

# A Holocene sedimentary record from Bosten Lake, China

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## Abstract

A 9.24 m long sediment record from the Kaidu River delta margin of Bosten Lake, northwestern China, provides evidence for changes in water balance of the lake during the past 8600 calendar years. Quantitative and qualitative analyses of detrital components, authigenic calcite, TOC and Sr/Ca molar ratios as well as comparisons with selected ostracod assemblages show that lake level fluctuations at minimum 5–6 m display changes in effective moisture supply, mainly driven by the west wind system. Distinct periods of negative water balances and thus dry conditions are dated to 8.5–8.1, 7.3–7.1, around 6.0, at 5.4–5.0, 4.6–4.3, 3.9–3.6, 3.4–3.2, 2.6–2.5, 1.9–1.1, 0.5–0.3 and 0.18–0.05 cal. ky BP and match the regional and global pattern of climate shifts during the Holocene. Temporal shifts of moisture availability during mid-Holocene time were recognised as well and may be attributed to regionally different airflow conditions. The last 150 years of rising lake levels are accompanied by strong eutrophication as a result of increased human impact.

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## 1. Introduction

Sediment records from lakes in northwestern China have been used to reconstruct changes in hydrological and environmental conditions and thus climate variability since the Last Glacial. Climate proxies derived from changes in salinity (Li et al., 1989; Yang et al., 1996), sedimentary variations of lake sediments, quantities of detrital components and soil erosion (Wang and Jiao, 1989; Gasse et al., 1991; Rhodes et al., 1996; Wünnemann et al., 1998), stable isotope variations (Fontes et al., 1993; Wei and Gasse, 1999), alternations of fossil remains with respect to ostracod and diatom assemblages (Gasse et al., 1991, 1996; Mischke et al., 2002), and vegetation changes (Campo van and

Gasse, 1993; Herzschuh et al., 2004) indicate shifts of the climate system from warm-wet to cold-dry conditions and vice versa as a response to moisture availability and radiation intensity during the Late Quaternary. Although it is widely accepted that unfavourable climate conditions during the Last Glacial Maximum (24–21 cal. ky BP), the Younger Dryas cold-dry episode (12.6–11.5 cal. ky BP) and during the Holocene (e.g. 8.2 cal. ky BP) occurred simultaneously worldwide, recently published papers indicate that asynchronous reactions of lake systems in China are the result of temporal and spatial shifts in moisture availability along the monsoon and west wind pathways (An et al., 2000; Yu et al., 2003; He et al., 2004).

As the validity of these implications is strongly dependent on a sustainable chronology and a consistent interpretation of various proxies taking local impacts on hydrological systems into account, we re-

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investigated the sediments of Bosten Lake in Xinjiang, China and revised the previously reported chronology with respect to the lake's development during the past 8600 calendar years.

## 2. Geological setting

Bosten Lake is located in the Chinese Autonomous Xinjiang Province ( $41^{\circ}56'–42^{\circ}14'N$ ,  $86^{\circ}40'–87^{\circ}26'E$ ) and fills the intramontane Yanchi Basin between the southern slopes of the Tian Shan range and the Taklimakan desert/Tarim Basin (Fig. 1). It is the largest inland freshwater lake in northwestern China, comprising a total lake area of approximately  $1000\text{ km}^2$  with a maximum water depth of 16 m. In 2000 the lake level reached 1048.90 m, nearly 1 m higher than

the year before. It was the highest level ever measured during the past 50 years, according to data from Zhang et al. (1995). However, palaeoshorelines documenting higher lake stands in the past have not been found so far.

The Yanchi Basin is bordered by the Elbin-Alagou Mts. and its pediments in the north (part of the Tian Shan) and the Kuruktag Mts. in the south, the latter being a tectonically very active threshold between the Yanchi Basin and the Tarim Basin. Slip rates of about 8 mm/year as well as supplementary vertical displacements of 1 mm/year since 25–35 ky have been inferred from right-lateral displacements of sedimentary features along the margin of the basin (Lin et al., 2002). However, little is known about the possible impact of single seismic faulting events on the sedimentary process

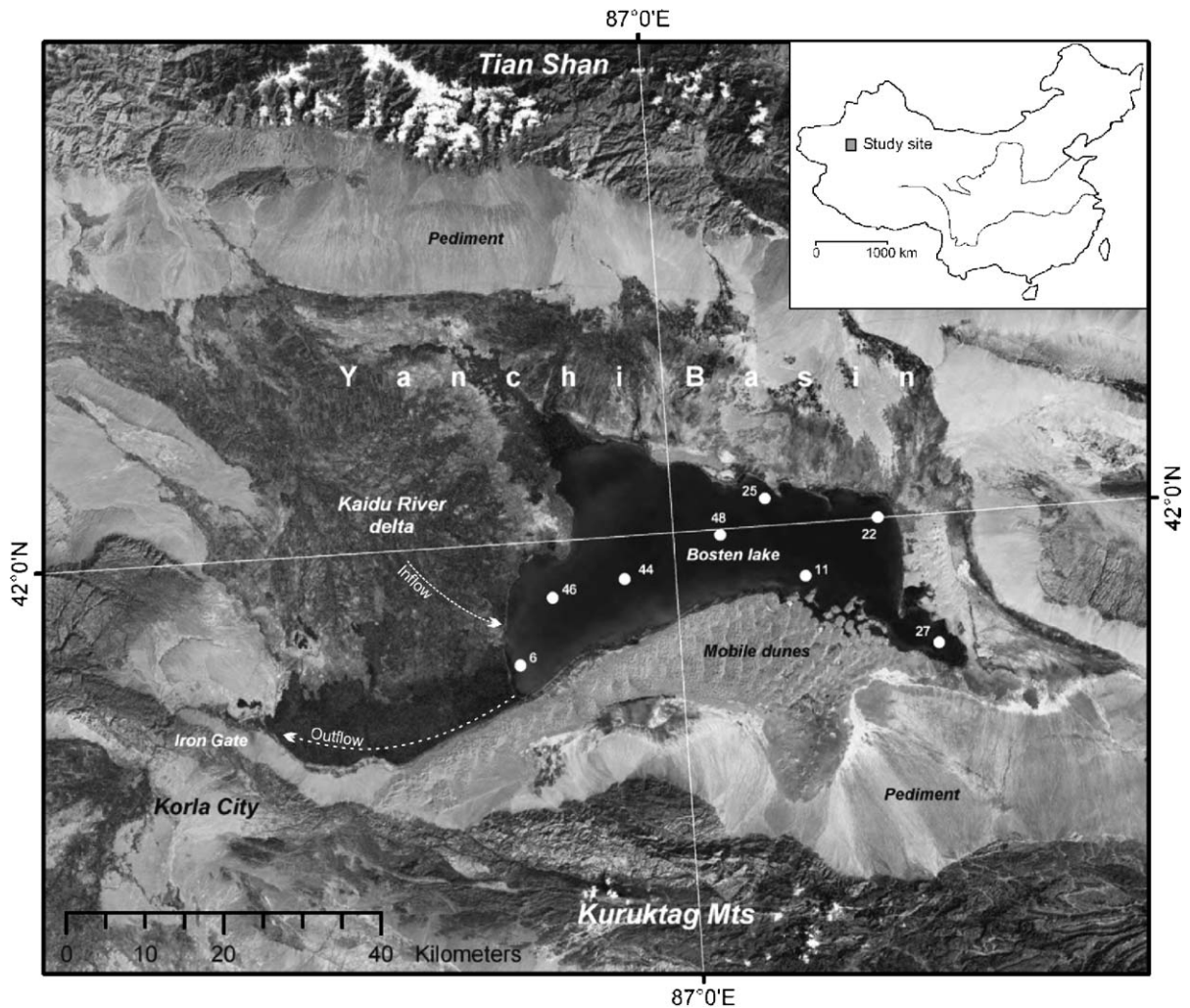


Fig. 1. Satellite image (Landsat 7, panchromatic band) of Bosten Lake in Xinjiang, northwestern China with locations of the drilling sites. Numbers indicate the cores of series XBWu.

