Z. Geomorph. N.F.	52	Suppl. 2	57 – 74	Berlin · Stuttgart	September 2008

Late Pleistocene Lake Level Fluctuations of the Nam Co, Tibetan Plateau, China

Brigitta Schütt, Jonas Berking, Manfred Frechen and Chaolu Yi

with 6 figures and 3 tables

Summary. The endorheic Nam Co Lake, southeastern Tibetan Plateau, was selected to investigate the interrelation between post-glacial glacier decay and lake level fluctuations. During the transition between MIS 2 and MIS1 glacier decay caused regional changes in water balance and a rise in lake level, which is presently shown by a marked cliff line visible all around Nam Co, with its base approx. 29 m above the present lake level. Simultaneously occurring melt water floods caused channel incision into the Pleistocene fan deposits; presently new fans are being deposited where the channels discharge into the wave-cut platform. More Holocene beach ridges on the wave-cut platform downslope of the cliff line are evidence of oscillating Holocene lake levels. LGM ice cap estimates for the tributary Nyainqentanghla Range explain about 50 % of the post-glacial lake volume growth compared to the present lake level. The remaining 50 % of post-glacial lake volume growth originates from increased inflow from the western and northern tributaries. As Nam Co is an endorheic lake, post-glacial water loss is primarily due to evaporation and moisture conditions. To understand late glacial interaction between glacier retreat and lake level fluctuation, a test site in the southeast of the Nam Co area was selected; investigations included geomorphological mapping, survey by DGPS and statistical data analysis.

Keywords. lake history, beach ridges, glacier retreat, water balance, chronology, Holocene

1 *Introduction*

The Tibetan Plateau is considered to be a major driver of the global climate system (Gasse et al. 1991). In this context, the current discussion about the Quaternary cold and warm stages of the Tibetan Plateau is gaining importance. In the past decades numerous studies investigated ice extents during various glaciations and glacial stages, as well as the timing of the ice build-up and decay across the plateau. However, due to orographic effects, monsoonal variability and inaccessibility of vast areas, the Quaternary climate throughout Tibet is poorly understood (Owen et al. 2005, Böse et al. 2003, Mügler et al. 2007).

Generally, glacial ice is a major reservoir in glaciated areas, and its decay strongly influences local and regional water balances (Owen 2006). Nam Co Lake, located on the southeastern Tibetan Plateau, was selected to investigate the interrelation between post-LGM glacier decay and lake level fluctuations. The particular suitability of the Nam Co basin for this purpose is due to its endorheic character, which excludes water loss by runoff, and to its location at the northern foot of the still-glaciated Nyainqentanghla Range. Investigation of Nam Co post-glacial lake level changes will give information on post-LGM water volume changes and hence provide an answer to questions about the lake water supply and the drainage basin's net balance.

DOI: 10.1127/0372-8854/2008/0052S2-0057 0372-8854/08/5202-0057 $ X.XX

Beach remains are used as the most important proxy to reconstruct lake level changes and as the integrative signal for changes in water balance (STREET 1980). The merging of information on lake water volume changes, its chronology, and the respective paleoenvironmental conditions will allow an estimation of the water balance. Water balance estimates are based on lake extents as derived from the beach remains and their surrounding topography. The volume is estimated by applying a semi-quantitative estimation of water balance. Additional analysis of elevation and exposition of the different beach ridges and the cliff lines allows conclusions on synsedimentary major lake currents and, thus, gives a rough idea of major wind fields. Investigation of lake level changes needs to be embedded into overall knowledge on the relief of the study site. As very little information on the relief of the Nam Co area is available, the topography of the site has also been recorded.

2 *State of the Art*

According to the Lake Status Data Base Documentation (YU et al. 2001) the Tibetan Plateau has more than 300 lakes with surface areas greater than 10 km^2. However, paleoclimatic information that covers the last glacial-interglacial cycle is available for only nine sites (YU et al. 2001). Studies of lake sediments published in the international literature mostly focus on lakes on the western, northern and northeastern Tibetan Plateau, and there are only a few well-dated multiproxy studies (e.g. GASSE et al. 1991, 1996, KELTS et al. 1989, LISTER et al. 1991, WEI & GASSE 1999, Yu & KELTS 2002, ZHOU & ZHU 2002, WU 2006a, ZHAI 2006, ZHANDONG 2001). Only sparse information is available from central (GOTO et al. 2003) and southern (ZHU et al. 2003) Tibetan Plateau lake sediments.

Along beach zones of lakes, abandoned shorelines, beach ridges, wave-cut platforms or cliff lines provide important information for the reconstruction of former lake level positions (BRADLEY 1999, LICCARDI 2001). In this way, reconstruction of changes in water balance due to lake level fluctuations promises reliable results especially for closed basins, because here lake water loss is mainly due to evaporation. Thus, periods of positive water balance most likely cause higher lake levels (AVOUAC et al. 1996). On this basis, various attempts have been made to model present and past water balances of lake systems (e.g. CHEN et al. 1999, STREET 1980, CAMPO & GASSE 1993, STREET & GROVE 1979, ZHU 2004).

In general, STREET & GROVE (1979) state that lake level changes are due to changes in climatic patterns while focusing on a global scale. FANG (1991) specifies this statement by applying a regional approach with a focus on East Asia. With reference to a 14C-dated limno-stratigraphic sequence, he emphasizes that especially during the transition from the LGM to the Holocene (MIS2-1) complex regional climatic patterns caused lake level highs on the Tibetan Plateau between 16–10 ka BP after the LGM lake level lows. This observation is confirmed by numerous case studies (e.g. CAMPO & GASSE 1993, AVOUAC et al. 1996, CHEN et al. 1999). Sediments recovered in a core from Siling Co (GU et al. 1994) indicate input of coarser sediments during the LGM when the lake had reached a lowstand level. Dry conditions during the LGM are also reported from other lakes in eastern Tibet (GASSE et al. 1996, HONG et al. 2003). In contrast, in the western Tibetan Plateau the LGM is characterized by higher lake levels (YU et al. 2003).

Parallel to the investigation and interpretation of the Tibetan Plateau lake systems, extensive research on Quaternary glacial extension and decay has been carried out. Early investigations suggest that a complete plateau-covering ice-sheet existed, an assumption still upheld by Kuhle (2001) (see also: Han 1989, Liu et al. 1999). In contrast, other authors argue that there was only a relatively small increase in the number of glaciated areas and that a large part of the Tibetan Plateau remained ice-free during the last glaciation (Burbank & Chen 1991, Derbyshire 1991, Lehmkuhl et al. 2002, Schäfer 2000, Zheng & Rutter 1998). Lehmkuhl et al. (2002) concluded that glaciers in the area of Nam Co, Silling Co, Gyaring Co und Dagze Co were relatively small during the LGM, and they found no evidence for an ice stream network or a large ice cap. Lehmkuhl et al. (2002) dated the two most extensive glacier advances in the Nam Co area and attributed the older and larger advance to the penultimate glacial stage, and the younger and smaller advance to the LGM. Yi (2002) found evidence that five moraine successions in the largest modern ice field of Puruogangri can be correlated to global glacier advances, such as the LGM between 19–23ka (Yi 1998).

3 *Study Site*

Nam Co Lake (30°30'-35' N, 90°16'-91°03' E) is located at 4722 m above sea level (Fig. 1). The lake covers about 1870 km^2 with a corresponding catchment area of approx. 15 000 km^2. Nam Co is the second largest saline lake in China with a salinity of about 2 g l^{-1} (Matthews et al. 2004).

