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Quaternary Science Reviews 23 (2004) 2537–2548

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Evidence for a warm-humid climate in arid northwestern China during 40–30 ka BP

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Received 17 February 2003; accepted 8 June 2004

Abstract

Former shorelines and sedimentary records from several lake basins in northwestern China (Xinjiang, Qinghai) give evidence for warm and humid climatic conditions during 40–30 ka BP. Further indications of this favorable climate period are derived from palaeosols from the Ili loess and from cemented calcareous layers on the terraces of the Keriya River at the southern margin of the Tarim Basin and in the Badain Jaran Desert in Inner Mongolia. At that time, annual mean temperature in the Qaidam Basin was 2 °C higher and in the western part of Inner Mongolia even 2–3 °C higher than today. Precipitation in most parts of northwestern China was between 60–300 mm greater than today. These changes were probably a consequence of an increase in ocean surface temperature and evaporation resulting from a higher radiation input at middle and low latitudes caused by changes in the Earth's precessional cycle. As a result of these orbital changes, it is suggested that the intensified westerly circulation was responsible for increased moisture over northwestern China.

1. Introduction

It is generally accepted that air temperatures during 40–30 ka BP, corresponding to the late episode of Marine Isotope Stage (MIS) 3, were higher than during the early and late stadials (MIS 4 and 2) of the Last Glacial period, but they were significantly lower than during the Last Interglacial period (MIS 5e) (Imbrie et al., 1984; Lorius, 1991; Fabre et al., 1995). However, studies of Guliya ice core at 6200 m elevation in the west Kunlun Mountains concluded that the amount of warming during MIS 3 was equivalent to that of the Last Interglacial (Thompson et al., 1997; Yao et al., 1997). Reconstructed temperature curves (Fig. 1) show that MIS 3 occurred between 58 and 32 ka BP, revealing two peaks and one trough in $\delta^{18}O$ concentrations. The last part of MIS 3 (MIS 3a, ca 40–32 ka BP) was the warmest. Maximum temperatures occurred around 35 ka BP and were about 4 °C higher than today. Around 55 ka BP, temperatures were about 3 °C higher than at present, whereas during the coldest period MIS 3b (ca 45 ka BP), temperature was ca 5 °C lower than today. Further studies by Shi et al. (1999, 2001) based on multi-proxy records from ice cores, lakes and pollen records found that the climate of the Tibetan Plateau was rather warm and humid during 40–30 ka BP, with temperatures about 2–4 °C higher than today, or even reaching the degree of warmth and humidity of the Last Interglacial. Furthermore, precipitation was 40–100% higher than the present average and the water level of many lakes was 30–200 m above today's major

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0277-3791/$ - see front matter
doi:10.1016/j.quascirev.2004.06.010

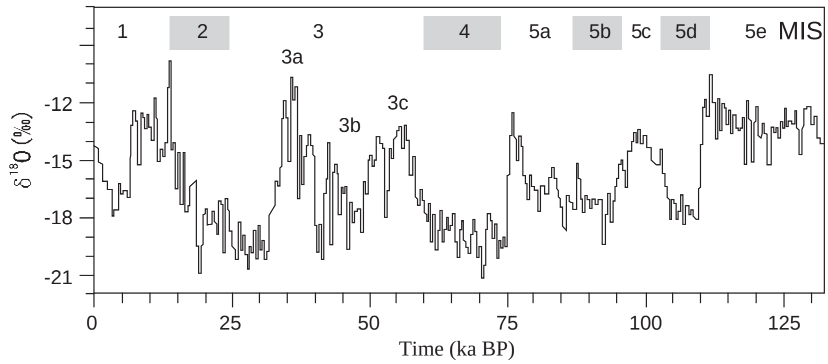

Fig. 1. High-resolution $\delta^{18}O$ series of Guliya ice core since Last Interglacial (after Thompson et al., 1997).

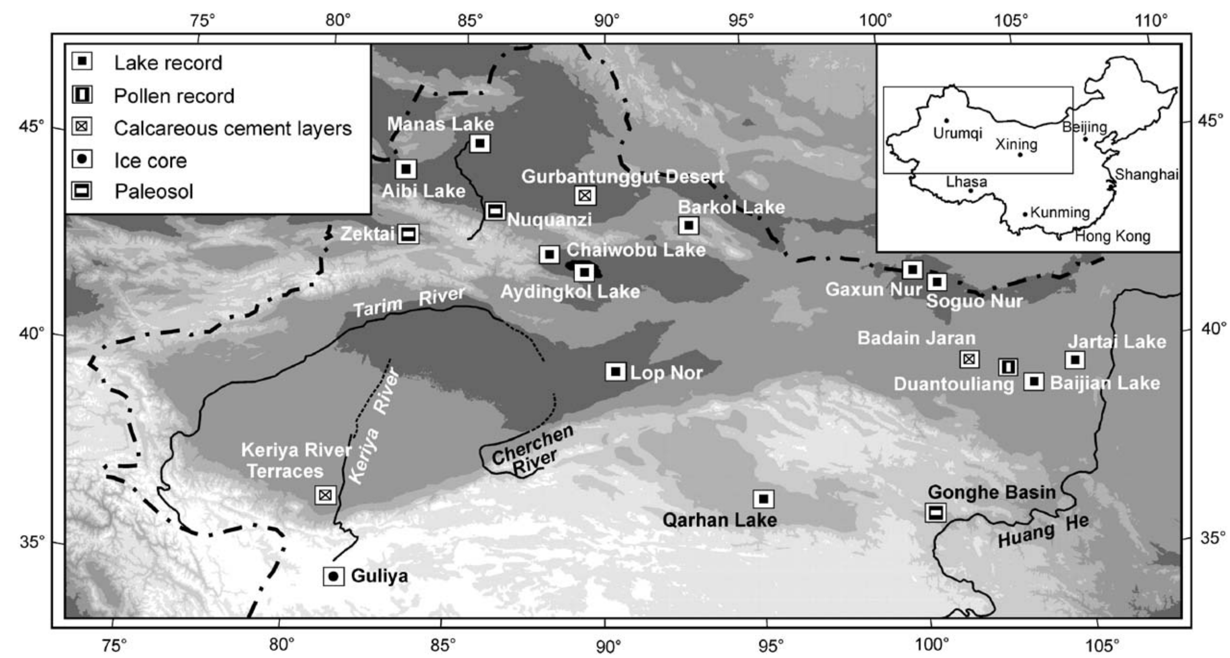

Fig. 2. Locations of main paleoclimatic records in arid northwestern China during 40–30 ka BP.

freshwater lake surface. Hence, Li (2000) called the period from 40 to 25 ka BP 'the greatest lake period of the Tibetan Plateau'. A reason for this may be an increase in solar insolation, which intensified the summer heat flow off the Tibetan Plateau, raised the temperatures of the Pacific and Indian ocean surfaces, and increased evaporation and the thermal contrast between ocean and continent, thereby resulting in a very strong summer monsoon on the Tibetan Plateau.