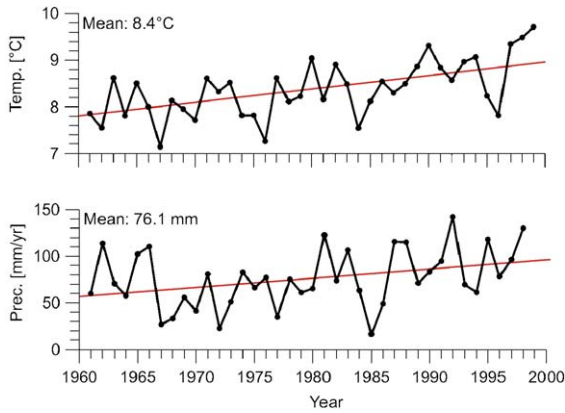


Fig. 2. Meteorological data (temperature and precipitation) of the last 38 years from the Yanchi station.

within the lake. A widespread mobile dune field with complex dunes of up to 100 m height has developed on the pediment plain between Kuruktag and the lake. The dunes partly migrate into the modern water body.

The catchment of Bosten Lake comprises an area of ~55,600 km<sup>2</sup> (Zhang et al., 1990, 1995), 75% of which is located outside the Yanchi Basin connecting the glaciated high mountain regions of the Tian Shan with the lake basin via the Kaidu River and 13 other first order rivers. The annual mean runoff of all drainages has been calculated to 3.95 \* 10<sup>8</sup> m<sup>3</sup>, while the Kaidu River provides more than 85% of the total input. As a result a large fan developed along the northwestern side of the lake and has been intensively used as irrigated farmland for centuries. Most of the annual runoff originates from precipitation; only approximately 15% is supplied by meltwater from the glaciated headwater area (Lanzhou Institute of Glaciology and Geocryology, 1987).

Bosten Lake drains at its western edge via the Peacock River and the Tiemenguan gorge (Iron Gate) towards the Tarim basin, merging in artificially altered tributaries of the Kaidu system before entering the fan at Korla City south of the Kurktag Mts. and petering

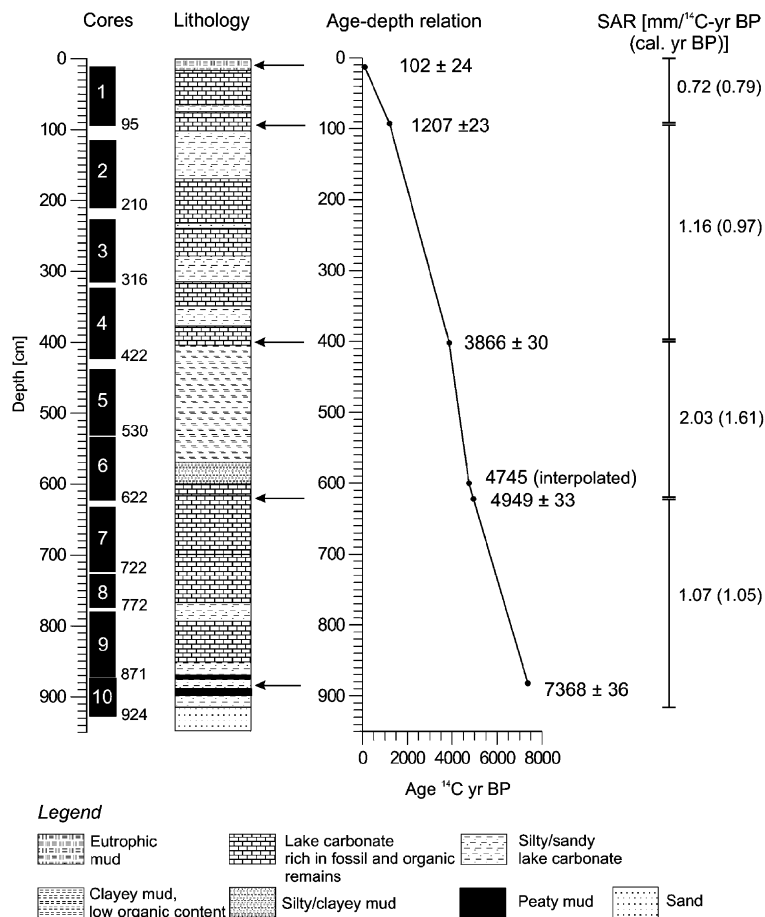


Fig. 3. Lithology and age-depth relation of the core XBWu46 from Bosten Lake at 41.94°N, 86.76°E.

out there. In former times this drainage continued farther east to the Lop Nor basin, as fossil drainages indicate. The contribution of meltwater and local rainfall transported via the Kaidu drainage system to the

lake basin and the perennial output via the Peacock River and Iron Gate are the main reasons for a high exchange rate of lake water protecting the lake from salinization. The mean residence time of the lake water

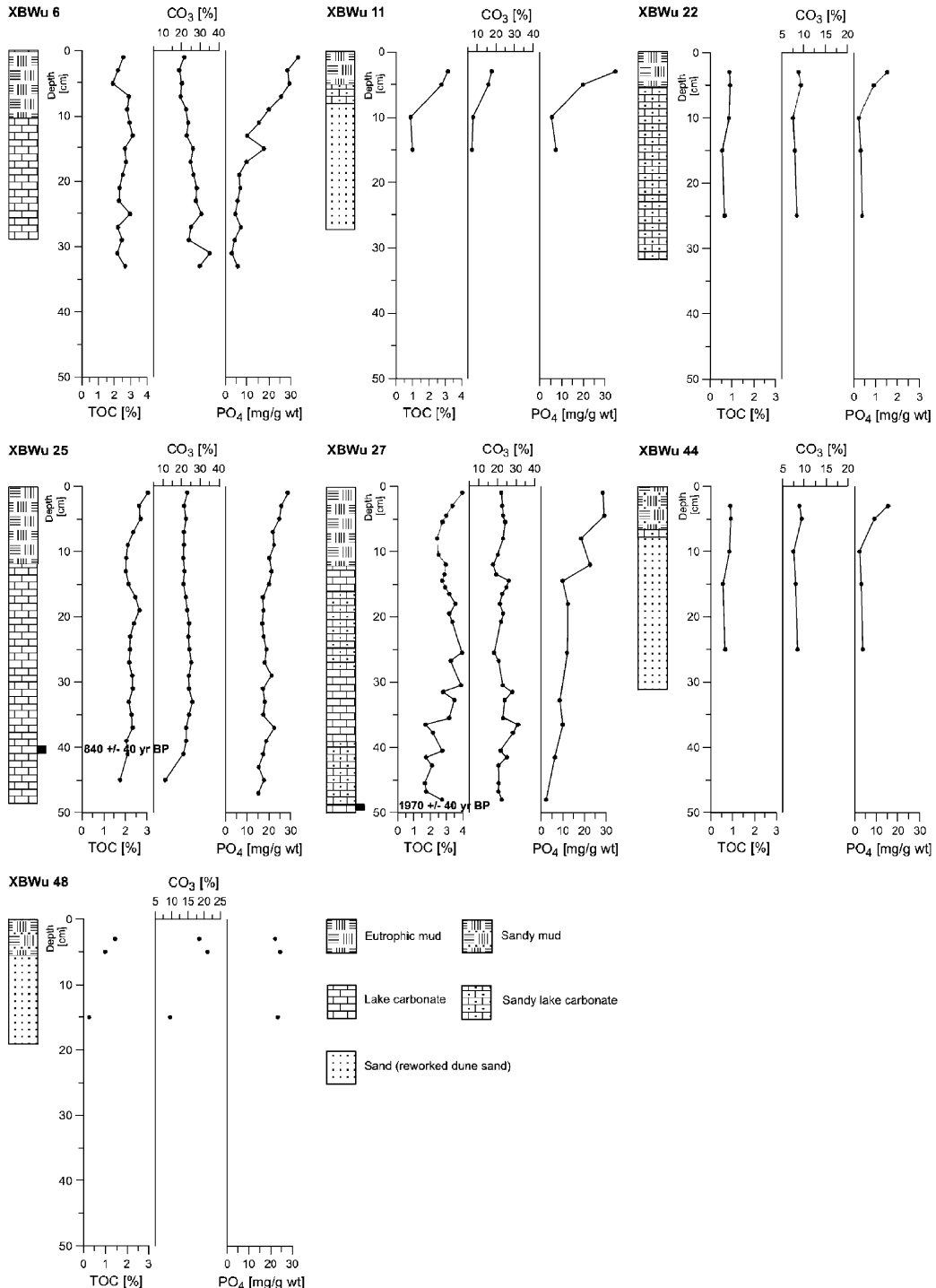


Fig. 4. Sediment and geochemical parameters of short cores from Bosten Lake. For locations see Fig. 1.

has been calculated to 1731 days with salinity variations between 0.2‰ and >2.5‰ (Jiu et al., 1990; Zhang et al., 1995). Since 1982 the natural outlet of the lake has been replaced by a channel and a pump station to control the water budget of the lake. The mean annual discharge varies between 24 m<sup>3</sup>/s in summertime and less than 4 m<sup>3</sup>/s during the winter months (Zhang et al., 1990).

