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A late Quaternary lake record from the Qilian Mountains (NW China): evolution of the primary production and the water depth reconstructed from macrofossil, pollen, biomarker, and isotope data

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Abstract

The history (45 - 0 ka BP) of the aquatic vegetation composition of the shallow alpine Lake Luanhaizi from the NE Tibetan Plateau is inferred from aquatic plant macrofossil frequencies and aquatic pollen and algae concentrations in the sediments. C/N (range: 0.3 - 100), $\delta^{13}\text{C}$ (range: -28 - 15 ‰), and *n*-alkane measurements yielded further information on the quantitative composition of sedimentary organic matter. The inferred primary production of the former lake ecosystem has been examined in respect of the alternative stable state theory of shallow lakes (Scheffer, 1989). Switches between clear and turbid water conditions are

explained by a colder climate and forest decline in the catchment area of Lake Luanhaizi. The macrofossil-based reconstruction of past water depth and salinity ranges as well as other OM proxies allowed climatic inferences of the summer monsoon intensity during the late Quaternary. Around 45 ka BP, conditions similar to or even moister than present-day climate occurred. The Lake Luanhaizi record is further evidence against an extensive glaciation of the Tibetan Plateau and its bordering mountain ranges during the Last Glacial Maximum. Highest lake levels and consequently a strong summer monsoon are recorded for the early Holocene period, while gradually decreasing lake levels are reconstructed for the middle and late Holocene.

Keywords

Marine Isotope Stage 3, Holocene, Tibetan Plateau, plant macrofossils, carbon stable isotopes, *n*-alkanes, lake productivity

1. Introduction

The preservation of plant organic material in lake sediments provides various proxies, which reflect environmental changes within the lake or in the catchment area and which can, therefore, be applied to reconstruct the palaeoenvironment and palaeoclimate. Pollen and plant macrofossil analyses yield information about vegetation assemblages at high taxonomic resolution (Birks, 1980; 1993; Battarbee, 2000) but due to species characteristics of seed production and pollen representation, it is difficult to deduce the quantitative composition of former aquatic vegetation. Approaches using bulk organic matter (e.g. $\delta^{13}\text{C}$, C/N, biomarkers) on the other hand allow a quantitative estimation of whether planktonic algae, submerged macrophytes or terrestrial plants predominantly contributed to sedimentary organic matter

(OM), but they provide little taxonomic resolution. In this paper it is shown that the combination of different approaches yields very detailed information on the primary production history of a shallow lake ecosystem of Central Asia.

On account of the strong influence of the Tibetan Plateau on northern hemisphere climate (Murakami, 1987) many scientists have been attracted by the late Quaternary climate history of this high-continental region (e.g. Van Campo & Gasse, 1993; Gasse et al., 1996; Wang et al., 2002b). Although single studies have yielded information on climate development in several regions, a general climate history is not yet available and different crucial questions are still unanswered. In contrast to other regions in Eurasia, precipitation and temperature values similar to Holocene conditions have been suggested between 40 and 30 ka BP for the Tibetan Plateau (Shi et al., 2001, Shi, 2002). Furthermore, completely different opinions exist about extent and duration of the last glaciation on the Tibetan Plateau (e.g. Kuhle, 1998, 1999; 2003; Schäfer et al., 2002, Shi, 2002); likewise, the chronological frame of the Holocene optimum in Central Asia is at issue (An et al., 2000).

The investigated area is situated at the northeastern margin of the Tibetan Plateau, a transitional area between the Asian summer monsoons and the westerlies. Therefore, ecosystems from the area are expected to respond very sensitively to climatic change.

The Lake Luanhaizi record of plant remains and various OM proxies ($\delta^{13}\text{C}$, C/N, *n*-alkanes) contributes to the detailed lake ecosystem reconstruction (Mischke et al., this issue), which provides further conclusions about climatic change during the last 45 ka in the investigated area. Lake phases have been distinguished and lake depth and salinity have been assessed. Furthermore, they have been assigned to alternative stable states according to the theory of shallow lake ecosystems (Scheffer, 1989).

2. Site

Since Mischke et al. (this issue) provide a detailed site description, only essential information on the investigated area is given. Lake Luanhaizi (37° 35.6'; 101° 21.0', Fig. 1) is situated in the eastern part of the Qilian Mountains at an elevation of 3200 m a.s.l., which represents approximates to the present-day timberline. The mean annual temperature is 0°C and annual precipitation amounts to ~ 500 mm, mainly caused by the summer monsoon (Committee..., 1993).

The vegetation patterns of the Qilian Mountains are described by Chen et al. (1994), Wang et al. (2002) and personal observation. Below 2600 m a natural temperate steppe with *Achnatherum splendens* and *Stipa* species exists only fragmentarily due to replacement by intensive agriculture. Remnants of the former forest belt consisting of *Picea wilsoni*, *P. crassifolia*, *Pinus tabulaeformis*, *Sabina przewalskii* and *Betula platyphylla* are poorly preserved between 2600 and 3200 m. Shrublands (mainly *Potentilla fruticosa*, *Salix orithrepha*, and *Caragana jubata*) are naturally common between 3200 and 3800 m, but due to deforestation have expanded down to 2600 m. Above 3800 m an alpine *Kobresia*-meadow gradually turns into a subnival vegetation and bare rock.

Today most of the area is heavily grazed mainly by yak herds. During summer the herds turn to high alpine meadows whereas the lower ranges are used for winter pasture. Recently, rape cultivation is very common on gentle slopes and broad valleys of the eastern and central Qilian Mountains up to ca. 3000 m (Committee..., 1993).

The freshwater Lake Luanhaizi (area: ca. 1.5 km²) has a present-day maximum depth of ~0.3 m and a pH of 8.4. Central areas of the lake bottom are covered by *Potamogeton* spp.

(*Potamogeton pectinatus* and *Potamogeton pusillus*), whereas *Hippuris vulgaris*, *Blysmus sinocompressus*, *Eleocharis uniglumis* and several sedges (e. g., *Carex enervis*, *C. parva*, *C. moorcroftii*) are common near to the shoreline. This sedge swamp grades into extensive swampy meadows, dominated by hygrophytes, such as *Gentiana pseudoaquatica*, *Ligularia*

tangutorum, *Parnassia trinervis*, *Pedicularis cheiranthifolia*, *Primula nutans*, and *Ranunculus longicaulis*.

3. Material and Methods

3.1. Core material

Core LH1 (length 12.93 m) and core LH2 (length 13.94 m) have been drilled from the central part of Lake Luanhaizi in winter from ice using a modified Livingstone corer. Detailed description of the sediment record as well as core correlation and discussion of the dating results are given in Mischke et al. (this issue). Therefore, only basic information is given here. Although the cores were drilled only 0.5 m apart from each other, a correlation via wiggle matching of magnetic susceptibility (MS) data was necessary, due to compaction of the sediment during the drilling process. Above ~7 m both cores show similar variations and can be easily correlated, while below ~7 m, MS correlation is less distinct. However, from 7 to 10 m depth the peaks can be related, but below 10 m LH2 MS correlation is rather unclear. Lithological inspection shows that the sediment consists mainly of lake marls, sandy and gravelly material occurs at the base and in two short sections of the middle part (Mischke et al., this issue).