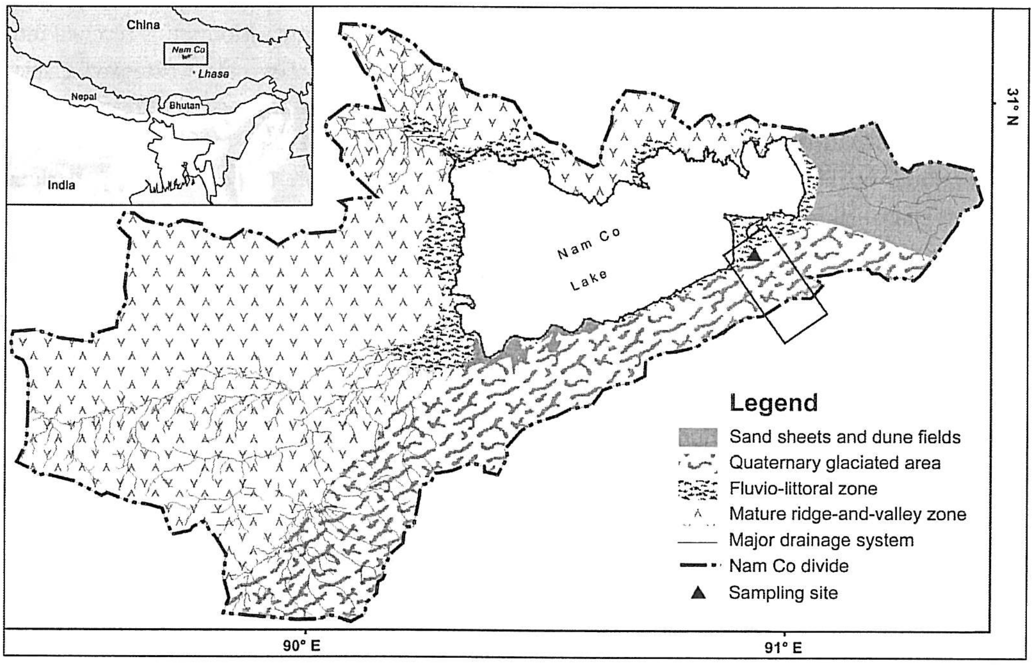

Fig. 1. Map showing Nam Co and its drainage, with the different subordinate geomorphological units of the lake's catchment area.

The tectonic lake basin is located in the central part of the Lhasa Block and is bounded by Paleozoic and Mesozoic rocks deformed by Paleogene and older thrusts in the north and west. In the south the divide of Nam Co runs along the Nyainqentanghla Range. Here, in altitudes above 7000 m asl, Proterozoic to Tertiary granitic rocks, gneisses and schists occur (KIDD et al. 1988). The Nam Co basin is endorheic. Major runoff into the lake is discharged from the W and E; it is generated by monsoonal precipitation and meltwater from the western Nyainqentanghla Range. Eastern Nyainqentanghla Range feeds low order channels directly, discharging into the Nam Co with runoff predominantly originating from meltwater.

The present climate of the Nam Co area is characterized by dry winters and precipitation occurring predominantly during summer (July to September). Precipitation is brought by the Asian monsoons with an average of 400 mm a^{-1} (Lhasa weather station 1961–1990, 30-year period of record defined by WMO 1967), where the present annual evaporation exceeds 400 mm a^{-1} (MÜLLER 1996, CHEN et al. 2006). Furthermore, the climate is characterized by a large diurnal temperature gradient. Recorded temperatures at Nam Co weather station range from +20°C to -41°C; the annual mean is about -1°C, and monthly means vary from 2°C to 5.5°C in July to -10°C to -12°C in January (YAO TAODONG CAS-ITP, pers. comm., 2004).

Present and past land use in the Nam Co area has adapted to the landscape and resulted in the coexistence of nomadic and sedentary populations.

The overall geomorphological character of the Nam Co drainage can be symplified by subdividing the area into four major units denoted by past and present morphodynamics (Fig. 1):

- In the southwest of Nam Co valley glaciers from Nianqingtanggula Mountains reached into the foreland during the LGM. LEHMKUHL et al. (2002) dated the two most extensive glacier advances in the Nam Co area and attributed the older and larger advance to the penultimate glaciation, and the younger and smaller advance to the LGM. The terminal and ground moraines of the maximum glacier advance are inundated by the present Nam Co. Various post-glacial lake level highs are marked by beach ridges accumulated on top of the LGM base moraine. In the southeast of Nam Co, the foreland of Nianqingtanggula Mountains expanded and LGM valley glaciers did not extend into the present lake area. Here, during the Pleistocene and still during the post-LGM, huge fans were deposited downhill of the valley glacier's terminal moraines. A marked cliff line, exposed over tens of kilometers, is cut into these poorly compacted fluvial deposits and marks the post-glacial lake level high (Fig. 2). LEHMKUHL et al. (2002) dated this shoreline cliff to the transition between late Pleistocene and early Holocene, using the age of overlying dune deposits.

Apart from the foreland of Nianqingtanggula Mountains glacial morphodynamics are lacking in the Nam Co drainage basin and therefore Quaternary glaciation of the lake basin can be excluded (SHI et al. 2002, LEHMKUHL 2000).

- The relief in the north and west of Nam Co can be characterized as a hilly landscape highly influenced by tectonics and covered by extensive fluvial deposits. The landscape has been strongly modified by fluvial and periglacial processes. Relief in this area can be described as a mature ridge-and-valley landscape.

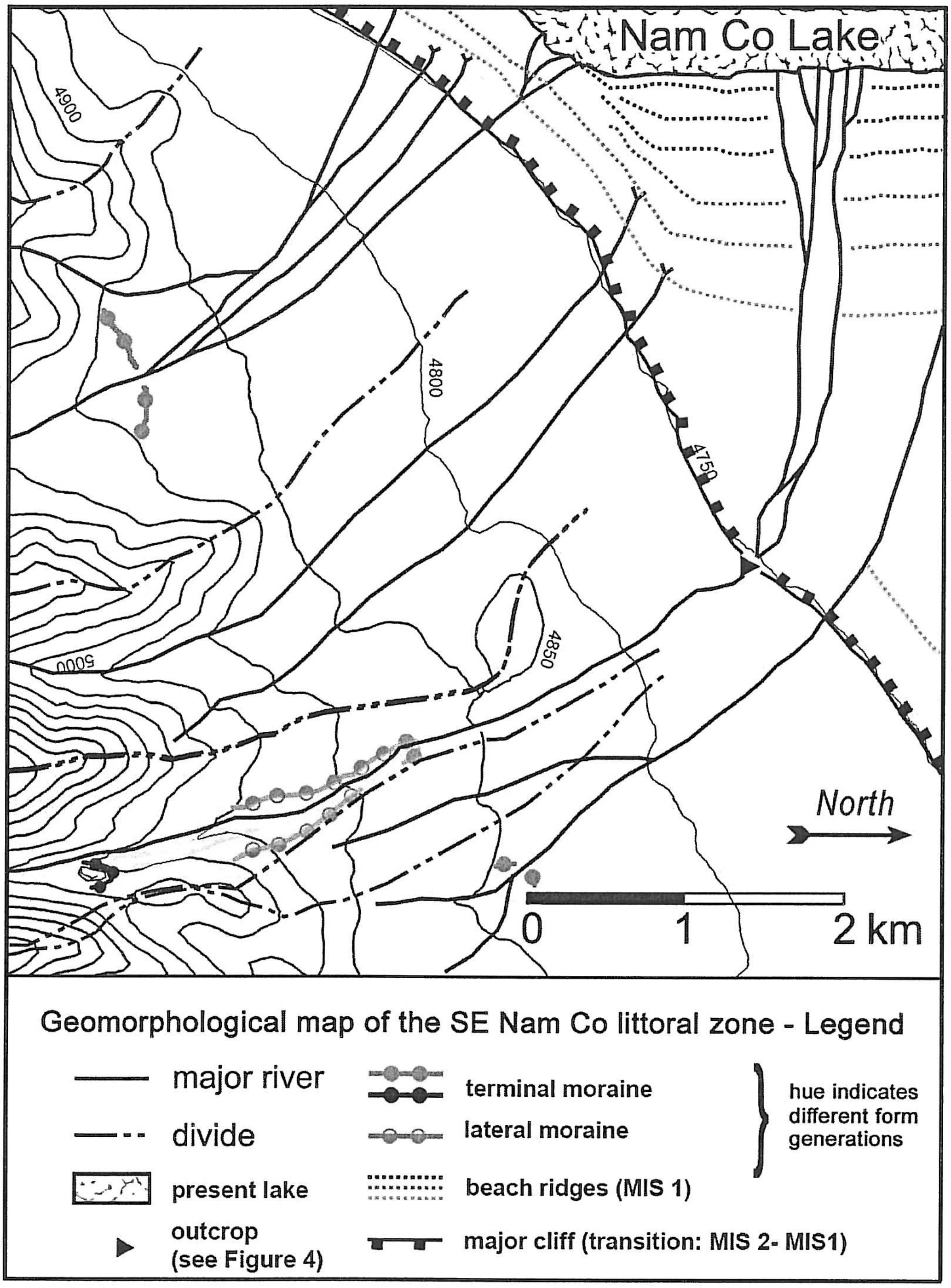

Fig. 2. Geomorphological map of the southeastern Nam Co Area (location see Fig. 1).