The study site is part of the arid region of western China with 76.1 mm annual precipitation, mainly falling during the summer months, and a mean annual temperature of 8.4 °C (Jiu et al., 1990). Evaporation amounts to roughly 2000 mm/year; winds come mainly from the southwest, indicating dominant influence by the westerlies throughout the summer season. Climate data from the Yanchi weather station (Fig. 2) show an increase in both mean temperatures and precipitation over the past 36 years.

### 3. Methods

A 9.24 m long sediment core (XBWu 46) was taken from the western part of the lake at 41.94°N, 86.76°E using a piston corer adapted to the Livingston system.

The water depth at the drilling site reached 5.88 m, based on a lake level of 1048.9 m in summer 2000. Owing to the drilling technique, sediment losses of some centimetres at the top of each 1 m long core could not be avoided (Fig. 3).

Sediment samples were taken every 2 cm, giving a mean temporal resolution of roughly 20 years. Several short cores of maximum 50 cm length were taken from different sites of the lake in order to compare them with the main core and to estimate local differences of sedimentation outside the influence of the river mouth.

All samples were analysed for TOC and TIC/CO<sub>3</sub> by two methods: loss on ignition (LOI 550 °C and 880 °C) and by a carbon analyser (Ströhlein instruments). The remaining residue, expressed as silicates, is derived from LOI excluding the remaining CaO and biogenic silica. The latter was dissolved on original samples by 1 mol/l NaOH and quantified by a photometer. As parallel analyses of TC and TIC by the carbon analyser revealed comparable results, we used both data sets (Figs. 4–6) for further discussion.

Multiple element analyses of Ca, Mg, Sr, Fe, K, and P on dried samples treated by aqua regia digestion (HNO<sub>3</sub>+HCl) and hydrochloric acid (HCl) digestion

**Bosten Lake, Xinjiang, core XBWu46, 5.88 m water depth**

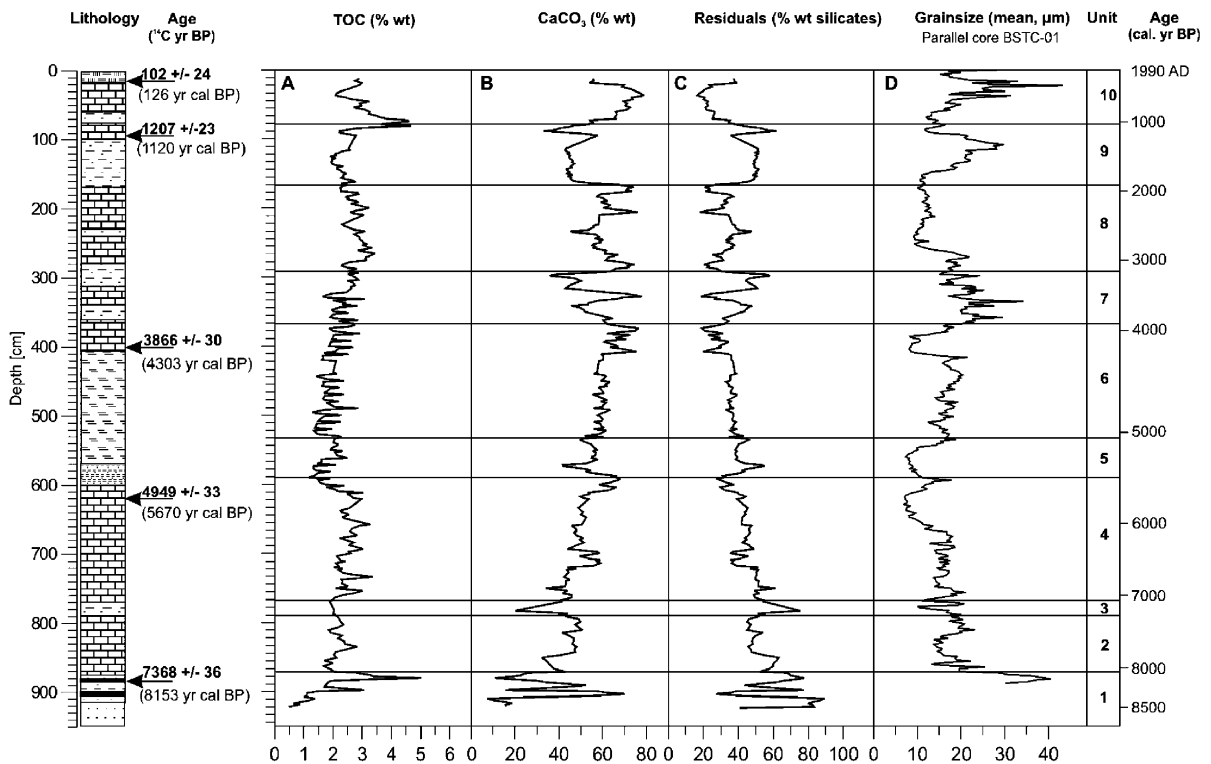


Fig. 5. Geochemical proxy data (TOC, CO<sub>3</sub> and silicates) from the core XBWu46 and grain size data from the parallel core BSTC-01, Bosten Lake versus depth. For legend see Fig. 3.

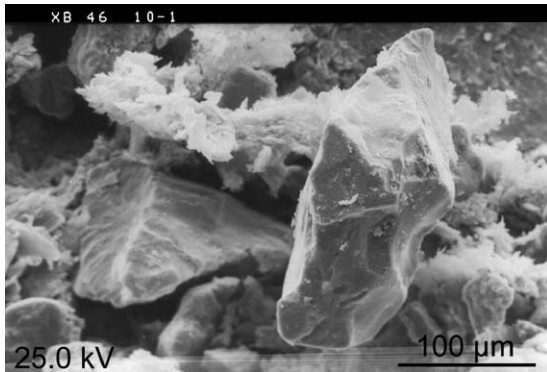


Fig. 6. SEM photograph shows angular shaped sand grains from the sediment core XBWu46, 920 cm depth.

were performed on a Perkin Elmer Inductive Coupled Plasma Atomic Emission Spectrometer (ICP-AES). Total phosphate in short cores was measured by a standard photometer. Quantities of Ca and Mg ions are related to the main carbonate minerals. Several control checks by X-ray and SEM-EDX analyses revealed that the only authigenic carbonate minerals consist of stoichiometric calcite and aragonite, the latter only found in mollusc shells. K and Mg have been used as typical detrital components derived from dissolved rock material of the catchment. Sr/Ca molar ratio, determined by hydrochloric acid (HCl) digestion is considered to indicate changes in salinity (Füchtbauer, 1988; Xia et al., 1997), while phosphate as the main nutrient serves as a tracer for inputs generated by soil erosion and farming activity. The total phosphorus in the lake water was estimated as 0.016–0.028 mg/l (Zhang et al., 1995) with rising values over the past 10 years.