The chronological framework of the sequence was determined by Mischke et al. (this issue) on the basis of 8 radiocarbon and 3 U/Th datings (Fig. 2). The sediment record of Lake Luanhaizi was divided into nine zones (zone 1 to zone 9) based on visual inspection of changes of lithology, element concentrations and ratios, organic and carbonate contents and the aquatic plant record (Mischke et al., this issue).

3.2. C/N, $\delta^{13}\text{C}_{\text{bulk organic}}$, *n*-alkanes

For details on the preparation methods applied and the operating conditions of the instruments it is referred to Herzsuh (2004).

Analyses of carbon and nitrogen content were carried out at core LH1. Analyses of organic carbon and organic nitrogen were made with an elemental analyzer Vario EL, CNS Mode.

The machine's precision for the carbon and nitrogen analyses is $\pm 0.1\%$.

Analyses of $\delta^{13}\text{C}_{\text{bulk organic}}$ (performed on LH1 core) and recent plant material were analysed using a Finnigan Mat delta plus isotope ratio mass spectrometer.

For *n*-alkane composition 20 samples (from the lake carbonate sections of core LH2) were analysed using a GC-MS instrument (HP 5890 Serie II capillary gas chromatograph - HP 5971 Series mass spectrometer) according to Wilkes et al. (1999)

Biomarker parameters were calculated using peak areas of the respective compounds in the gas chromatograms (Fig. 3). The biomarker ratios were calculated according to the following equations:

Carbon preference index for hydrocarbons (after Bray & Evans, 1961, slightly)

$$\text{CPI}_{\text{HC-25-31}} = [(C_{25} + C_{27} + C_{29} + C_{31}) / (C_{24} + C_{26} + C_{28} + C_{30}) + (C_{25} + C_{27} + C_{29} + C_{31}) / (C_{26} + C_{28} + C_{30} + C_{32})] / 2$$

aquatic/terrestrial ratio for hydrocarbons (after Meyers, 1997, slightly changed)

$$\text{ATR}_{\text{HC}} = (C_{15} + C_{17} + C_{19}) / (C_{15} + C_{17} + C_{19} + C_{27} + C_{29} + C_{31})$$

proxy for submerged/floating versus emergent/terrestrial plant input (Ficken et al., 2000)

$$\text{P}_{\text{aq}} = (C_{23} + C_{25}) / (C_{23} + C_{25} + C_{29} + C_{31})$$

3.3. Aquatic palynomorphs and macrofossils

Pollen samples were processed in the laboratory following Faegri & Iversen (1989). At least 400 pollen grains were counted in each sample, apart from few horizons with extremely low pollen concentration (< 5000 grains/ cm^3). In order to calculate the pollen concentrations,

Lycopodium tablets were added to the samples (Stockmarr, 1971). A total of 57 pollen

samples have been analysed. Fig. 4 shows the pollen concentrations of the most abundant aquatic pollen and non-pollen palynomorphs.

For plant macrofossil analyses a known weight of dry sediment (ca. 50 g) was prepared and investigated according to Birks (2001). 288 samples were examined, of which 189 of them contained identifiable macrofossil remains. The charophytic remains (oospores, gyrogonites) were picked from the samples used for ostracod analysis (for sample number and treatment see Mischke et al., this issue). For stratigraphic presentation the counted number of fossils in each sample were converted to number per 50 g dry sediment. Fig. 6 shows the concentrations of the most abundant macrofossils.

For each stratigraphic level containing higher aquatic plant macrofossils, the past water depth and salinity level were estimated by the determination of the range which is tolerated by all taxa present in a sample. The applied water depth ranges (table 2) are based on information given in Kantrud (1991), Hannon & Gaillard (1997), Brush & Hilgartner (2000) and Dieffenbach-Krall & Halteman (2000). For the estimation of the salinity levels information given by Brush & Hilgartner (2000) has been used, which does not represent physiological tolerance ranges of the species but shows real occurrence ranges under competition pressure. Charophyceae data are excluded from the procedure, since gyrogonites and oogonia can easily be transported within the lake and are therefore unsuitable for water depth reconstruction.

4. Results and discussion

4.1. Results and discussion of the single proxies

$\delta^{13}\text{C}_{\text{bulk organic}}$: All collected terrestrial plants and heliophytes from the vicinity of the lake and from the lake shore (table 1) show $\delta^{13}\text{C}$ values between -25 and -32 ‰, which represents the characteristic range of C_3 -cycle land plants (Ehleringer & Rundel, 1988). Similar $\delta^{13}\text{C}$ values for C_3 -cycle heliophytes were reported by other authors too (Ficken et al., 2000; Wang et al., 2003). Although the area experiences semi-arid climate conditions, C_4 -cycle land plants ($\delta^{13}\text{C}$

ca. -14 ‰) play a minor role or are totally absent in the present-day vegetation and hence in the recent contribution to lake organic matter. In fact, it is impossible to differentiate between OM derived from typical land plants growing on the mountain slopes around the lake and OM from emergent water plants growing in shallow areas within the lake due to their similar $\delta^{13}\text{C}$ ranges. The dominating aquatic plants in Lake Luanhaizi, *Hippuris vulgaris* and *Potamogeton pectinatus*, have completely different stable carbon isotope compositions, -27.7 ‰ and -13.4 ‰, respectively (table 1). Submerged water plants from other hard-water and saline lakes of NW China yielded very high $\delta^{13}\text{C}$ values (*Myriophyllum*: -15.8 ‰, -18.6 ‰; *Chara*: from -12.8 to -18.8 ‰). If the availability of dissolved CO_2 is limited, which is often the case under alkaline conditions, most algae and submerged vascular plants are able to utilize dissolved HCO_3^- (Steeman Nielsen, 1947; Raven, 1970; Allen & Spence, 1981; Bowes & Salvucci, 1989; Prins & Elezenga, 1989). It is through this mechanism high $\delta^{13}\text{C}$ values of the submerged are attained. *Hippuris vulgaris* plants assimilate partly above and partly below the water surface and consequently rely on both the water carbon cycle as well as on the air carbon cycle. However, *Hippuris* is proven to be a poor HCO_3^- -utilizer (Maberly & Spence, 1983) which results in ^{13}C -depleted organic material (Osmond et al. 1981). We did not analyse recent moss material, but according to data from Rundel et al. (1979) and Ménot & Burns (2001), submerged mosses (e.g. *Drepanocladus*) are unable to utilize HCO_3^- for assimilation.