Situated north of the Tibetan Plateau, northwestern China presently has a dry climate affected by the westerly circulation and the monsoon system. Annual precipitation varies between 50 and 150 mm, but can be lower than 50 mm in extremely dry regions. However, annual precipitation can reach several hundred millimeters in mountain areas. Thus, the regional climate differs greatly from the climates of eastern China and the Tibetan Plateau. Here, we discuss the possible climatic patterns that could have prevailed in northwestern China during the period 40–30 ka BP using evidence from the sedimentary records of lakes in Xinjiang, Qinghai, and Inner Mongolia and evidence from Ili loess-paleosol records and cemented calcareous layers at the southern margin of the Tarim Basin and the Badain Jaran Desert (Fig. 2).

2. Lake sedimentary records

2.1. The Turpan depression

The Turpan depression at the southern piedmont of the Tianshan Mountains (Fig. 2) is, at present, an extremely arid region. The water surface of the

Aydingkol Lake (42.7°N, 89.3°E) in the center of the depression lies 154 m below sea level, being the lowest point in China. The lake is mainly fed by groundwater streams originating from the Tianshan and had a surface of less than 3 km^2 in 1994. From the study of a 51 m deep borehole drilled in an old salt crust 500 m away from the eastern edge of the lake, Li et al. (1989) inferred that deposits at 11.6 m depth dated by ^{14}C have an age of 24.9 ± 1.24 ka BP. After that time the water surface lowered and the water became brackish due to the dry climatic conditions during the Last Glacial Maximum (LGM). Below this layer, freshwater lacustrine deposits, such as clay, silt, fine sand, and gravel, were formed under a humid climate. The deposit at 16.6 m depth dated by ^{14}C yields an age of 39.7 ± 4.87 ka BP. Inferred from the sedimentation rate, deposits at 42 m depth have an age of 115 ka BP, and so Aydingkol Lake has experienced a humid period between MIS 5 and MIS 3. Further investigations of freshwater deposits showed that the lake reached a maximum extent of 2500–3000 km^2 with a length of 95 km and a width of 20–35 km at an elevation of about −40 m (114 m above ground-level) (Fig. 3, Yan, 1996).

Chaiwobu Lake (43.5°N, 87.9°E), situated 150 km northwest of Aydingkol Lake at an elevation of 1100 m, now has a water surface of 30 km^2 and experiences an annual evaporation of 1319 mm. Sedimentary records of a 500 m deep borehole 7 km away from the northwestern edge of the lake show that deposits below 132 m depth formed under a deep-lake regime. In contrast, sediments above this depth consist of alternating layers of alluvial facies and shallow lake facies. In the 780 ka of the Brunhes Chron, five phases of lacustrine deposition occurred, corresponding to interglacial warm-humid climatic stages. The second of these lake facies at a depth of 13.4–23.4 m is dominated by dark gray and black clay. Organic matter from deposits at 16 m depth yield a ^{14}C age of 23.8 ± 0.76 ka BP (Shi and Qu, 1989). In addition, lake deposits were studied in the western part of the lake. At 18.5–33.0 m depth they consist of dark-gray silt interbedded with clay, indicating a shallow lake environment. Organic matter from their lower part yields ^{14}C ages of 35.34 ± 1.44 and 38.06 ± 1.25 ka BP (Shi et al., 1990), respectively, indicating that the lacustrine layer was deposited during the late MIS 3. Shrubs and herbs dominate the abundant pollen content of this layer. On average, Chenopiaceae and *Artemisia* occupy 23.4% of the total pollen sum, but also small amounts of *Picea*, *Betula*, and *Salix* pollen were found. This indicates relatively warm and humid climatic conditions, which is corroborated by the analysis of stable oxygen and carbon isotopes. In that period the lake covered a much larger area than today and the lake water even flowed southward to Aydingkol Lake (Shi and Qu, 1989).

2.2. The Junggar Basin

Manas Lake (45.5°N, 86°E) is located at the terminus of the Manas River at the northern piedmont of the Tianshan in the western part of the Junggar Basin (Fig. 2). Situated at an elevation of 251 m, the basin is now dry, but in 1957 there was a lake with a water depth of 6 m and an area of 750 km^2. The lake's desiccation is mainly attributed to a dramatic decrease in incoming runoff as a consequence of intensified irrigation. Annual mean temperature in the lake region is 4 °C, annual precipitation amounts to 100 mm, and annual evaporation is about 10 times this value (Lin et al., 1996). Carbonate samples from borehole LM-II yielded AMS ^{14}C ages of 32.1 ± 0.75 ka BP at a depth of 4.66–4.68 m and 37.8 ± 1.5 ka BP at a depth of 4.68 m. At that time,