As dolomite occurred only in relatively low amounts (up to 1.8% of the total carbonate), TIC and LOI (880 °C) have been calculated for calcium carbonate only.

Minerals such as siderite ( $\text{FeCO}_3$ ), rhodochrosite ( $\text{MnCO}_3$ ), pyrite ( $\text{FeS}_2$ ) or vivianite ( $\text{Fe}_3(\text{PO}_4)_2 \cdot 8\text{H}_2\text{O}$ ), indicate low Eh/pH ratios at the lake bottom and can produce significant errors within LOI analyses; however, they were only detected in the upper 5 cm of all cores.

For the age control we separated organic matter from selected samples by washing and sieving the sediment sample with distilled water and sorting out plant remains under a microscope. In three cases we were able to separate terrestrial plants (leaf stems), while all other samples only provided aquatic plant remains (e.g. charophytes). Radiocarbon dating by accelerator mass spectrometry (AMS) was performed at Leibniz Laboratory in Kiel, Germany. Two further AMS-dates on bulk organic matter from short cores (Fig. 4) were performed at Beta Analytics International, Miami, USA. For the uppermost and the bottom samples, age determinations were performed on the remaining lye fraction and on humic acid (Table 1). All dates were converted to calendar years, using the CALIB 4.4 program (equal to CALIB rev4.3) of Stuiver et al. (1998a,b). The tie points for our chronology refer to the weighted cal. years BP of 2 sigma probabilities (Table 1). Every sample age is calculated from the sediment accumulation rates (SAR, mm/year) between the dated samples in accordance with sedimentary boundaries. Differences to previously published data (Winnemann et al., 2003) are due to the revised sediment boundaries and depth and to corrected calibration procedure. Errors by lake-internal fractionation processes of subaquatic plants cannot be excluded. However, as the sample from 13 cm depth yielded an age close to the modern age and dates performed on the remaining lye fraction and humic acid only vary in a very narrow range, we assume that reservoir errors are of minor significance.

Table 1  
Radiocarbon (AMS) dating results from Bosten Lake

Core XBWu	Depth [cm]	Material	Lab. no.	Carbon [mg]	PMC (corr.)	Age [year BP]	$\delta^{13}\text{C}$ [‰]	Mean age (1 sigma) [cal. years BP]	Mean age (2 sigma) [cal. years BP]
25	41–42	OM <sub>bulk</sub>	Beta 143707			840 ± 40	−7.7	677	749
27	48–49	OM <sub>bulk</sub>	Beta 143708			1970 ± 40	−11.3	1917	1919
46-1	13–15	OM, lye	KIA 13113	2.2	98.74 ± 0.3	100 ± 25	−23.57		
46-1	13–15	Humic acid	KIA 13113	3.8	101.97 ± 0.28		−25.79		
46-1	13–15	OM <sub>mean</sub>	KIA 13113			102 ± 24		137	126
46-2	91–93	Plant	KIA 13184	4.1	86.05 ± 0.25	1207 ± 23	−9.39	1125	1120
46-3	400–402	Plant	KIA 13115	4.8	61.8 ± 0.23	3866 ± 30	−26.66	4298	4303
46-4	620–622	Plant	KIA 13116	1.7	54 ± 0.22	4949 ± 33	−9.61	5665	5670
46-5	880–882	Plant, lye	KIA 13117	3.5	39.96 ± 0.18	7370 ± 35	−25.61		
46-5	880–882	Humic acid	KIA 13117	4.8	39.77 ± 0.17	7405 ± 35	−26.73		
46-5	880–882	Plant <sub>mean</sub>	KIA 13117			7368 ± 36	−26.73	8149	8153

## 4. Results

### 4.1. Presetting and premisses

On the assumption that a fall in the level of Bosten Lake increases the extent of the Kaidu River delta and the deposition of fluviially transported coarser sediment load eastward, while in the reverse case rising lake levels result in the retreat of the subaerial part of the delta and only fine-grained suspension load can reach the coring site, we can use TOC, carbonate, detrital compounds, salinity indicators (Sr/Ca ratios) and nutrients (phosphate) to distinguish between high and low lake levels.

On the other hand, it has to be taken into account that an increased runoff induced by higher rainfall or snow/glacier melt in the upper catchment may result in stronger fluvial sediment transport towards the basin. Hence, increased deposition of coarse clastics may occur without any change in lake level. However, reconstructing lake level fluctuations based on our model, it was necessary to find an appropriate location far distant from the direct influence of the river mouth without losing the contact to the delta system. We assume that the contribution of sediment load towards the basin and the variations of the transport capacity then would not have overprinted the lake level-dependent sedimentation process at the coring site. For example, a very strong river discharge and high suspension load in July 1999 did not reach our site and all suspended load was deposited some kilometres apart, while the lake water at the coring site remained clear.

The choice of our coring site approximately 10 km northeast of the Kaidu river mouth at 41.94°N, 86.76°E was due to the fact that several short cores from the centre and the eastern part of the lake (Fig. 4) provided only some decimetres-thick sequences of pelitic lake deposits followed by unknown thicknesses of sandy mud or even pure sand (Fig. 4, cores XBWu 11, 22, 27, 44 and 48). Coring of long sequences at these locations was not possible using our piston corer. Unlike the sedimentary conditions in the delta region (see cores XBWu 6 and 46, Figs. 3 and 4), most of the lake bottom is influenced by lake-internal circulation patterns induced by wind activity (Zhang et al., 1990, 1995). In fact, lateral erosion of dune sand from southern and eastern coastlines favours the admixture of lake mud and reworked aeolian sand in the central part of the lake, but not in the delta region. The short core XBWu44 (Figs. 1 and 4) some 8 km east of core XBWu 46 already contained muddy sand from the top down-

ward, while we could not find any reworked sand layers of aeolian origin in cores XBWu 6 and 46 (Fig. 3).

### 4.2. Sediments of Bosten Lake

The core XBWu 46 provided 9.24 m soft sediment in ten 1-m-long sequences. The lithology can be subdivided into four major lithological units (Fig. 3):

- (1) Fluvial coarse sand at the bottom of the core (924–914 cm depth). The poorly sorted grains of medium to coarse sand and even gravels require a high energy transport by the river from nearby catchments. Only very few broken shells of ostracods and charophytes were found, indicating reworking processes during the depositional phase.
- (2) The majority of the sediments in core XBWu 46 consists of fine grained carbonate mud (914–15 cm depth) with strongly varying carbonate and TOC content. Ostracods (up to 10 species, Mischke and Wünnemann, in press), gastropods (9 species) and bivalves (3 species, Riedel et al., 2003) as well as charophytes and diatoms classify this sediment as lacustrine. Two layers of enriched plant felt at 904–900 cm and 884–880 cm depth indicate short phases of peat development. Higher proportions of fine sand within the carbonate mud occur at 914–850 cm, 795–765 cm, 375–350 cm, 315–278 cm, 238–230 cm, 167–100 cm and 75–64 cm depth.
- (3) Light-grey clayey-silty clastics with low TOC content dominate the sequence between 600 and 405 cm depth.
- (4) The uppermost sediment consists of dark-grey carbonate mud without any living metazoan invertebrates.

Fossil remains of gastropods, bivalves and ostracods have been found in nearly all parts of the sediments (Riedel et al., 2003; Mischke and Wünnemann, in press). They are all indicative of fresh or slightly brackish water, implying that during the entire period of sedimentation no severe changes towards higher salinities occurred. On the other hand, differences in the abundance of profundal and littoral taxa of ostracods indicate changes in water depth and thus climate-controlled variations in water balance. The absence of any living specimens in the uppermost sediments seems to be the result of a highly eutrophied water body over the last 150 years owing to the strong input of fertilizers from the irrigated farmland. Nearly all cores show a

distinct increase in phosphate concentration from about 10 cm upward (Figs. 4 and 6).