The $\delta^{13}\text{C}$ analysis of fossil organic matter (Fig.2) yielded a very broad range of values (between -28 and -15 ‰). High values of up to -15 ‰ (e.g. in zone 4 and in zone 9) can easily be explained by high contribution of aquatic plant taxa (algae, vascular macrophytes) to the OM, which utilized HCO_3^- - for assimilation. Other sections are characterized by low $\delta^{13}\text{C}$ values (upper part zone 2a; zone 2b, zone 3, transition zones 4 to 5, zone 6a, zone 8). These values can be caused by either a high input of terrestrial material or by an aquatic assimilation using dissolved CO_2 in isotopic equilibrium with the atmosphere, which is more likely the

case under cold climatic conditions. According to the results based on other methods (macrofossil and aquatic pollen analysis, C/N determination), both explanations might be responsible for the strong ^{13}C -depletion in zone 3 as well as at the transition from zones 4 to 5, but are not conclusive for other core sections. Most of the large shifts to depleted $\delta^{13}\text{C}$ organic matter (e.g. within zone 2a: from ca. -21 to ca. -27‰; at the beginning of zone 8: from ca. -20 to ca. -25‰) are correlated with the appearance of charophytes, especially *Chara* stems, *Chara* gyrogonites and *Chara*-stem encrustations in the macrofossil record. According to the analysed weak or non-encrusted modern *Chara* material, these taxa should cause high $\delta^{13}\text{C}$ values of the organic matter due to the HCO_3^- uptake from the water column mentioned above. This is obviously not the case in our fossil record. On the contrary the OM is even more depleted during periods of *Chara* occurrence. Hammarlund et al. (1997) presented a very similar record from a hard-water lake in Sweden and gave a plausible interpretation of their results, which might also explain our carbon isotopic data. Laboratory investigations threw light upon the connection between photosynthesis and calcite encrustation in charophytes (see McConnaughey, 1991; Hammarlund et al., 1997; Ray et al. 2003). During the assimilation of dissolved inorganic carbon by means of proton pumping the equal utilisation of the produced carbon dioxide for photosynthesis and carbonate precipitation allows a selective uptake of ^{12}C and hence induces a pronounced depletion of ^{13}C in charophyte organic material.

C/N ratios: The C/N extremes (Fig. 2) are between 0.3 and 100, but most ratios range between 10 and 20. Zone 3 and 5 yielded particularly low C/N ratios (less than 10) whereas zone 2a and 7 reach particularly high ratios (above 20). Plant groups, which mainly contribute to the lake organic matter, show different ranges of C/N ratios: phytoplankton from 4 to 10; aquatic macrophytes from 10 to 50 and terrestrial plants above 20 (Meyers & Lallier-Vergès, 1999; Spencer et al., 1997). According to these C/N ranges the most frequently recorded C/N

ratio between 10 and 20 suggest either a sole input from aquatic macrophytes or more likely a mixture of different components. C/N measurement of leaves of *Potamogeton pectinatus*, *Zannichellia palustris* and *Myriophyllum spicatum* by Spencer et al. (1997) yielded values of 17.2, 12.9, and 18.8, respectively, which is matched by our values. The high C/N ratios during zone 7 point to a predominant input of terrestrial material which hints to very shallow lake conditions during this phase. Difficulties in interpretation arise from the very low C/N ratios in zones 3 and 5. Such low C/N ratios indicate to a complete lack of terrestrial material input, which might be the case under sub-nival conditions, when OM input would be mainly derived from on algal and bacterial blooms during the short thaw period of the year. Partial degradation of organic matter, which can modify the elemental composition and hence the C/N ratios during early diagenesis, should also be taken into account (Meyers & Lallier-Vergès, 1999). However, the C/N fingerprint of different organic matter sources should not be destroyed by alteration processes. For sediments with very low OM content Meyers (1997) gave another explanation for unusually low C/N values, which is presumably caused by the analysis method. The measurement of carbonate-free samples yield organic carbon content on the one hand, but a combined organic nitrogen and inorganic nitrogen content on the other hand. In organic-rich sediments inorganic nitrogen concentration is low and hence the obtained C/N ratios represent the real organic carbon to organic nitrogen ratio. But in sediments with very low organic contents ($C_{org} < 0.3\%$), the inorganic part can play a substantial role, which leads to artificially low C/N ratios. In zone 5 the organic carbon content is very low, most values are below the marked limit of 0.3 %, thus methodological problems in determining the C/N ratio cannot be excluded.

***n*-alkanes:** The *n*-alkane distribution of most samples shows highest percentages of C₂₁-C₂₅ with weak or no odd-over-even predominance in this middle chain-length carbon number range (Fig. 4 - middle diagram), which is a typical pattern of submerged macrophytes (Rozentsvet et al., 2002; Nuñez et al., 2002). Hence, sedimentary organic material of most sections of the core predominantly refer to macrophyte detritus. Charophytes show a rather complex chain-length distribution (Nuñez et al., 2002): beside high percentages for C₂₁-C₂₇, they show also comparatively short chained *n*-alkanes C₁₇-C₁₉. Such a pattern has been found at sample depth 2.82 m (not illustrated), where the macrofossil record also points also to a charophyte dominance. Algae, which predominantly produce less-carbon-number *n*-alkanes (C₁₇-C₁₉) seem to contribute very little to the organic matter of most sections of the core. Only at sample depth 11.35 m algae might have dominated the OM input (Fig. 4 - lower diagram), which is also suggested by the high *Pediastrum* concentration of the aquatic palyno-facies record (Fig. 5). Although a high concentration of *Botryococcus* has been recorded in zone 9, only few amounts of short-chain *n*-alkanes have been found in the corresponding sample from 1.81 m and 1.14 m depth. In contrast to other algae, *Botryococcus* was shown to produce odd-carbon numbered *n*-alkanes in the range C₂₅-C₃₁ (Lichtfouse et al., 1994). However, contrary to the recorded macrofossil and algae record the *n*-alkane distribution suggests a predominant macrophyte OM input during zone 9.

Most samples (e.g. at 8.22 m and 10.89 m) show also a component of comparatively long chained *n*-alkanes (> C₂₅) with an odd-over-even predominance (Fig. 4 - upper diagram), which is typical for epicuticular leaf waxes of higher plants (Eglinton & Hamilton, 1963; Douglas & Eglinton, 1966; Kolattukudy, 1969, Reddy et al., 2000). After being deposited, these compounds are relatively resistant to biodegradation and could be well preserved in lacustrine sediments, which could lead to an overestimation of the terrestrial plant input (Meyers & Ishiwatari, 1993). Not only land plants show such *n*-alkanes composition but also emergent water plants (Ficken et al., 2000), e.g. the *n*-alkane distribution of *Typha latifolia*

maximizing at C₂₉ has also a strong odd-over-even predominance (Wang et al., 2003). At the upper part of zone 4 the water moss *Drepanocladus* sp. has been recorded, which has been shown to yield a *n*-alkane distribution pattern similar to terrestrial seed plants (Ficken et al., 2000), and may jointly be responsible for the high percentages of C₂₅, C₂₇, C₂₉, C₃₁ in the corresponding sample (e.g. at 7.23 m and 8.22 m depth; Fig. 4).