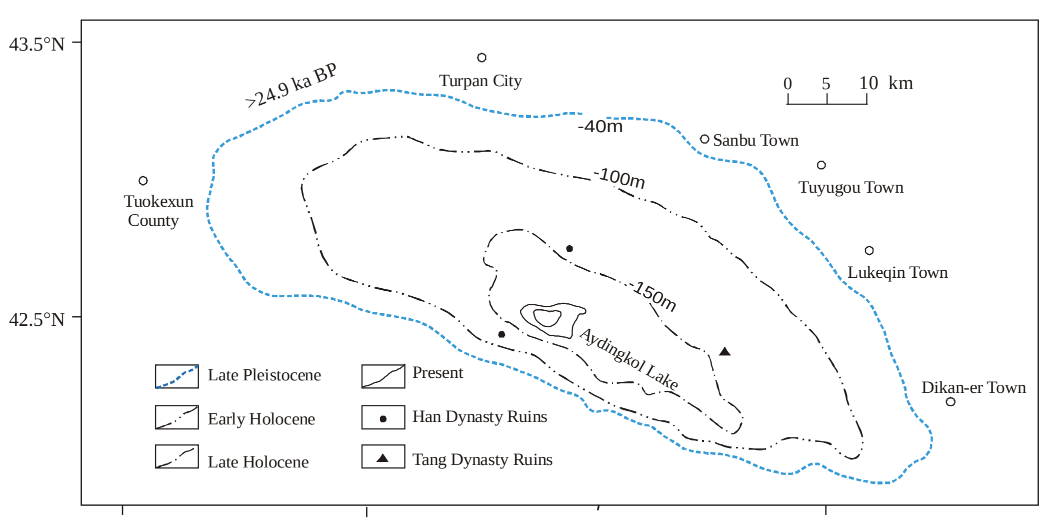

Fig. 3. Area change of the Aydingkol Lake since the late Pleistocene (redrawn from Yan, 1996).

carbonate deposits dominated by calcite exhibited lower $\delta^{13}C$ values (−0.6 to −0.5%), and aquatic algae indicate a relatively deep freshwater environment (Rhodes et al., 1996). The surface area of the lake probably reached $8000\,km^2$ or more (Fig. 4) (Zhou, 1994), demonstrating that climate at that time was by far more humid than at present. Geomorphic investigations show that at an earlier stage Manas Lake was fed by rivers coming from the northern piedmont of the Altai Mountains. Discontinuous and not well dated records imply that after 32 ka BP the lake level fell and the lake surface shrank until the early Holocene ($10.12 \pm 0.1 - 5.63$ ka BP) when the water level rose again and a new humid period began (Yu et al., 2001). The date 10.12 ± 0.1 ka BP was derived from AMS dating of carbonate samples from borehole LM-II, while the date 5.63 ka BP was extrapolated from the deposition rate between depths 3.24 and 4.00 m.

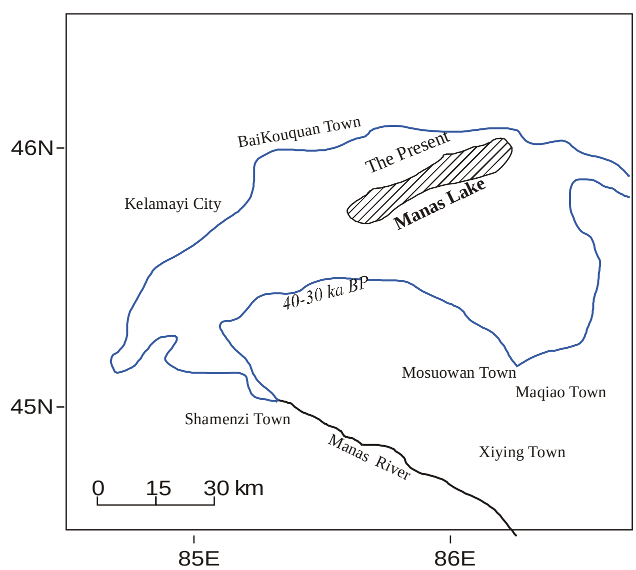

Fig. 4. Comparison of lake area 40–30 ka BP (closed dashed curve) with the present area of the Manas Lake (redrawn from Zhou, 1994).

Aibi Lake (45°N, 82.7°E) (Fig. 5) is located about 200 km southwest of Manas Lake at an elevation of 195 m (Fig. 2). At present, the lake covers an area of about $500–600\,km^2$ and has a depth of 1.5 m. Annual mean temperature in the lake region is 8.3 °C. Annual precipitation is 90 mm, and annual evaporation is about 14 times higher (Yan and Yang, 1996). As reconstructed from a lake terrace lying in 240 m elevation, the lake had a depth of about 40 m prior to 25 ka BP (Fig. 5) (Yan and Yang, 1996). At that time, Aibi Lake was a freshwater lake and covered an area of about $3000–3380\,km^2$, which is 5–6 times larger than the present lake area. From the interpretation of satellite images, it can be shown that Aibi Lake was probably connected with Manas Lake (Rhodes et al., 1996).

2.3. Barkol Lake

Barkol Lake (43.7°N, 92.8°E), located at an elevation of 1575 m in an intramontane basin of the Eastern Tianshan is a large brackish-water lake with an area of $112.5\,km^2$ (Fig. 2). Annual precipitation in the region ranges between 200 and 250 mm and annual evaporation amounts 1000–1500 mm. A sequence of terraces surrounds Barkol Lake. A terrace at the 29 m-level has an age of 7–8 ka BP, and the oldest terrace at the 40 m-level, is inferred to have formed under humid climatic conditions before the LGM (>24 ka BP). From study

