periods of the early Holocene.

8.45—8.15 cal. kaBP (zone 7): The percentage of *Picea* pollen and pollen concentration increases dramatically, reaching their maximum values. This was one of the wettest periods. During this period all plants, including forests at higher elevations, and herb and shrub communities at lower elevations, grew well. Plant diversity was high and the palaeolake expanded quickly.

8.15—7.95 cal. kaBP (zone 8): *Sabina* pollen dominates the pollen assemblage, and percentages of Gramineae, Compositae, and xerophyte pollen reach peak values. Aquatic plants disappear and pollen concentration reaches its lowest values. It was a short and extremely dry period. During this period *Picea* forest in the uplands almost completely disappeared, and the area of desert vegetation expanded at lower elevations.

7.95—7.55 cal. kaBP (zone 9): This period is similar to zone 7. *Picea* pollen dominates the pollen assemblage, and pollen concentration reaches peak values. The freshwater algae, *Zygnema* and *Mougeotia*, occur for the only time in the sequence. During this wet period the palaeolake expanded and it was at its lowest salinity.

7.55—7.33 cal. kaBP (zone 10): *Sabina* pollen dominates the pollen assemblage, and xerophytic plant pollen reaches peak values as pollen concentration decreases. Moisture declined and *Picea-Pinus* forests deteriorated in the uplands. The desert expanded in lower elevations.

5 Conclusion

The reconstruction of palaeoenvironments in open lake basins based on pollen assemblages alone is unreliable, and it is essential to investigate the source of the pollen, agents of transport, and the environmental signals of the pollen assemblage before the pollen-based reconstruction of palaeoenvironment is attempted. Our investigations in the Shiyang River basin lead us to conclude that the principal taxa of pollen assemblage from SJC section indicate the nature of upland vegetation rather than local vegetation. The ratio of *Picea* to *Sabina* pollen can be used as a moisture indicator, with high percentages of *Picea* pollen associated with high effective moisture, and high percentages of *Sabina* with low effective moisture.

In arid lands, the primary ecological factor controlling biomass is moisture; temperature is secondary. Variation in annual precipitation can cause a dramatic change in local vegetation. Biomass, degree of vegetational coverage, and diversity of local vegetation all increase when effective moisture increases. When moisture declines, some vegetation adapted to wet condition disappears, and biomass, coverage and plant diversity all decrease. Variations in temperature, on the other hand, are primarily reflected in the movement of vegetation zones rather than major changes in vegetational composition. Pollen assemblages of the SJC section have reflected these features. During wet periods, pollen concentration and plant diversity are high; during dry periods they decrease.

The early Holocene climate fluctuated dramatically in the Shiyang River basin, with each wet or dry period having subperiod changes on a century scale. The trend of the record, its details, and timing of abrupt events match other records from all over the world. The general trend of early Holocene environmental change in the Shiyang River basin matches the trend of Holocene climatic change based on records from loess deposits, advances and regressions of glaciers, and lake evolution in the deserts of northwestern China[22]. Some studies have suggested that the dust recorded in the Greenland ice cores came from the deserts of China [23], and high amounts of dust in Greenland ice cores during the Holocene should therefore match the dry events in Chinese deserts[24]. The ages of the fourth and fifth periods of high dust events in the Greenland Ice Core are comparable to the age of the SJC section. These two events appear to be reflected in pollen data from the SJC section and match pollen zone 2 and zone 6, respectively. The pollen data from the SJC section constitute a high resolution record, revealing some short and abrupt events, such as pollen zone 8, an extremely dry event lasting around two centuries. This extreme dry event has been documented by other records from all over the world. Environmental change records from ten sites across the Northern Hemisphere suggest that there was an intense cold and dry event 8—8.4 cal. kaBP[25]. Methane and δ^{18}O records from the GISP2 and GRIP ice cores show that the degree of temperature decrease during a cold event around 8.2 cal. ka BP is the most severe in the entire Holocene[26—28]. ROI records from Naujg 1 Lake, West Greenland document a cold event around 8.2 cal. kaBP, the coldest event in that record during the Holocene[29]. Average annual temperature and precipitation calculated by pollen-climate transfer functions in southeastern Tibet indicate that mean annual temperature and precipitation rapidly decline around 7.9 cal. kaBP[30]. Due to differences in the resolution of these records, dating methods, material dated, and extrapolation methods, the age of this event has an error of 100—200 a.

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