The calculation of different *n*-alkanes indicator ratios (Fig. 2, for equation) enables semi-quantitative comparison of OM source at different core sections. P_{aq} (a proxy for submerged/floating versus emergent/terrestrial plant input) ranges between 0.4 and 1, which indicates submerged macrophyte dominance during the corresponding time periods (Ficken et al., 2000) (except for once at 11.12 m). At 11.12 m only few macrophytes occurred, whereas high algal production is reflected by high values for the aquatic/terrestrial ratio (ATR_{HC}). High CPI_{HC} values (carbon preference index) at the lowermost and upper part of zone 4 suggest markedly higher emergent and terrestrial plant contribution, which is also supported by the macrofossil record at this section.

Aquatic vegetation record (aquatic palynomorphs, plant macrofossils): Recorded aquatic palynomorphs (Fig. 5) include the pollen of aquatic vascular plants (*Myriophyllum*, *Potamogeton/Triglochin*, *Hippuris*, *Typha angustifolia*-type, *Cyperaceae*), fungal remains (*Glomus*) and algae (*Pediastrum*, *Botryococcus*). Additionally, terrestrial pollen concentration and *Picea* percentages are shown.

The abundances of 14 different macrofossil remains are plotted in Fig. 6. Remains of the following spermatophyte taxa have been found: diaspores of *Myriophyllum spicatum*, *Potamogeton pectinatus*, *Potamogeton* cf. *pusillus*, *Batrachium* cf. *bungei*, *Ruppia maritima*, *Zannichellia palustris*, *Hippuris vulgaris*, *Carex* sp., *Carex* cf. *moorcroftii*, *Chenopodiaceae* and leaf fragments of *Rumex*. Charophytes are represented by oospores of *Chara* cf. *aspera* and *Chara* gyrogonites (according to identification of occasionally preserved oospores they

belong to *Chara tomentosa* [Haas, 1994]). Ehippia of *Daphnia* are the only identifiable animal remains. Numerically, *Potamogeton pectinatus*, *Zannichellia palustris* and *Chara* oospores and gyrogonites dominate the aquatic plant record.

According to the ecological requirement of the recorded submerged water plant species the inferred water depth ranges between 0 and 4.8 m (Fig. 2). Almost no macrofossils have been found in zones 1, 3 and 5, thus no water level reconstruction has been given. Shallow water conditions between 0.25 and 2.5 m have been reconstructed for zones 2a and 4. In these sections the maximum water depth is based on the requirements of *Zannichellia palustris*, which can occur in water depths up to 2.5 m, but commonly it prefers water depth of less than 1 m and is characteristic of disturbance e.g. eutrophication and fluctuating water levels (Van Viersen, 1982). Thus, in zones 2a and 4 mostly distinct shallower conditions can be assumed. If *Potamogeton pectinatus* and *Myriophyllum spicatum* dominate the record and shallow water plants like *Zannichellia* are very rare (transition zone 2b, zone 6, middle part of zone 9) the water depth likely exceeded 1 m and lake conditions should have been comparatively stable. The lake level reconstruction for zone 9 points to comparatively deep conditions in the lower and middle part and shallower conditions in the upper part of the zone, but due to the small amount of macrofossils the inference is tentative.

In Fig. 1 salinity reconstruction based on submerged plant remains is also shown. The known salinity ranges of submerged water plants taken from literature are given in Table 2. Since most plants show a comparatively wide salinity range only approximate salinity estimations can be inferred. According to the macrofossil record Lake Luanhaizi was characterized by fresh to mesohaline conditions. Oligohaline conditions can be inferred for zone 2a and zone 4, while in the upper part of zone 8 mesohaline conditions prevailed. In zones 2b, 3, 6 and 9 no reliable hints for higher salinities were found and mainly fresh water conditions very likely occurred.

4.2. Lake history and Late Quaternary climate variability in the Qilian Mountains

According to the age model given in Mischke et al. (this volume) the sediment zones which will be discussed in the following belong to the Late Quaternary periods Marine Isotope Stage 3, MIS2 and Holocene. Furthermore, the single MIS2-lake phase of Lake Luanhaizi have been related to periods of similar moisture availability in monsoon-influenced Central Asia, which are based on the review of climate records from the area (Herzschuh, 2004). Inferred changes in Lake Luanhaizi's water state, salinity and lake level as well as change in the climate conditions are summarized in Tab. 3.

Zone 1 (13.94 - 13.15 m; age unknown): The coarse sediment as well as the low carbonate and organic content point to predominant fluvial input to the basin (Mischke et al., this issue). The macrofossil and the pollen record give no hint for any aquatic vegetation. It can consequently be assumed that no lake existed during this period. Infrequent water inflow did not form a suitable environment for algae or macrophyte immigration, which indicates generally dry climate conditions. However, due to the lack of any dating the age of zone 1 is unclear.

Zone 2 (13.15 - 11.00 m; Marine Isotope Stage 3, ~45 ¹⁴C ka BP): At the transition from zone 1 to 2 the water supply improved gradually, and fluvial deposits were replaced by organic and carbonate rich lake sediments. *Potamogeton* occurs in the macrofossil and pollen records, which points to lake conditions lasting at least for several months of the year (Van Wijk, 1988; Kantrud, 1990). Later, *Potamogeton* is accompanied by *Zannichellia palustris* and *Chara cf. aspera*, forming a dense submerged macrophyte meadow. The species composition suggests a slight increase in lake salinity and temperature (Van Viersen, 1982; Haas, 1994). Besides the macrofossil record, the LOI values also indicate high lake productivity with vegetation induced high carbonate precipitation under favourable climate

conditions. Despite internal lake productivity, the contribution of terrestrial or emerged plants to the sedimentary organic component remained strong, as indicated by high C/N ratios and high *Glomus* sp. values as well as by *Carex* spp. and Chenopodiaceae seed occurrences, which imply near-shore conditions. However, during most of zone 2a a comparatively stable shallow, clear-water lake existed, which was dominated by macrophyte vegetation. The water plant assemblage changed completely at the transition to zone 2b. The former dense *Chara* vegetation was replaced by *Potamogeton pectinatus*, which is considered to tolerate much more turbidity than charophytes (Blindow, 2002). Van den Berg et al. (1999) showed that charophytes disappeared when Secchi depths is less than 0.4 m. In Lake Luanhaizi the macrophyte vegetation almost disappeared, and primary production in the lake was dominated by microalgal growth, as indicated by high *Pediastrum* values and high abundances of short-chain *n*-alkanes. The high and steady abundances of *Daphnia ephippia* in zone 2b is further evidence for changes in the lake system, since Cladocera are known to produce these resting eggs to survive phases of unstable conditions and environmental stress e.g. lake desiccation or lake freezing (Deng, 1996, Sarmaja-Korjonen, 2003). As macrophytes are crucial in shallow lake food webs and for the stabilisation of the clear water state, their decline has direct consequences for the whole organism assemblage in such ecosystems (Carpenter & Lodge, 1986; Jeppesen et al., 1997). The two patterns of a macrophyte dominated clear water lake on the one hand and a microalgae dominated turbid lake on the other hand represent two alternative stable states of shallow water lakes (Scheffer, 1989; 1998; Van Nes et al., 2002). A switch from one of these stable states to the other can be assumed at the transition from 2a to 2b. External nutrient loading and wind-induced resuspension of nutrient-rich sediment may have been the driving key mechanisms to support algal growth which caused an increase of turbidity (Hamilton & Mitchell, 1996; 1997; Scheffer, 1998). Parallel with increasing algal growth in zone 2b, the *Picea* forest around the lake declined, which could have strengthened

both the nutrient input from the unstable slopes around the lake and the wind influence, and hence may have caused the changes in the lake ecosystem.