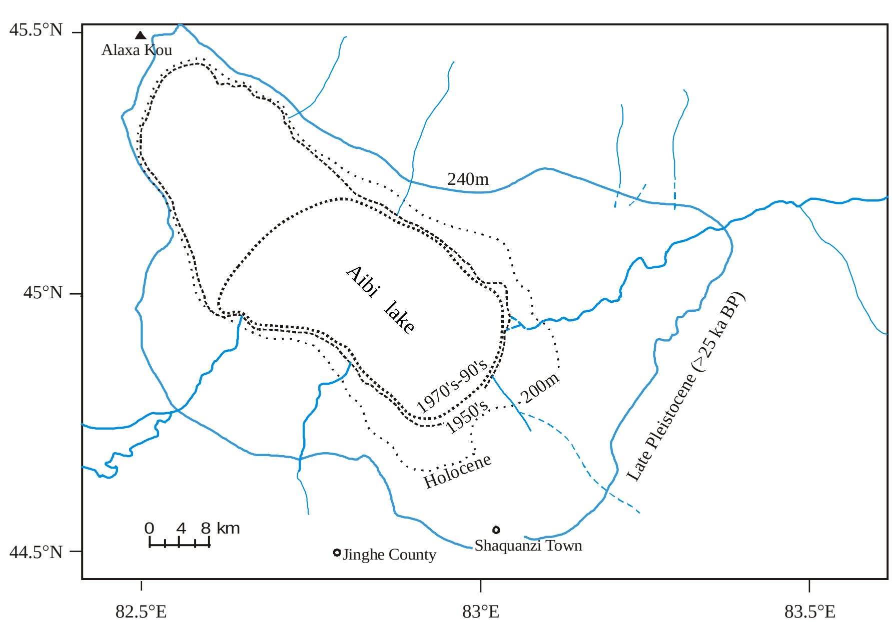

Fig. 5. Area change of the Aibi Lake since 25 ka BP (redrawn from Yan and Yang, 1996).

of the 13.6 m deep borehole ZK00A by Han and Yuan (1990) and Han et al. (1993) and comprehensive studies by Yu et al. (2001), it was deduced that layers of grayish and brownish clay and fine sand at 13.6–13.3 m depth, with ^{14}C ages of included organic matter between 36.7 ± 0.83 and 35.1 ± 0.74 ka BP, reflect a relatively deep lacustrine environment. Afterwards, an increase in the carbonate content in brownish-yellow calcareous clay deposits at 13.0–12.7 m depth implies a decrease in water depth between 32.85 ± 0.67 and 33.71 ± 0.17 ka BP. A greenish-gray silty clay at 12.7–12.1 m depth documents a rise of the lake level about 31.95 ± 0.11 ka BP. However, layers of fine gravel interbedded with the silt clay indicate that the lake level was shallow. Organic matter from deposits of grayish and yellowish lacustrine clay at 7.9 m depth, having a ^{14}C age of 24.31 ± 0.23 ka BP, document a deepening of the lake. The lake then maintained a relatively shallow level, although it experienced a number of lake-level fluctuations. After 12.15 ka BP, the salinity of the lake increased greatly (Yu et al., 2001). In general, the hydrological conditions of Barkol Lake are better than those of Aydingkol Lake and Manas Lake due to its higher elevation and lower evaporation rate.

2.4. Tarim Basin

Lop Nor (40.5°N, 90.5°E), located at an elevation of 780–795 m in the eastern part of the Tarim Basin (Fig. 2), is a playa. Annual precipitation in the region is less than 20 mm whereas annual evaporation amounts to 2600 mm or more. According to Yan et al. (1997), the upper 17.05 m of borehole K1, which is 100.2 m long, consist of yellowish and grayish lacustrine clay and were deposited during the Late Pleistocene. A comparison with Mid Pleistocene deposits, such as greenish-gray and grayish-green gypsum argillite and grayish-green argillite interbedded with gypsum, showed that the Late Pleistocene experienced a relatively humid climate. Organic matter from the deposits at 7.2 m depth in borehole K1 give a ^{14}C age of 26.17 ± 0.48 ka BP. The pollen assemblage is dominated by shrub and herb species, including *Artemisia*, Chenopodiaceae, *Tamarix*, *Ephedra*, and Gramineae, reflecting a paleo-vegetation typical of steppe-desert ecotones. The deposits between 8–17 m depth are older than 26.17 ka BP and include the latest period of MIS 3. The pollen assemblage contains abundant aquatic plant species, of which *Typha* constitutes 17.2%, showing that the lake had a broad brackish shallow-water zone at that time. According to a comprehensive study of two additional boreholes in the center of the basin by Yu et al. (2001), the lake experienced a number of fluctuations after 20 ka BP: during the period 20.8–20.47 ka BP the lake level was very high, during the period 20.47–19.67 ka BP, Lop Nur had a moderate water level, and during the period 19.67–11.02 ka BP the water level was high again. After 9600 BP, the lake dried up.

2.5. Qaidam Basin

Qarhan Lake (36.9°N, 95°E), located at an elevation of 2675 m, is a large playa in the central Qaidam Basin and covers an area of 5800 km^2. Annual precipitation in the region is 25–50 mm, annual mean temperature is 2–4 °C, and annual evaporation exceeds 3000 mm. According to Chen and Bowler (1986) and Chen et al. (1990), shell layers are preserved in sediments lying 3 m above the present lake level at the eastern lake shore. They include mollusc fossils of Pelecypoda, Gastropodes and mussels. The shell layers at 0.05 and 1.8 m depth have ^{14}C ages of 28.65 ± 0.67 ka BP and 38.6 ± 0.68 ka BP, respectively, showing that during the period 38–28 ka BP the lake had a high water level. It was estimated that at that time the lake had a fresh-brackish water quality and covered an area of 15,000 km^2, which is 2.6 times larger than the area of the present salt lake (Chen et al., 1990). Zhang et al. (1993) determined the δD and δ^{18}O values of primary halite-inclusion water in boreholes from the northern side of the Qarhan Salt Lake. They concluded that the period 41.9–30.9 ka BP was a freshwater stage and that temperature in the region from 50–30 ka BP was about 6 °C, which is 2 °C higher than the present annual mean. According to Hövermann and Süssenberger (1986), annual precipitation in the Qarhan region from 32–24 ka BP was 150–350 mm, which is 100–300 mm higher than today. It is inferred that annual precipitation was even higher during 40–32 ka BP.

Analysis of the pollen content in the samples from borehole Da 1 from the southeastern bank of the Dabuxun Lake reveals that by the palaeomagnetic age of 30 ka BP, thermophilous and hydrophilous trees, ferns, and aquatic plants diminished, and that forest and grassland vegetation was replaced by desert and steppe species (Jiang and Yang, 2001). Bore section Dacan I from the southern bank of Dabuxun Lake shows that around a ^{14}C age of 30 ka BP, a great number of Ostracode species suddenly became extinct (Jing et al., 2001), suggesting that a dramatic change in the region's climate, which became dry and cold.