- In the east of Nam Co eolian deposits cover wide areas. They form extended primary dune fields and sand sheets and cover most of the fluvial, littoral and periglacial landforms. At present they are dissected by fluvial erosion.
- Along the littoral zone, especially in the slightly undulating west and northwest of the lake, delta-like fluvial deposits interfinger with lacustrine deposits and form extended wetland areas.

4 *Material and Methods*

4.1 *Field work*

Geomorphological features were mapped all around the lake in summer 2005 and 2006. Topographical maps composed of contour lines derived from processing DEM (here: SRTM3 data) overlying panchromatic data of ETM^+ images (see paragraph below) are the map base. Additionally, beach remains such as beach ridges, cliff lines and wave-cut platforms were mapped by differential GPS (DGPS : Ashtech ProMark 2) mainly along cross profiles running upslope from the present lake level. DGPS measurements provided data with horizontal and vertical submeter accuracy. All DGPS data were corrected (postprocessed) by a portable base station, which was located within a range of 15 km.

4.2 *Data Analysis*

Differentiating landform units and mapping of landforms are based on ETM^+ images (Landsat 7, 2001). The digital elevation model (DEM) is generated from the data provided by the Shuttle Radar Topography Mission (SRTM3) of the NASA. The quality of the DEM is measured by the standard deviation of relative height, which totals ±3.7 m for areas recorded in Asia for 90% of the data points recorded (RODRIGUEZ et al. 2005, 25). Continuous data analysis included water balance estimation applying a semi-quantitative approach and water volume calculations with data processing using ARC GIS (ESRI). For statistical analysis the software package SPSS (v.14) was used.

4.3 *Lake Water Balance*

Estimates of water balances for catchments including a closed lake over time were carried out frequently (e.g. MASON et al. 1994, HOSTETLER 1991, MORILL 2004). For the general water balance model evaporation is the most challenging parameter.

Here we present a simple diachronological approach, including post-glacial lake level highs and present-day lake levels. This approach is semi-quantitative, referring to modern data of precipitation and evaporation of various neighboring sites (MORILL 2004, MÜLLER 1996, THOMAS & CHEN 2002, ZHANG et al. 2003). It takes into account that especially evaporation data vary greatly on a small scale, depending on the lake surface, lake salinity, land surface, land cover including ice cover, type and density of vegetation cover, and the distribution of wetlands. Evaporation data available from literature (eg. MÜLLER 1996) are Thornthwaite temperature-based estimates, rather than measured values. THOMAS & CHEN (2002) show that such temperature-based estimates are unsuitable for the specific insolation and radiation conditions on the Tibetan Plateau and will cause underestimations of 100% and more. To avoid uncertainties due to evaporation models unadjusted to the specific environmental conditions of the Tibetan Plateau, empirical data from neighboring Ahung Co (31.37°N, 92.04°E, 4600m asl, 150 km NE of Nam Co), determined by MORILL (2004) based on 12-year measurements were applied. MORILL (2004) states an annual lake evaporation of 760 mm a^{-1}; this value is transferred to Nam Co. For land surfaces, we differentiate between sublimation from ice surfaces and evapotranspiration from soil surfaces. Data for current ground evaporation are taken from ZHANG et al. (2003) and are based on lysimeter measurements made at the foot of Nyainqentanghla Mts; the value given totals 1.72 mm d^{-1}. Annual evapotranspiration is estimated according to MORILL (2004) for April to October as the growing season, whereas for November to March evapotranspiration is assumed to be near zero due to frozen ground. Resulting estimated annual evapotranspiration totals

$$(214\ \text{days} * 1.72\ \text{mm d}^{-1}) + (151\ \text{days} * \sim 0\ \text{mm d}^{-1}) = 368\ \text{mm a}^{-1}$$

Seepage from the lake might occur but is not considered in the calculations, as data are not available.

4.4 *Chronology*

For age determination of the lake level high causing the marked cliff line and the tributary channels, we have taken the most recent layer deposited before cliff undercut and channel incision started. OSL dating techniques were applied on eolian deposits.

Mineral luminescence is the light emitted from mineral particles when they are stimulated with heat (thermoluminescence = TL) or light (optically stimulated luminescence = OSL) after receiving a dose of natural or artificial radiation. A recent comprehensive review of OSL dating is given in LIAN & ROBERTS (2006). The present study establishes a preliminary chronological frame for the different levels of the marked cliff line at Nam Co lake. Luminescence dating including (1) the multiple aliquot additive dose (MAAD) protocol on sand-sized potassium-rich feldspar, and (2) the single aliquot regenerative (SAR) protocol on potassium-rich feldspars for infrared optically stimulated luminescence (IRSL) dating, following the methodological procedure as described in MURTON et al. (2007). The equivalent dose (De value) is given in Gray (Gy) (Table 1). Dose rates for all samples were calculated from potassium, uranium and thorium contents, as measured by gamma spectrometry in the laboratory, assuming radioactive equilibrium for the decay chains and an internal potassium content of 12.5±1% for the potassium-rich feldspars (HUNTLEY & BARIL 1997). The natural water content of the sediment is estimated to be 15±5% in relation to the porosity of the sediment and the variation of lake level during the geological past. The present moisture of the sediments does not match the true moisture of the past owing to lake level variations. IRSL age estimates are given in 1000 years (ka) and a 1-sigma standard deviation.

Table 1. Dosimetric results of OSL dating of samples from layers 2 and 4 (Fig. 3).

Layer Figure 3	FSP-MAA AD [Gy]	1 Sig [Gy]	FSP-SAR AD [Gy]	1 Sig [Gy]	Dose Rate [Gy/ka]	1 Sig [Gy/ka]	IRSL-Age FSP-MAA [ka]	1 Sig [ka]	IRSL-Age FSP-SAR [ka]	1 Sig [ka]	Grain size [µm]
2	132.1	1.9	92.3	1.5	5.70	0.37	23.2	1.5	16.2	1.1	100-150
4	88.6	1.1	85.9	1.2	5.01	0.33	17.1	1.2	17.2	1.2	106-212

5 *Results and Discussion*

5.1 *Geomorphology*

To understand late glacial interaction between glacier retreat and lake level fluctuation, a test site in the southeast of the Nam Co area was selected (Fig. 1). Geomorphological mapping of this test site shows that a valley glacier extended from the Nyainqentanghla Range into the mountain foreland, where it deposited a terminal moraine and several distinct lateral moraines (Fig. 2). Owing to the absolute height and pronounced shape of the terminal and lateral moraines a linkage to the Last Glacial Maximum with an age estimation of 18–32 ka BP (MIS 2) is likely (LEHMKUHL et al. 2002).