Ostracods from the core XBWu46 and their indications for changes in lake level and ecological conditions are described by Mischke and Winnemann (in press) in detail. However, for comparison with our sediment proxies we use the records from *Darwinula stevensoni*, *Candona neglecta*, and *Cyprideis torosa*, as they indicate changes in water depth and salinity of Bosten Lake. *D. stevensoni* typically inhabits shallow permanent water bodies (Ranta, 1979; Griffiths and Butlin, 1994) and therefore may reflect low lake level conditions. *C. neglecta* prefers relatively low temperatures and consequently has often been recorded from deeper parts of lakes (Bhatia and Singh, 1971; Diebel and Pietrzyk, 1975; Danielopol et al., 1993), although shells may be found in shallow water bodies too (Meisch, 2000). The species tolerates low oxygen contents of bottom waters (Danielopol et al., 1993) and co-

occurs with *Fabaeformiscandona caudata* in the Bosten Lake record. *F. caudata* is known as a characteristic inhabitant of the sublittoral and profundal zone of lakes (review in Meisch, 2000). Owing to the co-occurrence of *C. neglecta* and *F. caudata* as well as the opposite trends in the abundances of *D. stevensoni* and *C. neglecta*, we assume that the latter indicates deeper water conditions in Bosten Lake. Hence, we use the relative difference (percent abundance) between *C. neglecta* and *D. stevensoni* as markers for higher or lower lake levels (see Fig. 7).

#### 4.3. Age model

The age model is derived from AMS dates as tie points for linear calculations of the SAR on the basis of calibrated ages (Fig. 3). As the changes in sediment composition throughout the core are not very extreme and, except in the bottom part, the grain size distribu-

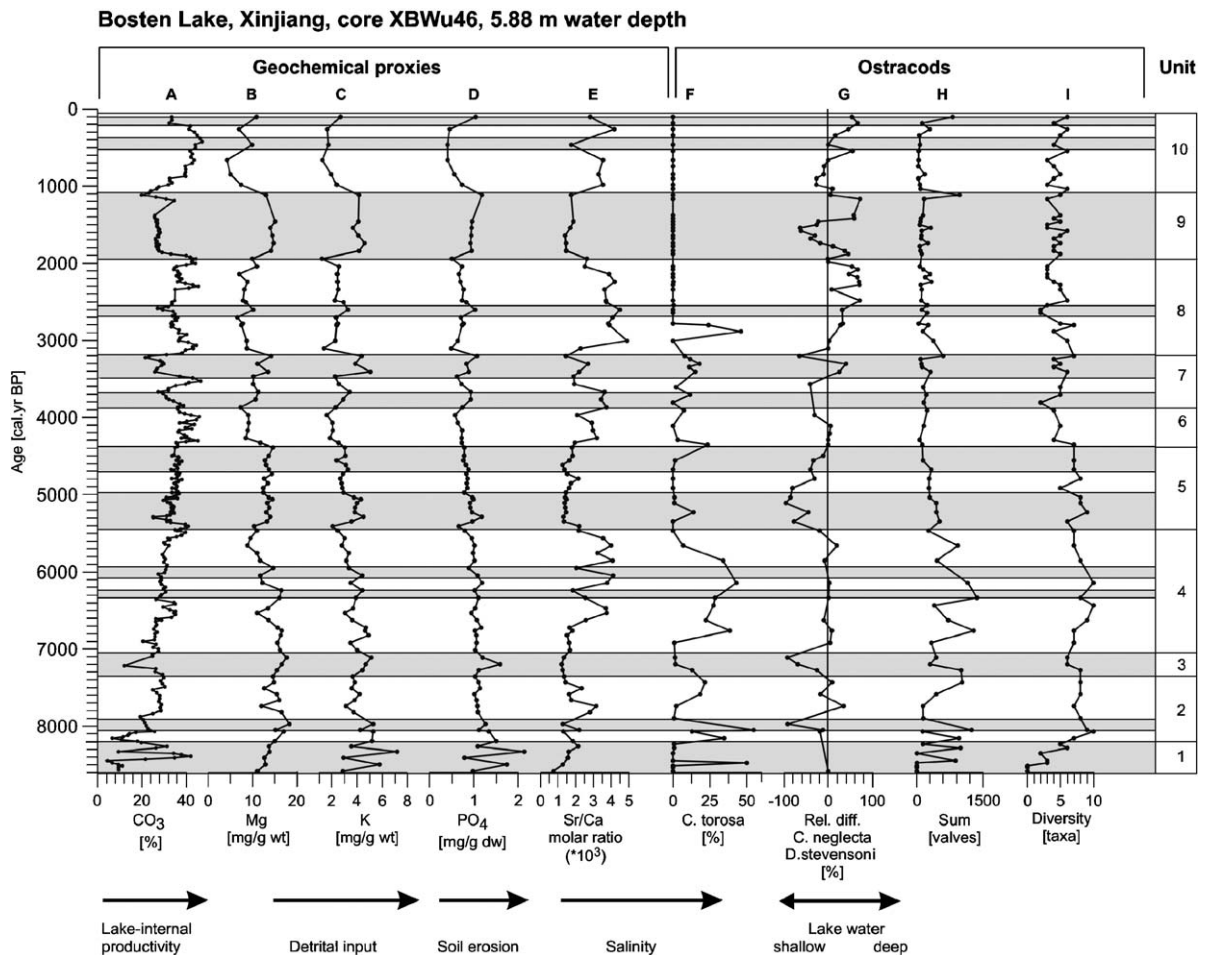


Fig. 7. Geochemical and ostracod proxy data from the core XBWu 46, Bosten Lake versus cal. years BP. Shaded areas indicate increased detrital flux and thus lower lake levels. For legend see Fig. 3.

tion is in a quite narrow range between clay, silt and fine sand (63–125  $\mu\text{m}$ ), we assume that the reconstructed chronology represents a good proximity to true ages. For the 20 cm thick bottom layer, composed of coarse to medium sand of fluvial origin, calculation of a reliable accumulation rate is nearly impossible. However, we calculated a bottom age of approximately 8600 cal. years BP, based on the assumption that the transition from silty mud at 9.14 m depth to the sand layer reveals a calculated age of 8500 cal. years BP.

Between 9.14 m and 6.2 m depth the SAR was calculated to be 1.05 mm/year, implying that the distinct lithological boundary at 6 m depth represents an interpolated age of 4745  $^{14}\text{C}$  year BP, equal to 5533 cal. years BP.

According to changes in sediment composition (clayey silt, low organic content) between 6 and 4.1 m depth, the SAR rises to 1.61 mm/year. With the occurrence of carbonate mud and higher amounts of organic remains between 4.1 m and 0.95 m depth, the SAR returns to similar accumulation rates of 0.97 mm/year to those in the lower part of the core. The lowest SAR of 0.79 mm/year in the upper 97 cm of the core is in accordance with the lowest proportions of clastic material but high carbonate precipitation.

#### 4.4. Interpretation of geochemical data

On the basis of alternations in sediment and geochemical composition we can distinguish 10 different units which reflect the impact of the Kaidu River delta and thus lake level fluctuations from 8600 cal. years BP to present (Figs. 5 and 7).

##### 4.4.1. Unit 1 (9.24–8.75 m; 8600–8150 cal. years BP)

Unit 1 (9.24–8.75 m; 8600–8150 cal. years BP) comprises two different sedimentary processes: fluvial input and the onset of lake development. The coarse/medium, dark coloured and poorly sorted sand at the very bottom of the core (Fig. 5) is of fluvial origin, containing high percentages of very angular grains (quartz and opaque minerals, Fig. 6) transported by the Kaidu River to the coring site at extremely low lake levels. The grain size composition based on a parallel core BSTC-01 shows highest mean values (Fig. 5D). The high proportion of opaque grains identified as amphibolites by X-ray analyses is remarkably different from the dune sand in the vicinity of the lake. Hence, the dune area south of the lake can be excluded as a possible source for sand transport for that period. The angular shaped grains indicate the influence of frost weathering due to the very low lake level and

total freezing of the water body down to the bed during wintertime. A completely dry lake bottom at the drilling site can also be assumed, leading to a further eastward extension of the Kaidu delta. This is supported by the fact that terrestrial fungal spores (pers. comm., D. Demske, Berlin) and higher amounts of phosphate have been identified, both indicating soil erosion from nearby land surfaces. However, the rapid change to a swampy environment or very shallow lake is indicated by the presence of ostracod shells, numerous charophyte oogonia and diatoms, as well as the sudden appearance of lake carbonate interrupted by peaty mud 8500 calendar years ago (Fig. 5). The TOC rises to 3% and 5% (Fig. 5A) and calcite ( $\text{CO}_3$  in Fig. 7A) amounts to 75% of the total sediment where organic enrichment disappears. The strong fluctuations of TOC, carbonate and silicates (Fig. 5) as well as the detrital element K and phosphate (Fig. 7C, D), even the number of ostracod valves (Fig. 7H) indicate a rather unstable lake under freshwater conditions until 8150 cal. years BP. The low diversity of ostracods starts to rise with the onset of lake formation (Fig. 7I).