2.6. Lakes in the Badain Jaran Desert

Located at the northwestern margin of the Badain Jaran Desert in the western part of Inner Mongolia, the Soguo Nur and Gaxun Nur lakes (Fig. 2) had an area of 35.0 and 267.0 km^2, respectively, in 1958. They were fed by the Heihe River, which originates in the Qilian Mountains, but they entirely dried up in subsequent years. Annual precipitation in the lake region is 40 mm, and annual evaporation is 3745 mm. At Gaxun

Nur, lacustrine beaches, consisting of mollusc-bearing coarse sand, were formed 22–35 m above today's lake surface between 29.4 ± 0.45 and 37.83 ± 1.4 ka BP (Pachur et al., 1995; Wünnemann et al., 1998; Wünnemann and Hartmann, 2002). The former maximum lake and swamp area was estimated to have exceeded 30,000 km^2. $\delta^{18}O$ isotope analyses of lake sediments indicated high lake levels around 34–37, 31 and 26–28 ka BP (Wünnemann and Hartmann, 2002). Comprehensive studies by Lehmkuhl and Haselein (2000) confirm that the highest water level of the Paleo-Juyan Lake occurred between 41–33 ka BP, when the lake was additionally fed by the Beida River, Qinshui River, and Liyuan River.

2.7. Lakes in the Tengger Desert

Baijian Lake (39.2°N, 104.2°E) is located at the terminus of the Shiyang River at the northern piedmont of the eastern Qilian Mountains (Fig. 2). It is now a salt marsh at an elevation of 1281 m and has a surface area of 42 km^2, with brackish water occurring 1 m below the surface. Annual mean air temperature in the region is 7 °C, annual precipitation is 48 mm and annual evaporation is 2600 mm. Based on studies of lacustrine terraces and borehole data by Pachur et al. (1995), precipitation in the lake region between 39 and 23 ka BP was much greater than today. The highest water level occurred after 35 ka BP and formed a terrace 30 m above the present lake floor, which consists of mollusc-bearing coarse sand and gravel. A second terrace lies 22–27 m above the present lake level and contains three sand dikes. The outermost sand dike gave ages of 33.5 ± 1.0 and 32.44 ± 0.84 to 23.37 ± 0.38 ka BP and represents a relatively stable high water level. The corresponding palaeolake surface, paralleling the 1310 m contour line, was 16,200 km^2. Studies by Zhang et al. (2002a, 2002b) showed that lake deposits even stretch beyond this limit and estimated the former lake's area to have exceeded 20,000 km^2. Abundant microfossils in the section, dominated by *Darvinula stevensoni* and *Candona neglecta*, indicate fresh to brackish water quality at that time (Zhang et al., 2002a, b).

Jartai Salt Lake (39.8°N, 105.7°E) is located 190 km northeast of Baijian Lake (Fig. 2). Formerly, it had an area of 120 km^2, but it shrank to 37 km^2 in the 1990s. Annual mean temperature in the lake region is 9.5 °C, annual precipitation is 115 mm, and annual evaporation is 3036 mm. The lake's water supply comes from the Helan Mountains to the southeast and the 1447 m high Bayanula Mountains to the northwest. From a study of borehole Ji 25, Geng et al. (1989) and Geng and Cheng (1990) inferred that the base of Pleistocene sediments is at a depth of 282.2 m, and that lacustrine sedimentation occurred throughout the Pleistocene. Deposits at 13.8–36.8 m depth consist of shallow lake facies, beach facies, and swamp facies, including clay, silt, and fine sand. Geng et al. (1989) and Geng and Cheng (1990) found that deposits at about 8 m depth indicated climatic and environmental change during the Holocene based on stratigraphic correlation and a ^{14}C age of 9959 ± 0.13 ka BP obtained from mollusc fossils in a sand layer outcrop. From this date, the authors inferred that the deposits at 13.8–36.8 m depth are late Pleistocene deposits. The uppermost 14.2 m consist of grayish-black muddy and clayey silt, with horizontal bedding and unconsolidated swamp facies. According to depositional rate, these deposits can be correlated with late MIS 3, and indicate a significant warm and humid climate. In addition, Tong et al. (1998) found that organic matter from 7.9 m thick lacustrine deposits formed in the Yingchuan Basin gives a ^{14}C age of 33.6 ± 1.4 ka BP. They reveal more humid climate conditions than today.

3. Pollen records

Pollen records representing the time period under consideration are rare in northwestern China. Ma et al. (1998) studied the pollen assemblage of the Duantouliang section in the Yabrai Mountain region. The period 42–38 ka BP is represented by a Betula-Cupressaceae (*Juniperus*) pollen zone. Coniferous and broad-leaved tree species represent 33.3–47.2% and 23.6–41.7% of the total pollen sum, indicating the presence of mixed coniferous and broad-leaved forests. Shrubs, including xerophilous and halophilous species are rare, accounting for 9.7–16.7% and 8.3–12.7% of the total pollen sum, respectively. It was thus inferred that *birch* and *oak* forests covered the hills of the Yabrai Mountains. In the 38–31 ka BP pollen assemblage zone, in which conifers and broad-leaved trees occupy 15.8–38.3% and 26.9–39.6% of the pollen sum, respectively, the abundance and diversity of broad-leaved tree species increased. This can be interpreted as a differentiation of temperate and warm-temperate broadleaved forests in the hilly region and Cupressaceae forests at an elevation of 1600–2200 m in the Yabrai Mountains. Because the lower forest limit was 400–600 m lower than at present, one may infer that air temperature at that time was 2–3 °C higher and precipitation was 250–300 mm higher than today. Furthermore, rainfall was more-evenly distributed throughout the year than today. In addition, the appearance of the thermophilous species *Ilyocypris gibba* and the temperature-sensitive Ostracod species *Limnocythere inopinata* in the Duantouliang section between 42–23 ka BP indicates that water temperature at that time was not lower than 10 °C, i.e., 2.2–3.0 °C higher than today (Peng et al., 1998; Zhang et al., 2002a, b).