The foreland of the terminal moraine displays no evidence of older glacial deposits. In fact, the terminal moraine is dissected by the valley's river, and extensive fluvial deposits are found in its foreland. The slightly rolling relief of the area and the slightly elongated convex shape of the surface are typical for fan deposits (see also Fig. 3). In these fan deposits, more or less parallel to the present shoreline of Nam Co, a distinct cliff line is formed with a wave-cut platform at its foot. The base of the cliff line is located approx. 29 m above the present lake level (4722 m asl). At the test site, the cliff is 8–10 m high, with a slope of 40–50°. Seawards the wave-cut platform is covered by beach ridges, which locally impound small areas with beach lakes (see following paragraph). Presently, fan deposits uphill of the cliff line are dissected by wide channels, in the case of the test site showing an average inclination of the channel bed of 2.7°. The incised valley is box-shaped with a valley floor about 10–12 m wide and 4–6 m deep, whereas the present channel does not exceed 1–2 m in width and is only a few decimeters deep. The floor of the box-shaped valley is aligned to the wave-cut platform, showing deposition of an alluvial fan complex with most recent deposits of the present channel on top, where the valley debouches to the wave-cut platform. Downhill from the cliff line, the channel network changes from straight to braided (Fig. 2).

In the box-shaped valley, where it intersects the cliff line, ideal exposure conditions prevail, allowing an insight into the sedimentary architecture (Fig. 3). Basal sediments are most likely linked to a mass movement with debris embedded in soil sediments due to the red color of the matrix (layer 16). A channel cut into these sediments was later filled with relocated, washed out sands with a grain size of ∅ 0.1–0.5 mm and well-sorted character suggest an eolian origin (layer 15). At a later stage fluvial dynamics intensified, and channels incised and were filled with fine- to coarse-grained pebbles, giving evidence for stronger fluvial dynamics (layer 14) (KNIGHTON 1988). These pebbles are discordantly overlain by a layer of rounded pebbles deposited in graded beds, each about 10 cm thick, pointing to deposition during flood events (glacial outbursts) (layer 13)

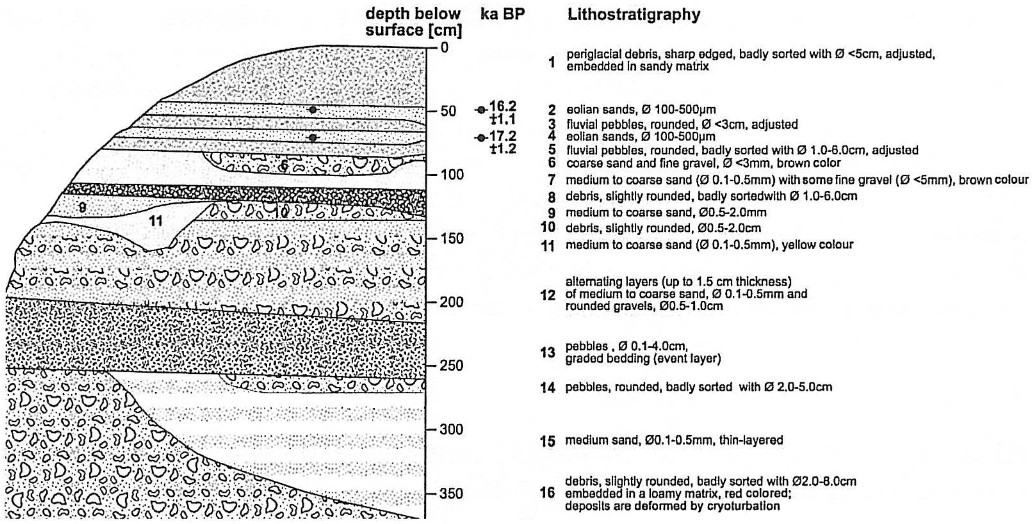

Fig. 3. Lithostratigraphy of fan deposits outcropping along the major cliff line (30.91° E, 30.71° N; location see Fig. 2).

(Rice and Church 1998). These depositional conditions continue to the top (layer 12, 10), but the decreasing diameter of deposits indicates reduced flow velocity, corresponding to an over-bank facies (Straffin et al. 2000). Overlying layers (11, 9–6) point to fluvial facies with repeated discordances, pointing to channel relocation in a braided system (Knighton 1984). The layers deposited above (5–2) correspond to a runoff system with relatively low flow dynamics (layers 5, 3) and distinct eolian dynamics, while channels were periodically running dry (layers 4, 2). The top exposed layer (layer 1) corresponds to periglacial debris, transported by slow mass movements on top of the fan surface and disrupted by cryoturbation processes.

Eolian deposits of layers 2 and 4 were sampled for OSL dating. The dosimetric results of the two samples are compiled in Table 1. Gammaspectrometry gave dose rates of 5.01±0.33 and 5.70±0.37 Gy ka^{-1}. The De values of the upper sample are between 132.1±1.9 Gy and 92.3±1.5 Gy, as determined by the MAAD protocol and SAR protocol, respectively. IRSL age estimates of 23.2±1.5 ka and 16.2±1.1 ka were determined. The lower sample gave De values of 88.6±1.1 Gy and 85.9±1.2 Gy, which are in agreement within the 1-sigma standard deviation for the two applied protocols. The IRSL age estimates range from 17.7±1.2 ka to 17.2±1.2 ka and make a correlation of these sediments with the transition from MIS 2-1 very likely. The interpretation of the present chronological data set has to be regarded with caution owing to methodological problems. First, there is no evidence that the sampled sediments were sufficiently bleached prior to deposition – a problem which could cause significant age overestimation. Second, potassium-rich feldspar can be affected by anomalous fading, resulting in age underestimation. More investigations are required, including independent age control to set up a more robust chronological frame for these deposits.

In summary, the outcrop along the cliff line distinctly shows fluvial deposits, corresponding to an alluvial fan, with frequently embedded eolian deposits and overlain by slope debris. The cliff line corresponding to the post-LGM lake level high is shaped in these unconsolidated fan deposits. Relief analysis shows that box-shaped valleys tributary to the post-LGM lake level high were incised into the fan deposits (Fig. 3). These results for the maximum post-LGM lake level high (29 m above present lake level) correspond to data given by LEHMKUHL et al. (2002), who postulate a post-LGM or early Holocene (10.4±1.5 ka BP) lake level high of Nam Co of approx. 20 m above the modern lake level. Age determination corresponds to a minimum age based on OSL analysis of eolian layers deposited on top of the cliff line (LEHMKUHL et al. 2002).

5.2 *Post-Glacial Lake Level Fluctuations*

All around Nam Co the major cliff line with its base 29 m above the present lake level (4751 m asl) can be recorded, showing a cliff height of 5–15 m. In the southeast of Nam Co the cliff line and its corresponding wave-cut platform are incised and superimposed by fluvial deposits. In contrast, in the southwest of the Nam Co cliff line and wave-cut platform occur in glacial deposits. On the wave-cut platform downslope from the marked cliff line and above the present lake level, up to 13 beach ridges and minor cliffs are recorded (shown with major generalization in Fig. 2). They indicate additional lake levels. Due to the location of the beach remains on the wave-cut platform of the post-LGM marked cliff line and their parallel run to the present shoreline, they are assigned a Holocene age.

Complementary to the field mapping of beach remains, their location (easting, northing) and altitude (m asl) were surveyed by DGPS. The beach remains were surveyed mainly along cross profiles all around the lake, reaching from the base of the marked cliff to the present lake level. The number of recorded beach remains totals 531. The elevation data of the beach ridges and the bases of the different cliff lines were taken as lake level indicators. They were classified in order to obtain discrete stable lake level positions by k-means cluster analysis (centroid analysis) (MACQUEEN 1967). Ten cluster centroids are defined and assumed to correspond to post-glacial stages owing to their topographical location downslope of the marked cliff line. The average standard deviation within classes 1–10 totals ±51 cm (Fig. 4). Additional beach remains were recorded uphill from the marked cliff. However, due to their insignificant, low-frequency occurrence and their age, which most likely correlates with stages older than LGM, they are not considered in the ongoing analysis focusing on post-LGM lake history (ZHU et al. 2004).