Zone 3 (11.00 - 10.17 m; ~45 ¹⁴C ka BP): Internal lake production declines as indicated by organic and carbonate content (Mischke et al., this issue) and macrophyte vegetation disappeared. The proxies suggest unstable lake conditions, which points to climate deterioration, particularly less available moisture, during this period.

Zone 4 (10.17 - 6.40 m; ~45 ¹⁴C ka BP): The beginning of zone 4 is marked by an immediate onset of macrofossil remains. At first, emergent and terrestrial vegetation predominated, as indicated by high C/N values and abundant *Carex* spp. nuts in the macrofossil record. Later, submerged macrophytes like *Myriophyllum spicatum*, *Potamogeton pectinatus*, *Batrachium* cf. *bungei* have higher abundances in the local plant composition. Furthermore, high carbonate and organic contents suggest high primary productivity within the lake leading to a limitation of dissolved CO₂ in the water column, which again causes the high OM δ¹³C values. During zone 4 a shallow lake (of ca. 1 to 2 m depth) with oligohaline to mesohaline conditions can be assumed, which was dominated by submerged vegetation with high productivity. The absence of charophytes during this zone are possibly the result of slightly turbid water conditions due to higher nutrient input from the treeless slopes. However, the algal record also shows small abundances of *Pediastrum* or *Botryococcus* during this zone. The reconstructed lake system suggests wetter climate conditions than in zone 3, but no indications for temperatures as high as those in zone 2 have been found.

Zone 5 (6.40-4.80 m; Last Glacial Maximum): Low organic and carbonate values and the lack of any aquatic vegetation remains point to lake desiccation or lake freezing during most of the year, which suggests cold and dry climate conditions during this period. Short thaw periods in the year are possibly characterised by blooms of algae and bacteria as indicated by low C/N ratios and δ¹³C values, mostly above the range of typical land plants.

Zone 6 (4.80 - 3.66 m; subsequent to the LGM ca. 18.5 – 17 cal. ka BP): The succession of *Hippuris vulgaris*, *Potamogeton pectinatus*, and *Chara* gyrogonites in the macrofossil record suggests a gradually increasing water level at the beginning of zone 6a. Assuming that *Chara* gyrogonites belong mostly to *Chara tomentosa* (see section 4.4.), a comparatively deep lake with clear water conditions can be inferred (Haas, 1994). Conditions changed at the transition from 6a to 6b, the dense charophyte vegetation was replaced by the vascular plant macrophytes *Myriophyllum spicatum* and *Potamogeton pectinatus*, as indicated by the macrofossil and pollen records. A slight decline of the water level very likely induced the vegetation change. Furthermore, increased terrestrial input, indicated by higher abundances of *Glomus* sp. and higher C/N values, points to a closer shoreline position than in zone 6a. Altogether, compared to zone 5 the lake record of zone 6 suggests a considerable climate amelioration. Higher temperature and especially moisture availability than before occurred during this period.

Zone 7 (3.66 - 3.12 m; around the Heinrich 1 event ~16 cal. ka BP): Playa-like conditions with low internal production and predominant external input, as suggested by high C/N values and low carbonate and organic content, can be assumed during zone 7. Therefore, drier and probably colder climate conditions than before are deduced.

Zone 8 (3.12 - 2.30 m; Bølling/Allerød-Younger Dryas) : The transition to zone 8 is marked by high abundances of *Chara* gyrogonites (*Chara cf. tomentosa*) and *Chara* stems in the macrofossil record, which constitutes almost the entire sediment. A stable and comparatively deep clear water lake can therefore be assumed during this period. Climate conditions became much wetter than during zone 7. The submerged vegetation composition changed at the end of zone 8. High percentages of *Chara cf. aspera* and the occurrence of *Ruppia maritima* and *Zannichellia palustris* points to a lake level lowering and lake instability. Furthermore, the species composition suggests an increase in salinity and temperature during the end of zone 8 (Van Viersen, 1982; Kantrud, 1991; Haas, 1994).

Zone 9 (2.30 - 0 m; Holocene): At the lower part of zone 9, the submerged plant indications decrease rapidly and large amounts of planktonic algae are recorded. A sharply increased water level possibly hindered the growth of vascular submerged plants at the drilling site. The input of both terrestrial plant material and soil into the lake was very small (as indicated by low *Glomus* and low C/N values), which is further evidence of the occurrence of a stable and deep lake during this period. But later, the succession of *Myriophyllum spicatum*, *Potamogeton* and *Hippuris vulgaris* in the pollen record suggests a gradually decreasing water level at the upper part of zone 9. Therefore, warm and wet climate conditions dominated in the lower part of zone 9, as suggested by the high algae productivity, the high lake levels and the occurrence of *Picea* forest around the lake. A gradual decrease in moisture can be assumed for the upper part of zone 9.

4.3. Comparison with other records and conclusion

Palaeoclimate interpretations derived from the primary production record presented here were compared to other palaeoclimate records from monsoon-influenced Asia. Around ~45 ¹⁴C ka BP temperate conditions similar or even moister than present-day climate occurred in the Qilian Mountains as indicated by deduced stable lake conditions and nearby dense *Picea* forests. In accordance with the high lake levels at Lake Luanhaizi, other evidence exists for favourable climate conditions during MIS 3 on the Tibetan Plateau, e.g. Zabayul Lake (Wang et al., 2002), Tianshuihai (Li et al., 1991), Akesaiqin (Fang, 1991). Further evidence for a comparatively warm and wet period comes from the Guliya ice core record (northwestern Tibetan Plateau; Thompson et al., 1997) and from records of the Loess Plateau (e.g. Chen et al., 1997; An et al., 1991) and Inner Mongolian desert areas (Pachur et al., 1995). Shi et al. (2001) attributed the favourable conditions at the Tibetan Plateau to a strongly enhanced

Indian summer monsoon, which - according to their interpretation- caused precipitation and temperatures exceeding present-day conditions.

Our record from Lake Luanhaizi is new evidence that even the mountain ranges at the margin of the Tibetan Plateau which receive a comparatively high amount of precipitation have not been covered completely by glaciers during the LGM period. This is in contrast to the idea of a large ice shield covering the entire plateau (Kuhle, 1998, 1999, 2003). Our record supports the idea of a restricted glacier extension which is at present advocated by the majority of scientists (e.g. Derbyshire et al. 1991; Lehmkuhl, 1997, 1998; Lehmkuhl & Haselein, 2000; Zheng & Rutter, 1998; Schäfer et al., 2002; for further references see Shi, 2002).