4. Records from layers of calcareous concretions and nodules

According to Yang (2000), the mega dunes occurring in the Badain Jaran Desert show four cemented layers, mainly consisting of calcium carbonate. These layers are interpreted as former dune surfaces, which is corroborated by cemented fossil plant roots found in the respective horizons. Although the reported radiocarbon dates to corroborate the evidence for warm and humid conditions during MIS 3, the derived ages should be used with caution since not the original organic material was dated, but secondary carbonatic minerals which can result in dating problems. The oldest layer, which gives a ^{14}C age of 31.75 ± 0.48 ka BP, varies in thickness between 30 and 40 cm. Occasionally, even 60 cm of thickness occur. The second and third cemented layers are <20 cm thick and yield ^{14}C ages of 19.1 ± 0.77 and 9.44 ± 0.35 ka BP, respectively. The youngest layer consists of a group of thin (2–8 mm) laminae, interbedded with sand, giving a ^{14}C age of 2.07 ± 0.1 ka BP. Presently, cemented calcareous layers develop in regions with an annual precipitation of 100–300 mm (Hövermann, 1988). It is assumed that the carbonate crusts in the Badain Jaran Desert were formed under a similar moisture regime, precipitation at that time was 60–260 mm higher than at present.

Gurbantunggut Desert (Fig. 2) is the second largest desert in China. A 34.5 m deep borehole which includes sediments formed during the last 80 ka was drilled in a depression 5–6 km away from the southern margin of Gurbantunggut Desert. Two clay layers with calcareous nodules at 30.5 and 19.8 m depth are interbedded between sands. The lower and upper clay layers are 0.8 m and 1.2 m thick and yield TL ages of 62.25 ± 9.96 and 28.76 ± 0.62 ka BP, respectively. Based on lithologic characteristics, pollen assemblage and geochemical elements, Huang and Zhou (2000) inferred that the two clay layers represent two humid climate periods. During the latter part of MIS 3a, climate was more humid and precipitation was higher than at present.

Calcareous concretion layers were also found on the terraces of the Keriya River (Yang, 2001), which is located in an extremely arid region at the southern margin of the Tarim Basin (Fig. 2). Annual mean temperature is 11.4 °C and annual precipitation amounts to 37.2 mm and even less in the hinterland of the desert. The highest terrace of the Keriya River 60 km north of Yutian city lies 20 m above the modern riverbed. A ^{14}C date on carbonates from a 1 m thick calcareous nodule layer (Yang, personal communication) on the terrace gives an age of 28.74 ± 1.5 ka BP (Yang, 2001). It is inferred that about 30 ka BP precipitation at the southern margin of the Tarim Basin was 60–260 mm greater than at present.

5. Loess–palaeosol records

The Zektai loess section (43.5°N, 83.3°E) in the eastern part of Ili Basin is located in the desert steppe zone of western Xinjiang (Fig. 2). Vegetation cover is less than 50% and is dominated by *Artemisia* and Chenopodiaceae. 21.4 m of the loess section is exposed. According to Ye et al. (2000) and Ye (2001), two poorly developed palaeosols are interbedded with a loess layer between 3.5 and 10.4 m depth in the section. They save on OSL ages of 26.1 ± 1.6 and 54.2 ± 3.3 ka BP, and are therefore related to MIS 3a and 3c, respectively. Pye (1987) found that particles $<10\,\mu m$ can be long-distance transported over several thousand kilometers, whereas it is impossible that particles $>20\,\mu m$ are transported to far distant sites. Through analysis of a grain size probability curve, Ye et al. (1998) concluded that the $<15\,\mu m$ component in the Yili loess section originated from long-distance transport while the $>15\,\mu m$ component belonged to proximal sedimentary deposit. Since the portion of the grain-size fraction $<10\,\mu m$ in the Zektai loess shows high agreement with the portion of the grain-size fraction $<15\,\mu m$ in the Yili loess, the former is chosen as an indicator of the intensity of the westerlies (Ye et al., 2000; Ye, 2001): the stronger the wind, the higher the dust deposition and the lower the percentage of the $<10\,\mu m$ grain size fraction in the loess and vice versa. Accordingly, the interval between 3.5 and 5.5 m depth corresponds to MIS 3a. As inferred from the deposition rate, its age is ca 26–40 ka BP (Fig. 6). Corresponding periods of intensified pedogenesis during MIS 3 have also been reported from the Chinese Loess Plateau and date about 55 ka and 30 ka BP (An et al., 1991).

Based on the soil-forming processes, it can be inferred that MIS 3a represents a relatively warm and humid period, probably with strong westerly winds. In the transition between glacial to interglacial periods, the Ili region has always been under the influence of the westerly circulation. Unlike in the monsoon region with dry winters and wet summers, rainfall is evenly distributed throughout the year. As pointed out by Ye (2001), there is only a small difference in the calcium carbonate content between loess and palaeosols from glacial and interglacial periods. From this it can be inferred that there is little difference in precipitation between cold and warm periods, and that the differences in particle size caused by changes in wind force are obviously indicators for changes in the thermal regime. Therefore, in the transition period from interstadial MIS 3 to stadial MIS 2, temperature and evaporation intensity dropped drastically, but precipitation was reduced only a little. As a result, the lakes still remained at a higher water level as for instance recorded by Barkol Lake during the period 20.73–12.15 ka BP.

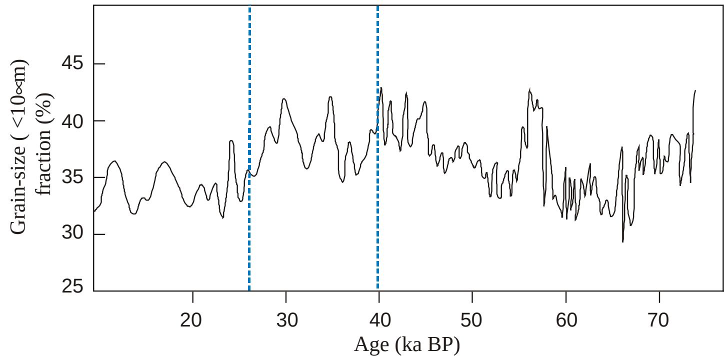

Fig. 6. Grain-size fraction ($<10\,\mu m$) curve of Zeketai section in Xinjiang region (redrawn from Ye et al. (2000); Ye (2001)). The dashed vertical lines indicate MIS 3a.