##### 4.4.2. Unit 2 (8.75–8.0 m; 8100–7300 cal. years BP)

This period is generally characterised by the stabilisation of the lake level. The relatively low input of detrital material, medium but continuously rising calcite precipitation (up to 40%) and TOC values between 1.7% and 2.7% (Fig. 5A), mainly derived from internal algae production, support the arguments for a relatively high lake level and increased distance to the river delta. Higher values of Mg (up to 18 mg/g dw, Fig. 7B) are due to detrital dolomite particles detected by X-ray and SEM-EDX analyses during a short phase of enhanced river discharge around 8000 cal. years BP. Afterwards, the total detrital input remained at a low level. A longer residence time of the lake water and thus slightly increased salinity can be derived from rising Sr/Ca molar ratios from 7900 to 7700 cal. years BP and from increasing percentages of the brackish water tolerating ostracod *C. torosa* (Fig. 7F). The relatively high number of ostracod taxa and the rising amount of species per 10 g sediment in the second half of unit 2 may be indicative of stable lake conditions until 7300 cal. years BP.

##### 4.4.3. Unit 3 (8.0–7.7 m; 7300–7050 cal. years BP)

The stable lake conditions are interrupted by a 250-year phase of increased detrital input (total silicates: 75%, Fig. 5C; peaks for Mg, and K, Fig. 7B, C) from the river delta, accompanied by the input of soil material (peak in phosphate concentration) and low Sr/Ca

molar ratio (Fig. 7E), the latter indicating stronger freshwater input under a lowered water body. Reduced salinity might be also inferred from the decrease in *C. torosa*. A lowered lake level is furthermore indicated by the abundance of *D. stevensoni* (negative values in Fig. 7G).

#### 4.4.4. Unit 4 (7.7–5.9 m; 7050–5400 cal. years BP)

The return to a higher lake level and nearly stable conditions for about 1700 years duration is marked by the continuous decrease of the detrital components (Fig. 5C) until 5600 cal. years BP. From about 6600 cal. years BP the residence time of the water body was significantly longer, leading to higher salinities and keeping the water body stable for at least 1000 years as indicated by high Sr/Ca mole ratios, increasing percentages of *C. torosa* and increased calcite precipitation. Two short-term intervals at 6280–6200 and 6020–5880 cal. years BP of a slightly lowered water body may have interrupted the stable lake phase. The TOC content, mainly derived from subaquatic plants and algae, fluctuated in similar magnitudes as in unit 2. In our opinion, this lake phase represents the most favourable period of lake development within the last 8500 years, also indicated by the balanced occurrence of *C. neglecta* and *D. stevensoni* (Fig. 7G). High biological activity is not only represented by the TOC values but also by numerous molluscs and a high number of ostracod valves in the core (Fig. 7H). High CaCO<sub>3</sub> values of up to 68% between 7.4 and 7 m and 6.2–5.9 m depth (Fig. 5B) are due to enriched aragonite derived from mollusc shells. The last 200 years can be regarded as a transition to deteriorating lake water conditions, marked by the sudden decrease in TOC (Fig. 5A). We assume that lake-internal phytomass production by subaquatic plants (e.g. charophytes) decreased owing to reduced water transparency as a result of enhanced input of suspended load, as charophyte oogonia could not be found.

#### 4.4.5. Unit 5 (5.9–4.1 m; 5400–4300 cal. years BP)

This unit comprises 1100 years of a mainly shallow freshwater lake with two phases of enhanced input of clastics and soil material, indicated by both peaks in detrital components and phosphate accompanied by reduced calcite precipitation (Fig. 7B, C, D). Lowest TOC values of <1.5% at the beginning of unit 5 indicate unfavourable conditions for lake-internal carbon storage and input of terrestrial plant remains as well. The generally low but slightly rising TOC content (Fig. 5A) continues throughout the unit and can be recognised by the light grey colour of the sediment.

The grain size (Fig. 5D) ranges from mean values <10 µm at the beginning of unit 5 to about 15–20 µm and may be due to a rising input of suspended load. Very low Sr/Ca values and low percentages of *C. torosa* as well (except two peaks at the beginning (~5200 cal. years BP) and at the end (~4350 cal. years BP) of unit 5) indicate low salinity of a shallow freshwater lake, supported by the negative values (occurrence of *D. stevensoni*) in Fig. 7G.

#### 4.4.6. Unit 6 (4.1–3.6 m; 4300–3850 cal. years BP)

Low detrital input and high carbonate precipitation (Fig. 5B, C) reflect a rising but fluctuating lake level, reaching its highest level around 4000 cal. years BP. Increased Sr/Ca values and the slightly increasing amount of *C. neglecta* correspond to a rising lake level and increasing residence time of the lake water.

#### 4.4.7. Unit 7 (3.60–2.90 m; 3850–3150 cal. years BP)

After 3850 cal. years BP the lake level started to fluctuate considerably within short periods, as indicated by strong shifts in carbonate content and clastic components reflecting unstable hydrological conditions. Periods of predominantly shallow freshwater conditions occurred at 3850–3640 and 3430–3150 cal. years BP, always accompanied by reduced carbonate precipitation due to the enrichment of silicates and the indicator elements Mg and K (Fig. 7B, C). Low salinity (Fig. 7E) and TOC, but varying ostracod values (Fig. 7F, G) may indicate freshwater input, probably without remarkable change in lake level. Increasing concentrations of phosphate (Fig. 7D) indicate additional input of soil material from near-shoreline locations.

#### 4.4.8. Unit 8 (2.90–1.65 m; 3150–1900 cal. years BP)

In comparison to the previous unit this period is dominated by deeper water conditions, as indicated by low detrital input, higher salinity (Fig. 7B, C, E) and the dominance of *C. neglecta* (Fig. 7G) although a minor fluctuation of about 180 years duration may have occurred between 2680 and 2500 cal. years BP.

#### 4.4.9. Unit 9 (1.65–0.8 m; 1900–1050 cal. years BP)

High quantities of detrital components, supplemented by the enrichment of silt (Fig. 5D) and lowest Sr/Ca molar ratios, imply freshwater conditions under a lowered lake level and thus an advance of the river delta close to the drilling site. However, the ostracod data indicate a fluctuating lake level from shallow to deeper conditions throughout the unit. The strong increase of TOC derived from reed remains at the boundary between units 9 and 10 is indicative of a water body not

deeper than 1 m at the drilling site approximately 1000 cal. years BP ago.

#### 4.4.10. Unit 10 (0.8–0 m; 1050 cal. years BP–present)

The reduced detrital input after 900 cal. years BP indicates a generally rising lake level with two short-term reverse trends at 500–300 cal. years BP (~1450–1650 AD) and at 180–60 cal. years BP (~1770–1890 AD). The strong increase of phosphate towards the top of the core (Fig. 7D) has also been detected in all short cores (Fig. 4) and is mainly due to the strong input of nutrient-rich irrigation water from farmland and can therefore no longer be used as an indicator of decreasing lake levels. The uppermost 13 cm of sediments (not recovered in the core) consists of nutrient-rich mud and abundant remains of green algae and diatoms. They record a strong human impact during the last 130–150 years of lake development. Lake level fluctuations of at least 3 m over the past 50 years (Zhang et al., 1995) provide comparable sediments to those found in the uppermost sequence of core XBWu 46. This would mean that changes in sediment structure and composition as described above require greater lake level changes than during the last 50 years.