The Late Glacial is characterized by strong changes of the Lake Luanhaizi's lake level suggesting that strong climate variability occurred in the Qilian Mountains. Subsequent to a playa phase, probably belonging to the LGM, a period of higher lake levels was recorded which possibly was caused by glacier melting. Afterwards again a phase of instable lake conditions with playa sedimentation occurred (around the Heinrich event 1). Higher levels and a higher *Picea*-treeline characterizes the Bølling/Allerød phase indicating that higher effective moisture and higher temperatures occurred in the area.

Other records from monsoon-influenced Asia and bordering off-shore areas yielded a similar sequence of climate change during the Late Glacial. Soon after the LGM a first amelioration as indicated in the Lake Luanhaizi archive is confirmed by increased continental runoff recorded in South China Sea sediments (Wang et al., 1999). It possibly represents the onset of summer monsoon circulation after the LGM. However, it is hard to decide whether this means that increased monsoonal precipitation already reached the interior of Asia or if mere local glacier melting leads to the wrong assumption of an increased monsoonal precipitation there. A return to drier and probably colder climate conditions as suggested by a playa phase at the

Luanhaizi centered around the Heinrich 1 event in the North Atlantic Ocean (~16 cal. ka BP; Bond et al., 1992; 1993) is also evident in loess profiles (e.g. Chen et al., 1997), in marine sediments (e.g. von Rad et al., 1999), and in the high resolution stalagmite archive from Hulu Cave in eastern China (Wang et al., 2001). Many records from monsoonal Asia prove that a first strong intensification of the Asian monsoon circulation after the LGM, especially the Indian Monsoon, took place at the beginning of the Bølling/Allerød period at ~14.8 cal. ka BP (Sirocko et al., 1993; Overpeck et al., 1996; Zhou et al., 1999). The expansion of coniferous forest vegetation in the Qilian Mountains and the Zoige Basin (eastern Tibetan Plateau, Yan et al., 1999) underlines this early enhancement of the Indian Monsoon during the Late Glacial.

However, the highest lake levels of the entire investigated period are reconstructed for the early Holocene (lower part of zone 9), whereas gradually decreasing lake levels are recorded for middle and late Holocene times.

Continuous off-shore sediment cores from the Arabian Sea and South China Sea (Wang et al., 1999; Sirocko et al. 1993, Overpeck et al., 1996) and a well-dated speleothem record from southern Oman (Fleitmann et al., 2003) indicate that the summer monsoon experienced an strong intensification during the early Holocene period, while a weakening trend since the middle Holocene is proposed. The early Holocene monsoon maximum is generally attributed to enhanced northern hemisphere solar insolation while its intensification was stimulated by the weakening of the glacial boundary conditions, such as North European ice shield, North Atlantic sea surface temperature and the Tibetan snow cover (Overpeck et al., 1996; Fleitmann et al., 2003). Even at the present-day the Qilian Mountains show a positive P-E budget during summer months, so lakes in the area should have had even higher lake levels during periods of higher temperature and precipitation values like those reconstructed for the early Holocene. The Lake Luanhaizi climate archive and also other records from Central Asia mirror this pattern of early Holocene monsoon maximum (e.g. Hong et al., 2003 in eastern

Tibet; Van Campo & Gasse, 1993 in western Tibet), but climate optima during the middle Holocene period are also reported especially from sites of the nearby Inner Mongolian Plateau (e.g. Shi & Song, 2003; Herzschuh et al., 2004). Most climate records reflect a trend towards a higher aridity since ca. 3 ka (e.g. Chen et al., 2003; Mischke et al., 2002) as is also supposed by our investigation of the Lake Luanhaizi record.

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Tab. 1 $\delta^{13}\text{C}$ values of characteristic land and water plants of the Qilian Mountains and neighbouring areas of NW China.

<u>$\delta^{13}\text{C}$ values, water plants , NW China (‰, VPDB)</u>	
<i>Chara</i> (Baritaolegai Lake)	-18,8
<i>Chara</i> (Lexiketu Lake)	-16,2
<i>Chara</i> (Sayingwusu Lake West)	-17,1
<i>Chara</i> (Sayingwusu Lake East))	-15,9
<i>Myriophyllum</i> (Wuzhuer Lake West)	-15,8
<i>Chara</i> (Wuzhuer Lake East)	-16,8
<i>Chara</i> (Sawu Lake)	-15,4
<i>Chara</i> (Qinghai Lake)	-12,9
<i>Myriophyllum</i> (Bosten Lake)	-18,6
<i>Chara</i> (Bosten Lake)	-18,0
<u>$\delta^{13}\text{C}$ values, water plants, Lake Luanhaizi (‰, VPDB)</u>	
<i>Hippuris vulgaris</i> L.	-27,7
<i>Potamogeton pectinatus</i> L.	-13,4
<u>$\delta^{13}\text{C}$ values, land plants, Qilian Mountains (‰, VPDB)</u>	
<i>Taraxacum sikkimense</i> Hand.-Mazz.	-25,4
<i>Saussurea arenaria</i> Maximow.	-25,7
<i>Leontopodium ochroleucum</i> Beauv.	-28,7
<i>Kobresia pygmaea</i> Clarke	-25,9
<i>Anemone obtusifolia</i> D. Don	-26,3
<i>Taraxacum brevirostre</i> Hand.-Mazz.	-27,9
<i>Carex przewalskii</i> Egerova	-24,9
<i>Carex supina</i> Willd. ex Wahlenb.	-26,9
<i>Pedicularis cheiranthifolia</i> Schwenk	-27,1
<i>Pedicularis verticillata</i> L.	-29,0
<i>Geranium pylzowianum</i> Maximow.	-25,9
<i>Gentiana aristata</i> Maximow.	-27,8
<i>Erigeron acer</i> L.	-28,1
<i>Oxytropis qilianshanica</i> C.W.Chang & C.L.Zhang	-27,5
<i>Microula pseudotrichocarpa</i> W.T.Wang	-28,4
<i>Pedicularis lyrata</i> Prain ex Maximow.	-28,6
<i>Ranunculus tanguticus</i> (Maximow.) Ovcz.	-25,2
<i>Saxifraga tangutica</i> Engler	-30,5
<i>Parnassia trinervis</i> Drude	-31,9
<i>Aster flaccidus</i> Bunge	-28,8
<i>Epilobium palustre</i> L.	-29,3
<i>Polygonum sibiricum</i> Laxm.	-27,7
<i>Campanula aristata</i> Wall.	-28,9
<i>Carex moorcroftii</i> Falc. ex Boott.	-26,2
<i>Kobresia capillifolia</i> (Decne.) Clarke	-27,7
<i>Picea crassifolia</i> Komarov	-26,4
<i>Pleurospermum pulszkyi</i> Kanitz	-26,8
<i>Saussurea nigrescens</i> Maximow.	-27,5