To diminish the influence of neotectonic subsidence or recent uplift, the distribution of paleo-shorelines was spatially analysed. For this purpose, the regional distribution of the paleo-shoreline measurements was tested by a sectoral analysis according to the northern, western, southern and eastern margins of Nam Co. Spatial analysis shows that lake level clusters (LLC) 3–10 are more or less even distributed around the lake, except the two lowest lake level clusters, which are concentrated along the northern shoreline (Table 2). Furthermore, lake level clusters all around Nam Co occur at the same elevation above present lake level. However, the cumulative frequency of LLC 01 and LLC 02 totals 1.0 % and is therefore not significant.

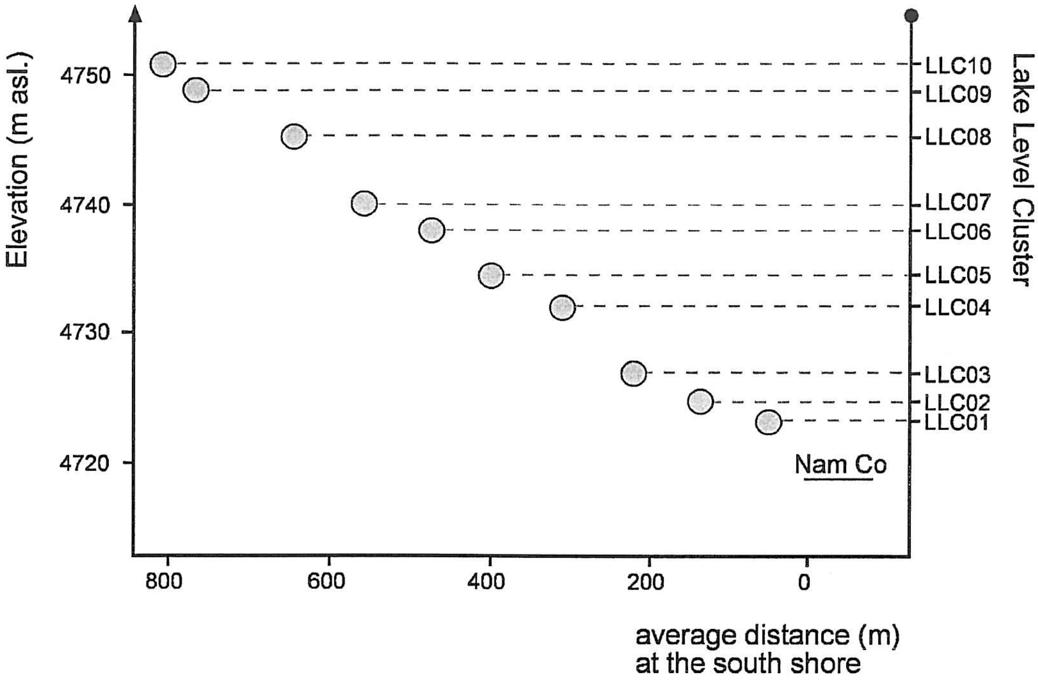

Fig. 4. Altitudinal location of lake level clusters in the Nam Co area and their average distance to the present shore line. For frequency and spatial distribution see Table 2.

Table 2. Spatial output of cluster analysis (n=531; ✓ – cluster persistent; np – cluster not persistent).

Lake Level Cluster	Altitude m asl	North shore	East shore	South shore	West shore	Frequency (%)
1	4723	✓	np	np	np	0.2
2	4725	✓	np	np	np	0.8
3	4727	✓	✓	✓	✓	2.6
4	4730	✓	np	✓	✓	7.0
5	4734	✓	✓	✓	✓	19.8
6	4737	np	✓	✓	✓	22.8
7	4740	✓	✓	✓	✓	23.9
8	4743	✓	✓	✓	✓	13.0
9	4747	✓	✓	✓	✓	6.2
10	4751	✓	np	✓	✓	3.8

Holocene age is assumed because the beach remains outlined in LLC 1–10 are located downslope from the post-LGM marked cliff line, deposited on top of the corresponding wave-cut platform. Relative frequency of the LLCs allows conclusions on the length of time or intensity of littoral processes (cf. OTOVOS 2000). The high frequency of beach remains of LLC 5–7 points to their development during a probably longer period of stable lake level or to short-term intensified wave dynamics. Altogether, even altitudinal distribution of LLC 3–10 points to stable tectonic conditions (BAO & FAN 1987). Accordingly, the distribution of the lake level clusters all around the lake does not allow conclusions to be drawn about predominant wind directions affecting wave motions and, thus, depositing beach ridges. However, it has to be considered that the sites included in the cluster analysis were recorded, but not differentiated into beach ridges and other kinds of beach remains, such as cliff lines (base) or lacustrine deposits.

5.3 *Post-Glacial Water Balance*

Post-glacial lake Nam Co covered an area of 2462 km^2 (Fig. 5a), i.e. it was about 30 % larger than it is today. Coinciding with the Holocene lake level decrease, a lake volume loss of 59.7 km^3 took place (data are calculated based on the Digital Elevation Model as given by SRTM3).

An exact dating of the post-LGM lake level high is subject to uncertainties as it is only possible to determine a maximum age of an erosion form (Table 1). The OSL data still lack the results of OSL dating of quartz grains and might, but not necessarily do, include an age underestimation. Literature review shows that many lake level investigations in Central Asia and on the Tibetan Plateau point to a Late Glacial lake level high around 12 ka BP and thus confirm OSL dating as presented above (Table 3, scenario 2; cf. CHEN et al. 1999, WÜNNEMANN et al. 1998, FANG 1991). Furthermore, global investigations also show evidence for Early Holocene lake level high stands (cf. STREET & GROVE 1979, GASSE et al. 1991) (Table 3, scenario 1).

It is assumed that the post-LGM lake level high was caused by glacier meltwater inflow from the Nyainqentanghla Range. The area of the Nyainqentanghla Range LGM ice cap is estimated to be approx. 1220 km^2 (see also DONG 2004). Aligned to the present-day extent of the ice cover (approx. 93 km^2) and assuming that the present-day average ice thickness of 80 m also accounts for the LGM ice cap (pers. comm. B. XU, CAS-ITP, 2006), a difference in ice volume of 35 km^3 is assumed (ρ_{ice}=0.9 g cm^{-3}). The resulting meltwater amount provided by the LGM glaciers in the Nam Co drainage totals approx. 30 km^3. This amount explains about 50 % of the post-LGM lake volume high compared to the present-day lake level, not including a possible lower lake level during the LGM. In consequence, the remaining 50 % of post-LGM lake volume increase corresponds to heightened inflow from the western and northern tributaries due to a temporary rise in precipitation (cf., KELTS et al. 1989, VAN CAMPO et al. 1993, FONTES et al. 1996). However, Nam Co is an endorheic lake and consequently post-LGM water loss is primarily explained by evaporation (cf., HÖVERMANN 1998, KELTS et al. 1989, VAN CAMPO et al. 1993, FONTES et al. 1996) and might be corrected by input and by discharge. More recent studies focus on regional moisture conditions as drivers for lake level changes. For the Ahung Co (150 km NE of Nam Co) MORRILL (2004) defines effective moisture as the difference between precipitation and evaporation and correlates changes in effective moisture with varying intensity of the Southeast Asian monsoon. An intensified monsoon brings both higher precipitation and higher humidity, owing

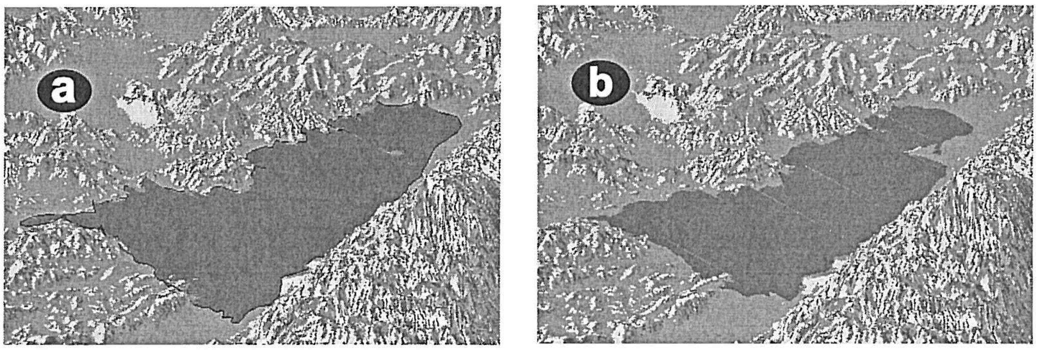

Fig. 5. 3D-sketch of Nam Co drainage basin showing (a) lake extent during post-glacial high stand and (b) present lake extent.