## 5. Discussion

The sediment record of Bosten Lake covers the last 8600 cal. years BP. Quantitative and qualitative geochemical and sedimentary analyses of the core XBWu46 indicate variable depositional conditions close to the margin of the Kaidu River delta.

The close relationship between lake level changes and depositional processes of coarser clastics originated from the Kaidu River seems to be valid, if we consider carefully that the distance from the modern river mouth to the coring site is more than 10 km, and thus coarse sediments cannot reach the site, even during extreme flooding events. If the river course changed considerably, the minimum distance to the core amounted to >5 km; in our opinion too far for coarse material (e.g. sand) to be transported as suspended load through a stillwater body, except the pelitic components. As the widely distributed reworked sand of aeolian origin appears as intercalated sand layers or even massive sand in several short cores east of the Kaidu river delta (Fig. 4), but not in the core XBWu 46, we assume that the deposition of dune sand within the lake either happens by wave-induced lateral erosion along the southern shoreline or by aeolian transport mainly following the path of strong southwest winds. Hence, we assume that lowering of the lake level and thus shortening of the distance be-

tween river mouth and coring site may be the main reason for the contribution of river sand to the coring site. This means that during low lake levels the clastic content and the grain size increased considerably (Fig. 7). This is supported by the fact that the ostracod assemblages (Fig. 7) indicating increasing salinity (*C. torosa*), shallow water (*D. stevensoni*) or deeper water (profundal environment; *C. neglecta*) follow the sedimentological and geochemically reconstructed changes as well.

On the other hand, we cannot exclude the possibility that dune sand from the southern catchments of the lake may have been transported by wind to the coring site in periods when southeasterly winds prevailed. However, as the analysed sandy carbonates include large amounts of dark sand grains, which are not found in the dune sand, we conclude that most of the sandy material was transported from the Kaidu River to the coring site.

In contrast to the general opinion that low lake levels are attributed to strong evaporation and the enrichment of ion concentration in lake water towards saline conditions under warm and dry climate conditions, we find just the opposite relation at our coring site. This is due to the fact that every strong freshwater pulse from the Kaidu river leads to a dilution of the lake water in the western part of the lake, while this effect weakens with increasing distance from the river mouth. The closer the distance between the coring site and the river mouth (during low lake levels), the stronger the refreshing of the lake water. This would explain why low lake levels are related to low salinity and vice versa. However, low lake levels are also related to generally negative water balances with respect to the entire water volume of Bosten Lake, thus indicating reduced runoff, either as a result of reduced rainfall or meltwater supply, the latter implying glacier advance in the upper catchment.

The reconstruction of lake status changes at Bosten Lake as summarised in Fig. 8 follows the methods used in the Chinese Data Base Documentation (Yu et al., 2001) and provides a centennial resolution of lake level changes within 5 status classes between 1 (very low lake level) and 5 (highest lake level). Coarse grained and predominantly angular clastics of fluvial origin at the very bottom of the core (unit 1) were deposited when the subaerial part of the river delta expanded eastward as a result of a strong lake level decline. Taking into account that no fossil shorelines at higher elevations than 1049 m (summer 2000) have been found and the mean subsidence rate of roughly 1 mm/year within the Yanchi basin (Lin et al., 2002) corresponds to the mean sediment accumulation rate

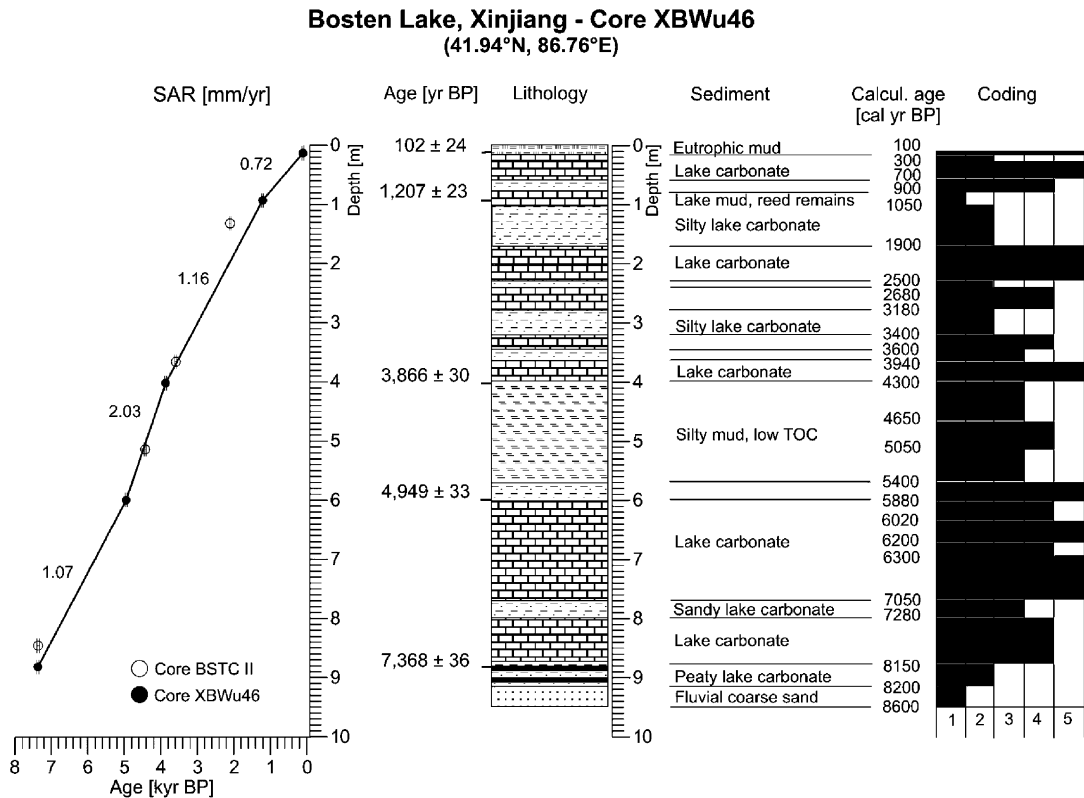


Fig. 8. Lake status record from Bosten Lake, Xinjiang (41.94°N, 86.76°E) based on geomorphology, sediment data, geochemical proxies and microfossils (ostracods). The status coding is adapted to the Chinese Data Base Documentation (Yu et al., 2001). Coding of lake status with respect to lake levels: 1=very low or dry; 2=low; 3=medium; 4=high; 5=very (extremely) high. Open circles within the age–depth column mark AMS dates from a nearby sediment core (BSTC-II, Chen F. et al., in prep.).

of 0.8–1 mm/year, a lake level decline of minimum 5–6 m has to be assumed. This phase happened between 8600 and 8150 cal. years BP owing to reduced local rainfall and meltwater flux from the Tian Shan headwater area. This period of enhanced dry and probably colder conditions, corresponding to the previously described 8.2 ka dry-cold event (e.g. Wang et al., 2002; Staubwasser et al., 2003) were also recognised in records from Bangong Lake (Gasse et al., 1996), Hongshui section (Zhang et al., 2000) and Juyan Lake (Herzschuh et al., 2004), supporting the global climatic significance of this event. The fluvial deposits and the following period of swampy environment with peat development seem to have been the most unfavourable lake conditions during the entire period under consideration (Fig. 7). According to our chronology this time span lasted approximately 450–500 years, similar to model-data comparisons for the 8.2 ka BP-event reported by Wiersma and Renssen (2004).