Additional evidence comes from the Nuquanzi section in the northern piedmont of the Tianshan (Fig. 2). Organic matter from a layer of grayish-brown palaeosol intercalated between the upper and the lower Malan Loess layers gives a ^{14}C age of 24 ka BP (Wen and Zhen, 1988). It corresponds to an OSL age of 26.1 ± 1.6 ka of the first layer of the palaeosol in the Ili Zektai section and is considered to be a product of a warm, humid climate during MIS 3a. In the Gonghe Basin (Fig. 2), 0.8-m-thick reddish-brown palaeosol is intercalated between the lower and the upper Malan Loess layers which yield TL ages of 59.7 ± 5.4 and 21.4 ± 1.6 ka BP and give maximum and minimum dates for the formation of this soil layer.

6. Discussion

6.1. Possible causes for a warm and humid climate during MIS 3a in arid northwestern China

The lake level fluctuations, palaeosols, cemented calcareous layers in dune sands, vegetation changes, Ostracode assemblages and isotope compositions of lacustrine sediments give ample evidence for a humid and also warm climate during MIS 3a in northwestern China. Frenzel (1995) estimates an increase in precipitation for northwestern China of 100–200 mm for the time 35–25 ka BP.

The position of the study area in relation to present-day circulation systems is shown in Fig. 7. There are two possible sources of increased moisture that could have contributed to a more humid climate in northwestern China at this time. The first is the summer monsoon circulation, including the southeast monsoon and the southwest monsoon. According to Prell and Kutzbach (1992), the Asian summer monsoon is extremely sensitive to changes in insolation caused by variations of the Earth's orbit around the sun. Incident radiation in middle and low latitudes was enhanced about 20 W/m^2 during the period 35–30 ka BP (Berger, 1978). This led to an increase in the heat contrast between ocean and continent and might be a direct cause for the intensification of the summer monsoon (Shi et al., 2001). In this case, the strengthening of low pressure over the Tibetan Plateau is not only favorable for the northward advance of southwest monsoon at the southern side of the plateau, but would also help the wind in the northern part plateau to penetrate further into the inland of northwestern China. Furthermore, an increase in incident radiation would result in a rise of ocean surface temperatures and an increase in evaporation and air humidity. A strengthened summer monsoon would bring large amounts of rainwater to the Qaidam Basin, Tengger Desert, Badain Jaran Desert and adjacent regions (Shi et al., 2001) and even to Xinjiang. Additional evidence for periods of strengthened Indian summer monsoon comes from deep-sea cores off the coast of Pakistan, where records of the abundance of eolian dust reflect a series of humid intervals during MIS 3 that seem to be related to Daansgard-Oeschger cycles in the North Atlantic (Leuschner and Sirocko, 2000).

A second source of moisture, which is of more importance for northwestern China, is a strengthening of the westerly circulation, which is probably coupled with a weakening of the winter monsoon and the Central Asian anticyclone (Frenzel, 1994; Frenzel and Gliemeroth, 1995; Pachur et al., 1995; Wünnemann et al., 1998; Lehmkuhl and Haselein, 2000). Calculations by Berger (1978) showed that a positive anomaly of the Northern Hemisphere July insolation during the period 35–30 ka BP was concentrated in mid to low latitudes ($>20\,W/m^2$ relative to present values) rather than at high latitudes (about $10\,W/m^2$ relative to present values). This is a unique phenomenon for the precessional cycle during the last 125 ka. As a consequence, the temperature gradient between low and high latitudes increased and thus induced and strengthened the

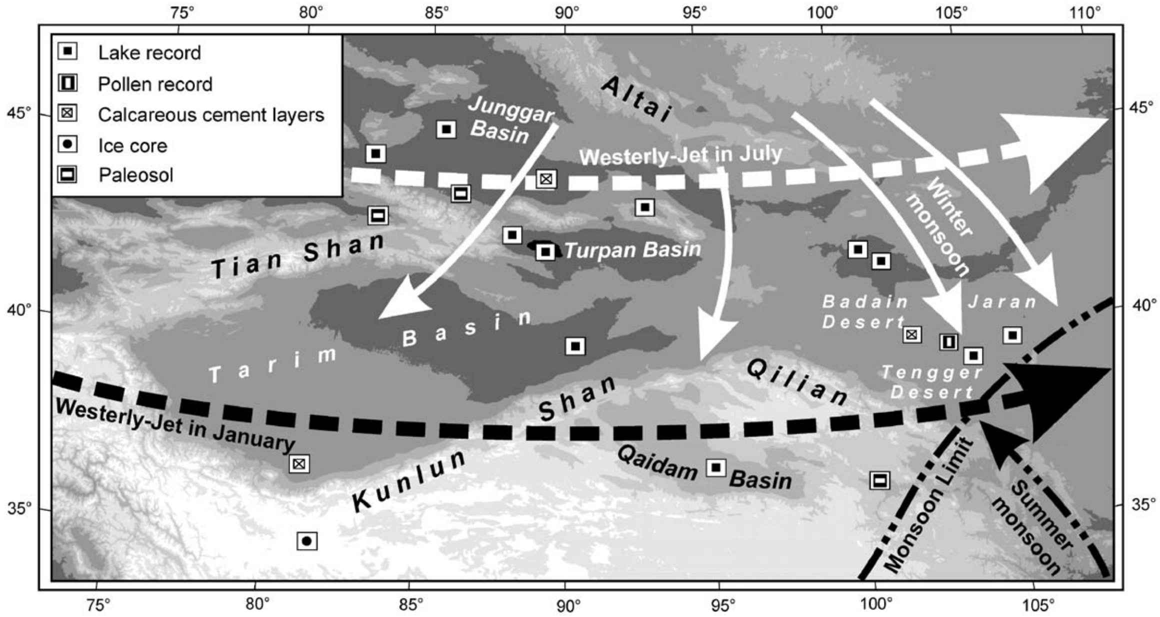

Fig. 7. Distribution of the study area (for site names see Fig. 2) in relation to present-day wind systems (after Zhang et al. (2002a, b); Xiao et al. (1995)).