Table 3. Age models and dependent volume change of Nam Co (m^3 ka^{-1}) referring to present lake level.

Model	Time (ka BP)	Comment	Volume change scenarios (m^3 / ka)
1	10	based on results of Street, Grove (1979) Gasse et al. (1991)	$5.97 * 10^9$
2	12	based on OSL dating and results of Chen et al. (1999), Wünnemann et al. (1998), Fang (1991)	$4.97 * 10^9$
3	16	due to uncertainties with OSL dating without quartz protocol and FSP-MAA	$3.73 * 10^9$

to increased cloud cover and reduced evaporation. Furthermore, Morrill (2004) notices a strong correlation between lake level changes and winter length because evaporation is reduced as long as ice covers the lake. Above all, Xue (2000) asserts – on the basis of the lake status database of China – that during the LGM a southward shift of the Westerlies caused locally increased precipitation on the Tibetan Plateau, and he assumes that until today temporarily increased precipitation might be due to a short-term southward deflection of Westerly waves.

Based on the results presented, a maximum age of the post-LGM lake level high of 16.2±1.1 ka BP is assumed. For this scenario and respective scenarios of comparable paleoenvironmental investigations, the plausibility of a decline from the post-LGM lake level high to the present lake level controlled only by evaporation (output) and precipitation (input) is proven. Assuming a Nam Co lake level high around 16 ka BP (Table 3, scenario 3), the decrease in volume totals approx. 3 km^3 per 1000 years. Assuming a post-LGM lake level high around 12 ka BP (Table 3, scenario 2; CHEN et al. 1999, WÜNNEMANN et al. 1998, FANG 1991), the corresponding calculation yields a lake volume decrease of 5 km^3 in 1000 years. Reckoning 10 ka BP as the maximum age of the lake level high (Table 3, scenario 1; STREET and GROVE 1979, GASSE et al. 1991), the rate of lake volume decrease totals approx. 6 km^3 per 1000 years. The extrapolation of the present-day evaporation-precipitation ratio given by MORILL (2004) for the Ahung Co lake – transferred to the drainage basin of Nam Co and assuming constant climatic conditions – totals approx. 4 km^3 in 1000 years. Even though these calculations are very rough and include assumptions still under discussion data show that the observed imposed Holocene lake level decline can be mainly explained by changes in precipitation and evaporation rates.

6 *Landscape Development*

Late Glacial landscape development of the southern Nam Co littoral zone is depicted in Fig. 6: huge fans were deposited in the foreland of the Nyainqentanghla Range. During the Last Glacial Maximum fluvial deposits were transported from the mountains and accumulated in the foreland, most likely fed by meltwater of the Nyainqentanghla Range's valley glaciers (Fig. 6). During the post-LGM (transition between MIS2 and MIS1; e.g. RUDDIMAN 1977) changes in water balance caused changes in relief forming processes (Fig. 6, post-glacial): The lake level of Nam Co increased and reached its high at approx. 29 m above the present lake level. Strong local winds, land-sea breezes and mountain winds presumably caused intense surging. Wave attacks caused erosion and the retreat of the cliff foot. Finally, the major cliff line and its offshore wave-cut platform were formed. At the same time, changing relief due to channel shortening and a lowering of

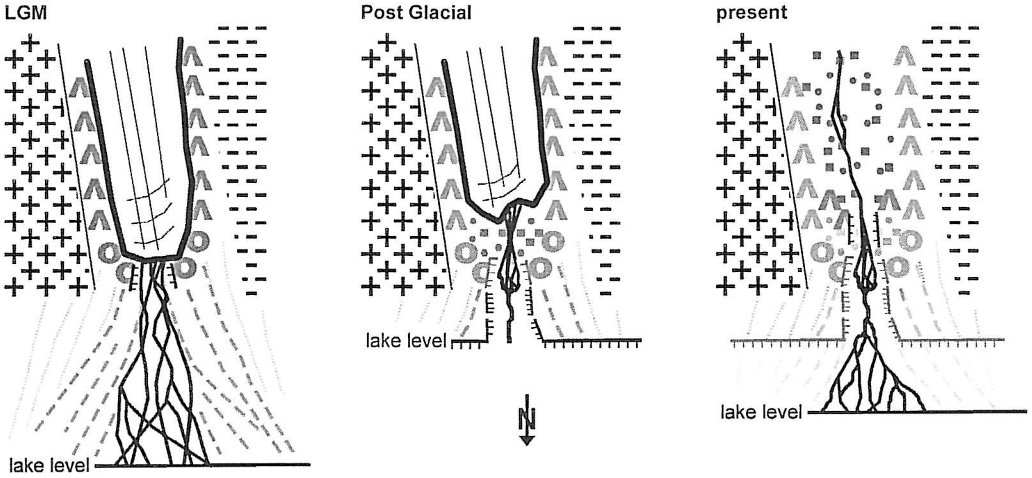

Fig. 6. Sketch of Late Glacial relief development in the southern margin of Nam Co (ΛO – lateral and terminal moraine, ●■ – base moraine; ------ – fan deposits; π – major cliff line; +++ ---- – bedrock).

the local base-level caused stronger inclination of the channel and affected runoff dynamics. As a result, flow velocity increased and caused incision of the channels into the basal fan deposits. With declining lake level (Fig. 6, present), a new fan is deposited where the channel meets the wave-cut platform, whereas beach ridges mark Holocene lake level decline.

Comparison with studies on young Quaternary landscape development of other Tibetan lake systems confirms this hypothesis. Furthermore, ages of lake terraces at Nam Co confirm a general decrease in lake level during the Holocene stages mentioned in LEHMKUHL et al. (2002). For the Holocene, sediments from neighboring Siling Co indicate three phases with humidity conditions similar to or even more humid than today's levels (8.4–5.5 ka BP, 3.3–2.4 ka BP, 1.4 ka BP – present) and arid conditions between 5.5 and 4.2 ka BP (data area based on 14C and OSL datings; LEHMKUHL et al. 2002, GU et al. 1993). Differentiation of oscillating Holocene moisture conditions, as shown for Siling Co, suggests that paleoenvironmental information derived from lake sediments might draw a more detailed picture than the "snapshots" provided by lake terraces. In addition, it is not clear whether rising post-LGM lake levels were the result of enhanced meltwater input as a consequence of increased temperatures or already the result of the strengthening of the summer monsoon during the Early Holocene.

Lake sediments are the last member in the sequence of the sediment cascade of a catchment (alluvial deposits, colluvial deposits, littoral sediments). The advantage of lake sediments is their more or less undisturbed and continuous deposition, whereas fluvial and colluvial deposits allow more detailed conclusions on process dynamics in the catchment area and are spatially more discrete. A realistic approximation of changes in a lake's water balance and corresponding lake level fluctuations can only be achieved by an integrated analysis of lacustrine and littoral deposits. To achieve this goal for the Nam Co basin, additional sediments of beach remains located downhill from the major cliff line were sampled for dating during field work in August 2006. OSL and ^{14}C analyses for age determination are in progress at the Leibniz Institute for Applied Geosciences, Hanover, Germany.