The highest lake level and thus weakest influence of the river delta was accompanied by increased salinities, the latter indicating a long residence time of the lake

water under stable hydrological conditions, which occurred between 8100 and 5400 cal. years BP (units 2–4). Accordingly, a high diversity of ostracods and maximum numbers of valves as well as pollen data from the vicinity of the lake (Zhong and Xiong, 1998) indicate a warm-wet climate and high biological productivity. Considering the presently low contribution of meltwater to the lake without significant change during the early Holocene, local rainfall must have increased to establish a long-lasting positive water balance, known as the Holocene climate optimum (e.g. Yan and Petit-Maire, 1993; An, 2000). Warm-wet conditions between 9500 and 6300 year BP at Bangong Lake (Gasse et al., 1996) have been attributed to a strengthening of the summer monsoon circulation. Assuming that the present water vapour transport to the Tian Shan region is not only governed by the summer monsoon but more frequently by the west wind system (Sun et al., 1998), which transports moist air masses along the east–west striking valleys to the Bosten Lake catchment, we can conclude that the increase of precipitation between 8100 and 5400 cal. years BP may have also resulted

in a strengthening of the west wind system. If we consider a stronger influence of the summer monsoon circulation, effective moisture transport from southern directions must have shifted from Bangong Lake more than 8° latitude (equal to approx. 900 km) northward, crossing high mountain ranges as well as the hyper-arid Tarim Basin. However, the enhanced effective moisture availability is also corroborated by the advances of glaciers in the northern Tian Shan between 7400 and 6100 cal. years BP (Gu and Li, 1990; Shi et al., 1992; Yi et al., 2004). It seems plausible to assume that increased precipitation (snow in the high mountains and rainfall in lower altitudes) occurred during early autumn and not only during summertime as it does today, thus letting the glaciers grow and preventing the snow from melting. Enhanced winter precipitation can be excluded because the developed high pressure cell over Siberia in wintertime transporting cold-dry air masses south- and southwestward (winter monsoon) also existed during the entire period under consideration. Furthermore, an enhanced summer precipitation would not automatically induce glacier growth, because higher radiation and temperatures would also enhance snowmelt at high altitudes, as it does at present. Strong meltwater discharge during summertime could explain the positive water balance but contradicts the glacier advance at that time. The seasonal shift of enhanced precipitation to the later part of the year would also contradict the modern behaviour of the summer monsoon circulation pattern, which starts to shift southward with the development of the high pressure cell over Central Asia in September/October (Domroes and Peng, 1988). Despite the postulated northward shift of the summer monsoon boundary (Yan and Petit-Maire, 1993; Gasse et al., 1996; An et al., 2000; Ding and Yang, 2005) which might have affected the northwestern regions of China more than at the present time, it seems more likely that effective moisture transport to the catchment of Bosten Lake was closely related to the west wind system.

The intermittent short dry spell between 7300 and 7100 cal. years BP (unit 3 in Fig. 7) probably corresponds to the closure of Lake Issyk-Kul in the western Tian Shan (Ricketts et al., 2001) and to a regressional lake phase of Chaiwopu Lake (Zhou et al., 1991) north of the Tian Shan. Simultaneously a weak monsoon is recorded at Bangong Lake (Wei and Gasse, 1999), indicating reduced moisture transport by both circulation systems at that time. Reduced moisture supply in the Badain Jaran Desert (Herzschuh et al., 2004) and Tengger Desert as well (Wünnemann, 2003; Zhang et al., 2004) supports the argument for dry conditions with

regional rather than local effects on the water balance. However, a second dry period between 6800 and 5300 cal. years BP, reported from Manas Lake north of the Tian Shan (Rhodes et al., 1996; Wei and Gasse, 1999) and from the Gobi desert (Chen et al., 2003, 2005), cannot be confirmed in general but supports short-term dry intervals at Bosten Lake of approximately 100 years duration around 6200 and 5900 cal. years BP and more distinctly between 5400 and 5000 cal. years BP.

The climate deterioration centred at 5800 cal. years BP over monsoonal Asia, as reported by Gasse et al. (1991), Sirocko et al. (1993), Overpeck et al. (1996), Enzel et al. (1999) and Chen et al. (2003) does not exactly match the lowstand at Bosten Lake between 5400 and 5000 cal. years BP. Increased detrital input of clastics via the Kaidu River, enhanced soil erosion, lowest TOC values and ostracod assemblages all indicate shallow water. They are evidence of dry climate conditions delaying the period of weak summer monsoon by at least 400 years. If considerable moisture transport to northwestern China and to the Tian Shan region was frequently influenced by the west wind system, sufficient rainfall until 5400 cal. years BP might have overprinted the summer monsoon signal at that time, resulting in contrasting regional moisture patterns outside the summer monsoon limit. The asynchronous response of lakes affected by different sources of moisture transport at least supports the arguments of temporal and spatial shifts of the climate system over Central Asia (An et al., 2000; He et al., 2004).

However, the return to a more positive water balance and thus higher lake level between 4900 and 3900 cal. years BP at Bosten Lake with a short-term reverse trend between 4650 and 4350 cal. years BP corresponds to increased moisture availability deduced from sediment records at Manas Lake (Rhodes et al., 1996), from lakes in the northern foreland of the Tibetan Plateau (Wünnemann et al., 1998; Mischke et al., 2002; Chen et al., 2003) and from the Loess Plateau (Huang et al., 2000; Li et al., 2003).

Since about 4300 cal. years BP (Fig. 7, units 6–10) frequent alternations in lake level at Bosten Lake have indicated short-term climatic fluctuations with reduced rainfall and hence negative water balances dated to 3840–3600, 3420–3120, 2650–2500, 1900–1050, 500–300 and 180–50 cal. years BP. The reported dry spell around 4200 cal. years BP (Rhodes et al., 1996; Wei and Gasse, 1999; Staubwasser et al., 2003) cannot be deduced from the sediment proxies at Bosten Lake, although higher proportions of littoral ostracod taxa at that time indicate a lowering of the lake (Mischke and Wünnemann, *in press*). In addition, the relatively long

period of drier conditions between 1900 and 1050 cal. years BP may have experienced some very short reversals as indicated by the profundal ostracod taxa *C. neglecta*. Short-term dry spells at 500–300 and 180–50 cal. years BP (~1450–1650 AD; ~1770–1900 AD) are probably related to cooling periods during the Little Ice Age with ice advances in the Tian Shan.

The high-frequency variations in Bosten Lake levels since about 4300 cal. years BP seem to be a response to various forcing mechanisms affecting the Tian Shan region and its hydrological systems. The general trend to aridity since about 4500 cal. years BP (Gasse et al., 1991) can be deduced from several records (e.g. Pachur et al., 1995; Rhodes et al., 1996; Chen et al., 2003) but in fact not from the Bosten Lake record. One reason might be the increasing human impact influencing the water balance of the lake since historical times by improved irrigation techniques and channel constructions. They may have resulted in minor lake level fluctuations, presently not quantified. More important is the change of the water quality towards eutrophication (Zhang et al., 1995) over the past 150 years as also deduced from our short cores probably due to enhanced use of fertilizers. However, periodically repeated seismic events over the past 2500 years (Lin et al., 2002) may have had an important impact on the catchment characteristics, but their influence on the water balance and sedimentation dynamics seems to be minor. The core XBWu 46 shows no variations in sediment composition (e.g. gravel input as an indicator of tectonically induced sudden increase of the river's flow velocity) whose presence would have clearly reflected tectonic pulses.

## 6. Conclusion

Our record from Bosten Lake displays strong fluctuations in water balance without complete desiccation during the past 8500 calendar years. According to geomorphological investigations and to tectonic impacts on the basin structure, the size of Bosten Lake probably did not exceed 1100 km<sup>2</sup> during the last 8500 years. The major factors governing the water budget of the lake since the early Holocene is the interrelation between the dominant west wind system and the changing but much weaker influence of the summer monsoon as the main sources for potential moisture availability, as well as the influence of temperature-driven meltwater supply. Temporal and spatial differences between records from Bosten Lake, western Tibet, northern Tian Shan and the northeastern Tibetan foreland support the arguments of asynchronous responses of lakes and sedimentary basins to climate

shifts along the monsoon and west wind paths (An et al., 2000; He et al., 2004). However, the interrelation between both circulation patterns governing the effective moisture supply over northwestern China is still not fully understood and needs more detailed investigations with respect to high resolution sediment records in this sensitive area.

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