Tab. 2 Preferred water depth and water salinity ranges of submerged water plants

	water depth preference (m)	salinity preference
<i>Myriophyllum spicatum</i>	1 - 4.8 ⁽³⁾	tidal fresh - mesohaline ⁽⁴⁾
<i>Potamogeton pectinatus</i>	0.25 - 3.9 ⁽³⁾	tidal fresh - mesohaline ⁽⁴⁾
<i>Potamogeton pusillus</i>	0.25 - 2 ⁽⁵⁾	tidal fresh - oligohaline ⁽⁴⁾
<i>Ruppia maritima</i>	0 - 4.5 ⁽¹⁾	mesohaline - polyhaline ⁽⁴⁾
<i>Zannichellia palustris</i>	0 - 2.5 ⁽⁴⁾	oligohaline - polyhaline ⁽⁴⁾
<i>Batrachium bungei</i>	0.25 - 2 ⁽⁶⁾	n.d.
<i>Chara aspera</i>	0 - 1 ⁽²⁾ (tolerant to desiccation)	n.d.
<i>Chara tomentosa</i>	2 - 5 ⁽²⁾ (intolerant to desiccation)	n.d.

n.d. not documented

definition of salinity ranges (g/l): tidal fresh 0-0.5; oligohaline 0.5-5; mesohaline 5-18; polyhaline 18-30

(1) Kantrud, 1991; (2) Haas, 1994; (3) Hannon & Gaillard, 1997; (4) Brush & Hilgartner, 2000;

(5) Dieffenbacher Krall & Halteman, 2000; (6) observation at the eastern Tibetan Plateau by the authors

Tab. 3 Lake water state, lake leve and lake salinity of Lake Luanhaizi climate conditions from the Qilian Mountains reconstructed from proxies of the aquatic primary production.

zone	climate period	lake water state	lake level	lake salinity	inferred climate conditions
9	Holocene	?	high/interm. at top	low	warm/very wet
8	B/A ; YD	clear	interm.	low/high at top	warm/wet (dry at top)
7	Heinrich 1event	-	low	-	dry
6b	1 st -warming	clear	interm.	low	wet
6a					
5	LGM	-	low	-	dry/cold
4	MIS 3	clear	interm.	interm.	wet
3	MIS 3	-	low	-	dry
2b		turbid			colder
2a	MIS 3	clear	interm.	interm.	warm/wet
1	MIS3 ?	-	low	-	dry

Herzschuh
Fig. 1

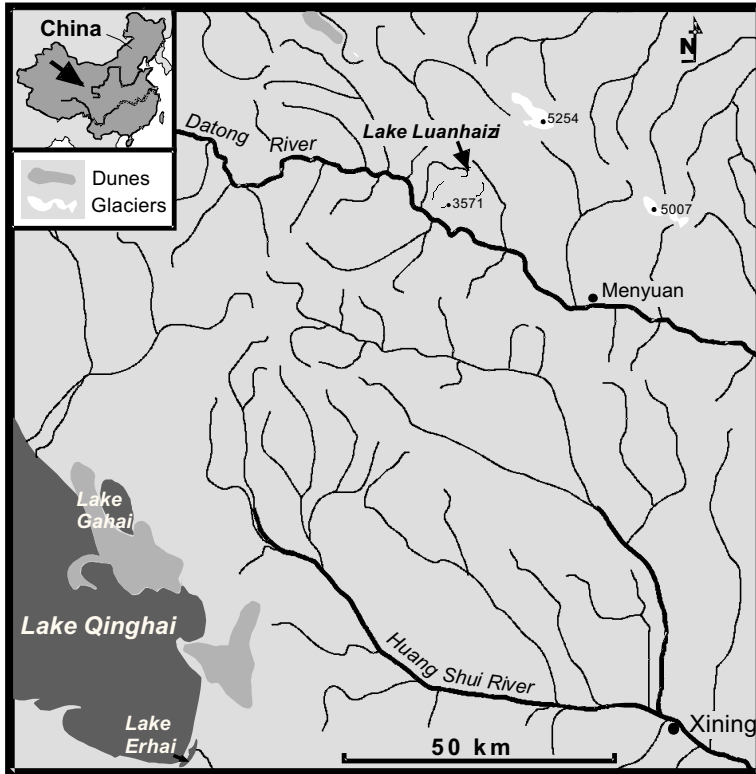
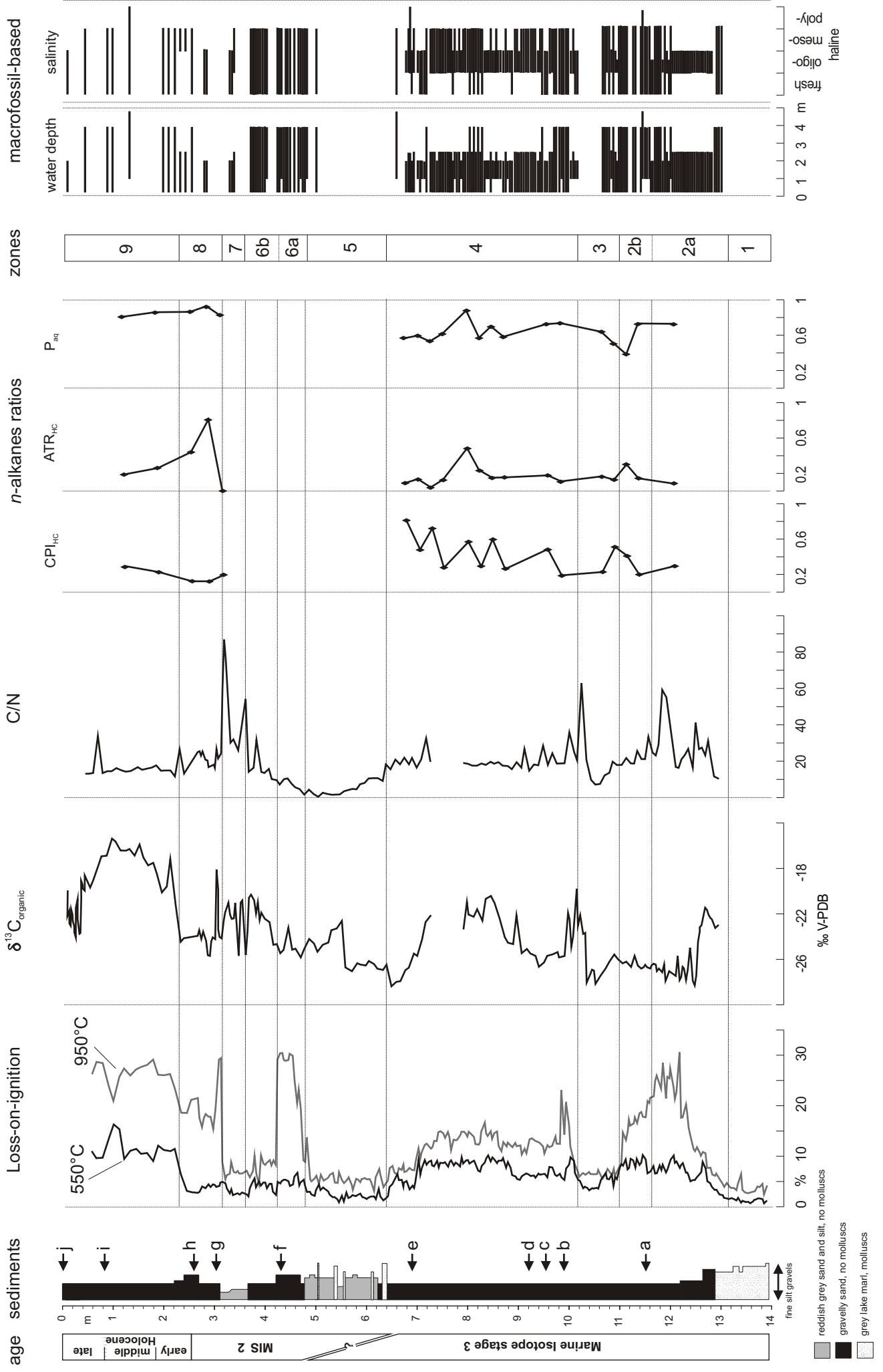
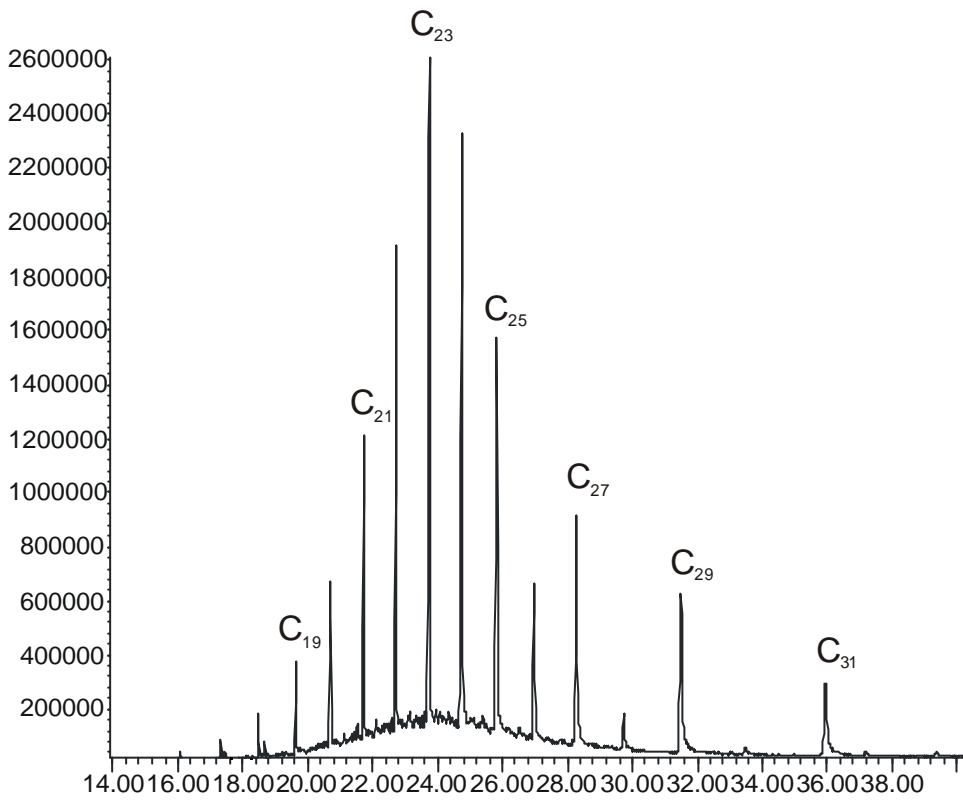