Acknowledgements

The project has been supported since July 2005 by the Deutsche Forschungsgemeinschaft (DFG) and is part of the DFG bundle project: "The Tibetan Plateau: Geodynamics and Evolution – Lake System Response of Nam Co Area, Central Tibet, to Late Quaternary Monsoon Dynamics" – in joint cooperation with CAS / ITP.

References

AVOUAC, J.-P., DOBREMEZ, J.-F. & BOURJOT, L. (1996): Palaeoclimatic interpretation of a topographic profile across middle Holocene regressive shorelines of Longmu Co (Western Tibet). – Palaeogeogr. Palaeoclimat. Palaeoecol. **120**: 93–104.

BAO, W.-F. & FAN, C.Y. (1987): Climatic Changes in the Qinghai-Xinzang (Tibetan) Region of China during the Holocene. – Quartern. Res. **28**: 50–60.

BÖSE, M., HIRAKAWA, K., MATSUOKA, N. & SAWAGAKI, T. (2003) (eds.): Glaciation and periglaciation in Asian high Mountains. – Z. Geomorph. N.F. **130**: 1–276.

BRADLEY, R.S. (1999): Palaeoclimatology: reconstructing climates of the Quaternary. – Harcourt Academic, London.

BURBANK, D.W. & CHENG, K. (1991): Relative dating of Quaternary moraines, Rongbuk valley, Mount Everest, Tibet: implication for an ice sheet on the Tibetan Plateau. – Quatern. Res. **36:** 1–18.

CAMPO, E.V. & GASSE, F. (1993): Pollen and diatom inferred climatic and hydrological changes in Sumix Co basin (west Tibet) since 13000yr BP. – Quatern. Res. **39:** 300–313.

CHEN, S., LIU, Y. & THOMAS, A. (2006): Climatic change on the Tibetan Plateau: Potential Evapotranspiration trends from 1961–2001. – Climatic Change **76:** 291–319.

CHEN, F.-H., SHI, Q. & WANG, J.-M. (1999): Environmental changes documented by sedimentation of Lake Yiema in arid China since the Late Glaciation. – J. Paleolim. **22:** 159–169.

DERBYSHIRE, E., SHI, Y., LI, J., ZHENG, B., LI, S. & WANG, J. (1991): Quaternary glaciation of Tibet: the geological evidence. – Quatern. Sci. Rev. **10:** 485–510.

DONG, C. (2004): Mass Balance of Nyainqen Tanglha Glacier, Tibet, 1977 to 2001. – Derived by topographical maps and Satellite Images. – Master Thesis. University of Bergen, unpublished.

FANG, J.-Q. (1991): Lake Evolution during the past 30,000 years in China, and its Implications for Environmental Change. – Quatern. Res. **36:** 37–60.

FONTES, J.-C., GASSE, F. & GIBERT, E. (1996): Holocene environmental changes in Lake Bangong basin (Western Tibet). Part 1: Chronology and stable isotopes of carbonates of a Holocene lacustrine core. – Palaeogeogr. Palaeoclimat. Palaeoecol. **120:** 25–47.

GASSE, F., ARNOLD, M., FONTES, J.CH., FORT, M., GIBERT, E., HUC, A., LI, B., LI, Y., LIU, Q., MELIERES, F., VAN CAMPO, E., WANG, F. & ZHANG, Q. (1991): A 13,000-year record from western Tibet. – Nature **353:** 742–745.

GASSE, F., FONTES, J.CH., VAN CAMPO, E. & WEI, K. (1996): Holocene environmental changes in Bangong Co Basin (Western Tibet). Part 4: Discussion and conclusions. – Palaeogeogr. Palaeoclimat. Palaeoecol. **120:** 79–92.

GU, Z.Y., LIU, J.Q., YUAN, B.Y. (1994): Lacustrine authigenic deposition expressive of environment and the sediment record from Siling Co, Xizang (Tibet), China, – Quatern. Res. (in Chinese), 1994, **2:** 162–174.

HONG, Y., HONG, B., LIN, Q., ZHU, Y., SHIBATA, Y., HIROTA, M., UCHIDA, M., LENG, X., JIANG, H., XU, H., WANG, H. & YI, L. (2003): Correlation between Indian Ocean summer monsoon and North Atlantic climate during the Holocene. – Earth and Planetary Sci. Lett. **211:** 371–380.

HOSTETLER, S.W. (1991): Simulation of lake ice and its effect on the late-Pleistocene evaporation rate of Lake Lahontan. – Climate Dynamics **6** (1): 43–48.

HÖVERMANN, J. (1998): Zur Paläoklimatologie Zentralasiens – quantitative Bestimmungen von Paläoniederschlag und -temperatur. – PGM, **142** (3+4): 251–257.

HUNTLEY, D.J. & BARRIL, M.R. (1997): The K content of the K-feldspars being measured in optical dating or in thermoluminescence dating. – Ancient TL **15:** 11–13.

KELTS, K., CHEN, K.Z., LISTER, G., YU, J.Q., GAO, Z.H., NIESSEN, F. & BONANI, G. (1989): Geological fingerprints of climate history: a cooperative study of Qinghai Lake, China. – Eclogae geol. Helv. **82/1:** 167–182.

KIDD, W.S.F., PAN, Y., CHANG, C., COWARD, M.P., DEWEY, J.F., GANSSER, A., MOLNAR, P., SHACKLETON, R.M. & SUN, Y. (1998): Geological Mapping of the 1985 Chinese-British Tibetan (Xizang-Qinghai) Plateau Geotraverse Route. – Philosophical Trans. Royal Soc. London. Series A, Math. and Phys. Sci. **327** (1594): 287–305.

KNIGHTON, D. (1998): Fluvial forms and processes. – Oxford, 383 pp.

KUHLE, M. (2001): The Tibetan Ice Sheet, its Impact on the Palaeomonsoon and Relation to the Earth's Orbital Variations. – Polarforschung **71** (1/2): 1–13.

LEHMKUHL, F., KLINGE, M. & LANG, A. (2002): Late Quaternary glacier advances. Lake level fluctuations and aeolian sedimentation in Southern Tibet. – Z. Geomorph. N.F., Suppl. **126:** 183–218.

LIAN, O.B. & ROBERTS, R.G. (2006): Dating the Quaternary: progress in luminescence dating of sediments. – Quatern. Sci. Rev. **25:** 2449–2468.

LICCIARDI, J.M. (2001): Chronology of latest Pleistocene lake-level fluctuations in the pluvial Lake Chewaucan basin, Oregon, USA. – J. Quatern. Sci. **16** (6): 545–553.

LISTER, G.S., KELTS, K., ZAO, C., YU, J.Q. & NIESSEN, F. (1991): Lake Qinghai China: closed-basin lake levels and the oxygen isotope record for ostracoda since the latest Pleistocene. – Palaeogeogr. Palaeoclim. Palaeoecol. **84:** 141–162.

MACQUEEN, J. (1967): Some methods for classification and analysis of multivariate observations. – In LECA, L.M. & NEYMAN, J. (eds.): Fifth Berkeley Symposium on Math. Stat. and Prob. Proceedings: 281–297. Univ. California Press.

MASON, I.M., GUZKOWSKA, M.A.J., RAPLEY, C.G. & STREET-PERROTT, F.A. (1994): The response of lake levels and areas to climatic change. – Climatic Change **27** (2): 161–197.

MATTHEWS, J.P., WALLIS, S.R. & YAMAGUCHI, Y. (2004): ASTER Views A High Altitude Tibetan Lake in Stereo. – EOS Trans. **85** (43): 439.

MORRILL, C. (2004): The influence of Asian summer monsoon variability on the water balance of a Tibetan lake. J. Paleolim. **32:** 273–286.

MÜGLER, I., GLEIXNER, G., SCHWALB, A., SCHÜTT, B., MÄUSBACHER, R., DAUT, G., XU, B., YAO, T., ZHU, L. & YI, C. (submitted): A multi-proxy approach to reconstruct the hydrological changes and Holocene climate development of Nam Co, Central Tibet. – J. Paleolim.