westerlies during the period 35–30 ka BP, which was indicated in the loess–palaeosol record of Ili Zektai, which shows that wind speed increased during the time period discussed here. The higher radiation at middle and low latitudes led to a temperature rise of the Atlantic Ocean surface (Voelker and Workshop participants, 2002). The Atlantic Ocean thereby provided abundant moist air carried by strong westerly flow to northwestern China. Especially in Xinjiang, total amount and spatial extent of rainfall were enlarged. Thus, both sides of the Tianshan, the Junggar Basin, the Qaidam Basin, and the western highlands in Inner Mongolia became moister. From the different isotopic signals of $\delta^{18}O$ in lake sediments of the Guliya glacier in Tibet (Thompson et al., 1997) and Gaxun Nur, Wünnemann and Hartmann (2002) conclude that the precipitation that led to high lake levels in northwestern China during MIS 3 was brought from the westerlies. This is also corroborated by the lake-level evidence from the Uvs Nuur basin (about 50°N) of the northwestern part of Mongolia. The region presently has a relatively dry climate, annual precipitation in the basins is less than 100 mm, and is about 200 mm at the altitude of 2000 m. However, during the 40–30 ka BP, lake levels were assumed to be generally high, indicating the climate was more humid at that time (Grunert et al., 2000). In addition, $\delta^{18}O$ records and clay content in deep sea sediments in the northern South China Sea indicate an intensity of the Asian summer monsoon during the later stages of MIS 3 that were higherthan during the LGM but weaker than during the Holocene (Wang et al., 1999).

On the other hand, high water levels occurred repeatedly after 40–30 ka BP at the Barkol Lake. The Chaiwobu Lake and Aydingkol Lake also had high water levels during 20–15.03 and 24.9–15.7 ka BP, respectively. Periods of high water levels of lakes in the Tengger Desert lasted from 35 to 22 ka BP and again from 20 to 18.6 ka BP. The second cemented calcareous layer in the Badain Jaran Desert was formed around 19.1 ± 0.77 ka BP. These findings lead to the conclusion that the large-scale precipitation increase in northwestern China was mainly controlled by a strengthening of the westerly circulation (Porter and An, 1995). This is corroborated by paleoclimate models of the LGM that confirm that widespread high lake levels in Western China were closely associated with changes of the westerly circulation (Kutzbach et al., 1998; Yu et al., 2000). Hence, compared with the summer monsoon, the strengthening of the westerly circulation may be of more importance to explain the occurrence of the widespread humid period during MIS 3a in the study area. In addition, another possible reason beside climate has to be mentioned here. According to Wünnemann et al. (1998) and Thompson et al. (1997), the filling of basins with melt water from Tibetan glaciers that existed during MIS 4 might have been partly responsible fore higher lake levels in MIS 3.

6.2. Validation and accuracy of dating methods

However, it must be mentioned that the paleoecological interpretations of the field evidence are mainly based on ^{14}C dates on organic and carbonate sediments.

In arid regions, the ^{14}C content of lake sediments can be heavily biased by input of dissolved older and isotopically impoverished carbonates which could lead to an overestimation of the real ages of up to several thousand years (Chen et al., 1990; Fontest et al., 1996; Frenzel, 1998; Gehy et al., 1999). ^{14}C-ages from laminated lake carbonates from a terrace situated 35 m above the present level of Lake Cheligeri in the Badain Jaran Desert had to be corrected from 33.23 ± 4.92 to 32.15 ± 4.92 ka BP (Hofmann and Geyh, 1998). In addition, the varying depth of a water body itself influences the so-called 'reservoir effect' (Geyh et al., 1998) and thus may bias the radiocarbon chronology of lake sediments and lead to a misinterpretation of the timing of events and deduced climate changes. Therefore, potential dating inaccuracies should be taken into account, especially if discrepancies between terrestrial and lacustrine organic material occur. Thus, chronologies of lacustrine sediments based on calibrated and uncalibrated ^{14}C-ages cannot be directly compared with each other (Lehmkuhl and Haselein, 2000).

7. Conclusions

There is abundant field evidence for a warm and humid climate period between 40 and 30 ka BP in northwestern China. The surface areas of lakes (Aydingkol Lake, Chaiwobu Lake, Manas Lake, Barkol Lake, Lop Nur, Qarhan Salt Lake, Juyan Lake, Baijian Lake and Jartai Salt Lake) increased and water salinity decreased. Calcareous concretion layers formed on the terraces of the Keriya River at the southern margin of the Tarim Basin and in the Badain Jaran Desert. Pollen records in the Yabrai Mountain region in the Tengger Desert indicate a drop of the lower limit of forest and an increase in forest cover. Possible explanations for this climatic episode can be found in the strengthening and expansion of the summer monsoon, which extended its influence to the interior of northwestern China. The Tengger and Badain Jaran deserts lay at the margin of monsoon influence at that time. However, even more important for northwestern China was the strengthening of the westerly circulation. Higher radiation input at middle and low latitudes related to the Earth's precessional cycle led to a rise in the surface temperature of the Atlantic Ocean, thereby providing abundant moisture that was carried to northwestern China. The filling of basins with melt water from Tibetan glaciers that existed during MIS 4 might have also been partly responsible for higher lake levels during that time.

Current scenarios of global warming related to an increase in atmospheric CO_2 suggest that China's climate will inevitably change. Based on predictions of regional climate models, air temperature in northwestern China may rise by 2.8 °C or more if CO_2 concentration is doubled (Gao et al., 2001). A rise in air temperature will lead to changes in the hydrologic cycle. The warm and humid climate period that occurred in northwestern China during 40–30 ka BP can provide a possible historical analogue for climate conditions expected in predictions of long-term climate change in the area.

Acknowledgements

This research was jointly funded by the National Natural Science Foundation of China (Grant Nos. 40201011, 40372085, and 90102005), the Knowledge Innovation Project of the Cold and Arid Regions Environmental and Engineering Research Institute, Chinese Academy of Sciences (CACX204005, 2004106). We further want to thank W.D. Blümel, J. Rose and the anonymous reviewers who significantly helped to improve the manuscript.

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