Fig. 2
Herzschuh



Herzschuh, Fig.3

Abundance



Time-->

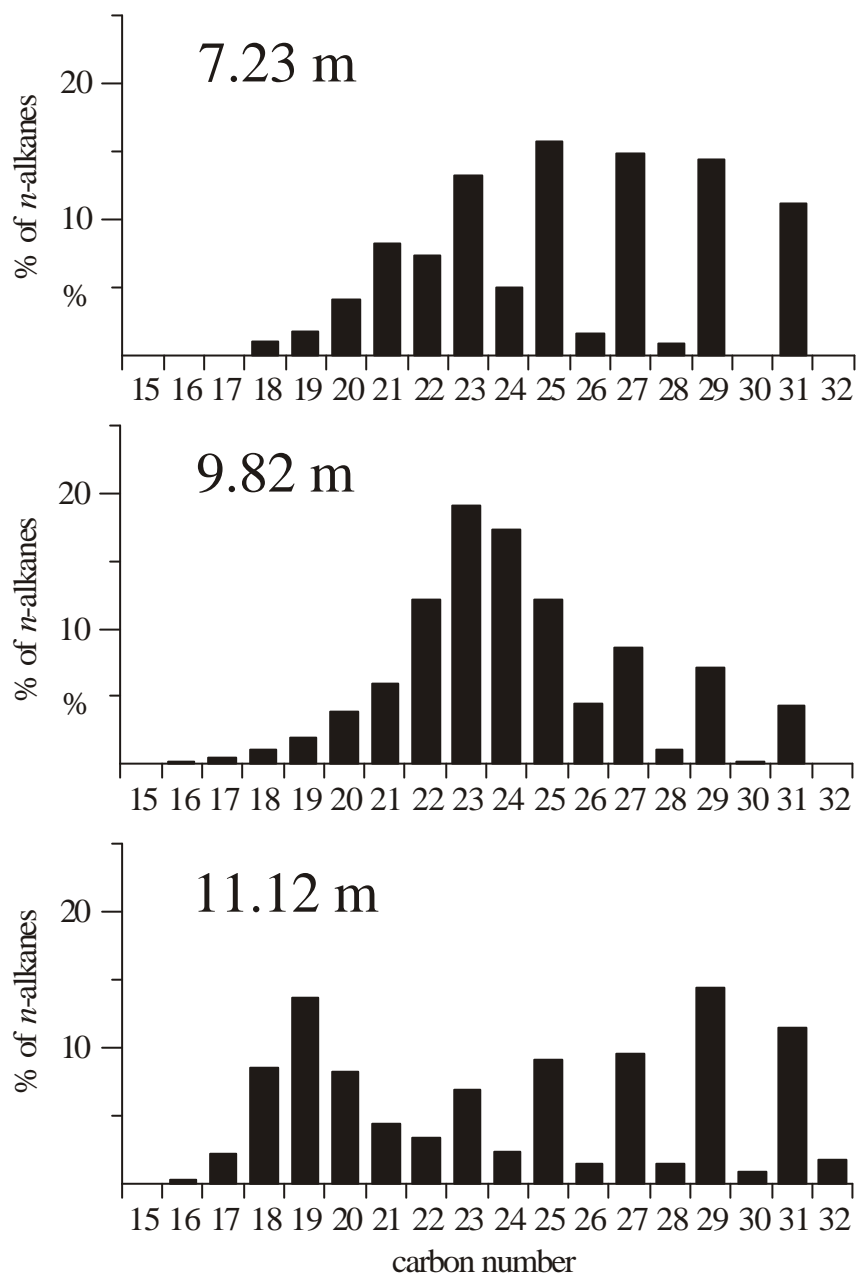


Fig.6
Herzschuh