MÜLLER, M.-J. (1996): Handbuch ausgewählter Klimastationen der Erde. –Forschungsstelle Bodenerosion 5. Trier.

MURTON, J.B., FRECHEN, M. & MADDY, D. (2007): Luminescence dating of the last advance of the Laurentide Ice Sheet into the Beaufort Sea, NW Canada, during Marine Isotope Stage 2. – Canad. J. Earth Sci. **44:** 857–869.

OTOVOS, E.G. (2000): Beach ridges – definitions and significance. – Geomorphology **32** (1): 83–108 (26).

OWEN, L.A., FINKEL, R.C., BARNARD, P.L., HAIZHOU, M., ASAHI, K., CAFFEE, M.W. & DERBYSHIRE, E. (2005): Climatic and topographic controls on the style and timing of Late Quaternary glaciation throughout Tibet and the Himalaya defined by 10Be cosmogenic radionuclide surface exposure dating. – Quatern. Sci. Rev. **24** (12-13): 1391–1411, July 2005.

OWEN, L.A., FINKEL, R.C., HAIZHOU, M. & Barnard, P.L. (2006): Late Quaternary landscape evolution in the Kunlun Mountains and Qaidam Basin, Northern Tibet: A framework for examining the links between glaciation, lake level changes and alluvial fan formation. – Quatern. Int. **154—155:** 73–86, October 2006.

RICE, S. & CHURCH, M. (1998): Grain size along two gravel-bed rivers: statistical variation, spatial pattern and sedimentary links. – Earth Surf. Proc. and Landforms **23** (4): 345–363.

RODRIGUEZ, E., MORRIS, C.S., BELZ, J.E., CHAPIN, E.C., MARTIN, J.M., DAFFER, W. & HENSLEY, S. (2005): An assessment of the SRTM topographic products. – Tech. Rep. JPL D-31639, Jet Propulsion Laboratory, Pasadena, California, 143 pp.

RUDDIMAN, W.F. (1977): Late Quaternary deposition of ice drafted sand in the sub-polar North Atlantic (lat. 40–65°N). – Geol. Soc. Am. Bull. **88:** 1813–1827.

SCHÄFER, J.M. (2000): Reconstruction of landscape evolution an continental palaeoglaciations using insitu comogenic nuclides: examples from Antarctica and the Tibetian Plateau. – Diss. ETH Zürich. Der Andere Verlag, Osnabrück.

STRAFFIN, E.C., BLUM, M.D. & STOKES, S. (2000): Alluvial stratigraphy of the Loire and Arroux Rivers, Burgundy, France. – Quaternaire **10:** 271–282.

STREET, F.A. (1980): The relative importance of climate and hydrogeological factors in influencing lake-level fluctuations. – Paleoecol. Africa **12:** 137–158.

STREET, F.A. & GROVE, A.T. (1979): Global maps of lake-level fluctuations since 30,000 yr BP. – Quatern. Res. **12:** 83–118.

Thomas, A. & Chen, S. (2002): Landwirtschaft und klimatische Trends im zentralen Yarlong Tsangpo-Tal, Tibet. – Erdkunde **56** (4): 371–384.

Wang, F.B. & Fan, C.Y. (198): Climate changes in the Qinghai-Xizang (Tibet) region of China during the Holocene. – Quatern. Res. **28:** 50–60.

Wei, K. & Gasse, F. (199): Oxygen isotopes in lacustrine carbonates of West China revisited: implications for post-glacial changes in summer monsoon circulation. – Quatern. Sci. Rev. **18:** 1315–1334.

Wu, Y.H., Lucke, A., Jin, Z.D., Wang, S.M., Schleser, G.H., Battarbee, R.W. & Xia, W.L. (2006a): Holocene climate development on the central Tibetan Plateau: A sedimentary record from Cuoe Lake. – Palaeogeogr. Palaeoclimat. Palaeoecol. **234** (2-4): 328–340.

WMO (1967): A Note on Climalological Normals. – WMO No. 208, T.N. No. 84, World Meteorological Organization, Geneva, Switzerland.

Wünnemann, B., Pachur, H-P., Jijun, L. & Hucai, Z. (1998): Chronologie der pleistozänen und holozänen Seespiegelschwankungen des Gaxun Nur/Sogo Nur und Baijian Hu, Innere Mongolei, Nordwestchina. – PGM **142:** 191–206.

Xue, B. & Ge, Y. (2000): Changes of Atmospheric Circulation since the Last Interstadial as Indicated by the Lake-status Record in China. – Acta Geol. Sinica: **74** (4): 836–845.

Yi, C., Liu, K. & Cui, Z. (1998): AMS dating on glacial till at the source area of the Urumqi River valley in the Tianshan Mountains and its implications. – Chin. Sci. Bull. **43:** 1749–1751.

Yi, C., Li, X. & Qu, J. (2002): Quaternary glaciation of Puruogangri – the largest modern ice field in Tibet. – Quatern. Int. **97–98:** 111–121, 2002.

Yu, G., Harrison, S. & Xue, B. (2001): Lake status records from China: Data base Documentation. – Tech. Rep. **4**, Max-Planck-Inst. für Biogeochemie, Jena; 243 pp.

Yu, J.Q. & Kelts, K.R. (2002): Abrupt changes in climatic conditions across the Late Glacial/Holocene transition on the N.E. Tibet-Qinghai Plateau: evidence from lake Qinghai, China. – J. Paleolim. **28:** 195–206.

Yu, G., Xue, B., Liu, J. & Chen, X. (2003): LGM lake records from China and an analysis of climate dynamics using a modelling approach. – Global and Planetary Change **38:** 223–256.

Zhai, Q., Guo, Z., Li, Y. & Li, R. (2006): Annually laminated lake sediments and environmental changes in Bashang Plateau, North China. – Palaeogeogr. Palaeoclimat. Palaeoecol. **241** (1): 95–102.

Zhang, Y., Ohata, T., Ersi, K. & Tandong, Y. (2003): Observation and estimation of evaporation from the ground surface of the cryosphere in eastern Asia. – Hydrol. Proc. **17** (6): 1135–1147.

Zhangdong, J. (2001): Chemical weathering since the Little Ice Age recorded in lake sediments: a high-resolution proxy of past climate. – Earth Surf. Proc. and Landforms **26** (7): 775–782.

Zheng, B. & Rutter, N. (1998): On the problem of Quaternaryglaciations, the extent and patterns of Pleistocene ice cover in the Qinghai-Xizang (Tibet) Plateau. – Quatern. Int. **45/46:** 109–122.

Zhou, H. & Zhu, Z. (2002): Oxygen isotopic composition of lacustrine carbonates since 130 ka BP from a Tianshuihai Lake core, Tibet: an overall increasing 18O trend and its implications. – J. Asian Earth Sci. **20:** 225–229.

Zhu, D.G., Meng, X.G., Zhao, X.T., Shao, Z.G., Feng, X.Y., Yang, C.B., Zheng, D.X., Ma, Z.B., Wu, Z.H., Wang, J., Wang, J.P. & Zang, W.S. (2004): On the Quaternary Evolution of the Nam Co Area, Tibet. – Inst. Geomech., Chinese Acad. Geol. Sci., Beijing.

Zhu, D.G., Meng, X.G., Zhao, X.T., Shao, Z.G., Xu, Z.F., Yang, C.B., Ma, Z.B., Wu, Z.G., Wu, Z.H. & Wang, J.P. (2004): Evolution of an ancient large lake in the southeast of the northern Tibetan Plateau. – Acta Geol. Sinica-English Ed. **78** (4): 982–992.

Zhu, L.-P., Zhang, P.-Z., Xia, W.-L., Li, B.-Y. & Chen, L. (2003): 1400-year cold/warm fluctuations reflected by environmental magnetism of a lake sediment core from the Chen Co, southern Tibet, China. – J. Paleolim. **29:** 391–401.