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A large Middle Pleistocene freshwater to oligohaline lake in the contemporary hyperarid Qaidam Basin (China)

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The Qaidam Basin (NW China) at the northern margin of the Tibetan Plateau is one of the driest places on Earth with mean annual precipitation not exceeding 25 mm in the western central part. Flat salt plains and wind-shaped hills characterise the bare ground over thousands of square kilometres. In contrast to present-day conditions, remnants of ancient shorelines in high positions identified by Chen and Bowler (1986) and Hövermann and Süßenberger (1986) about 20 years ago herald of a former large lake but were not investigated further till now.

Here we present the results of microfossil analysis and optically stimulated luminescence (OSL) as well as uranium-series (TIMS) dating of sediments from a thick sequence of predominantly lake deposits in the eastern central Qaidam Basin. Based on abundant ostracod (micro-crustacean) shells from this sequence, we infer that a large lake of several metres depth at least maintained primarily fresh to oligohaline conditions in the late Middle Pleistocene.

Introduction

The Qaidam Basin (Figure 1) is a large and almost flat region at the northeastern margin of the Tibetan Plateau, about 120,000 km² in size (Sun et al., 1995). High mountain ranges exceeding 5000 m above sea level (asl) border the basin in the south (Kunlun Shan) and north (Qilian Shan, Altun Shan). With an altitude between about 2700 and 3000 m asl, the mean annual temperature is about 4 °C (Wang, 1999). Due to its continental position and the shading effect of the surrounding mountain ranges, the Qaidam Basin is one of the driest places in the world with less than 25 mm precipitation in its western part and the highest precipitation variability in China comparable only to the largest desert of the country, the Taklimakan Sand Sea (Zhu, 1999a, 1999b).

However, a number of shallow salt lakes such as Dabusun Lake and Xiao Qaidam Lake persist in the basin owing to inflowing underground and surface waters from the snow and ice covered peaks in the surroundings of the basin (Figure 2). Large flat playa surfaces are overtopped by isolated hilly remnants of wind erosion known as Yardangs.

Figure 1 Position of the Qaidam Basin (broken line) and sites mentioned in the text: 1 Erling Lake and Zaling Lake in the Yellow River source area, 2 Zoige Basin, 3 Longyang Gorge, 4 Qinghai Lake. (Tibetan Plateau outlined by dotted line.)

Some evidence for the existence of larger lakes in the Qaidam Basin in the past comes from remnants of shoreline deposits. Chen and Bowler (1986) reported on shoreline deposits at about 2800 m asl whereas Hövermann and Süßenberger (1986) found beach bar sediments even at about 2950 m asl. The elevation data presented in these papers have to be viewed with caution due to the absence of GPS data 20 years ago. However, dating results are not available for these shoreline deposits. Chen and Bowler (1986) suggested an Early to Middle Pleistocene age based on Pliocene underlying strata whereas Hövermann and Süßenberger (1986) proposed a Late Pleistocene age for the shoreline deposits at about 2950 m asl in consideration of dated freshwater lake sediments from cores in the basin centre. These cores were drilled in the course of petroleum exploration activities in the Qaidam Basin exclusively. Accessible information from the investigation of cores and exposures concerning the environmental evolution of the basin in the Quaternary is relatively scarce and often lacking a sound age control as well as an appropriate sample resolution to trace the Quaternary climatic cycles (Wang et al., 1986; Tan and Di, 1991; Han et al., 1995; Sun et al., 1995; Wang et al., 1996; Yang et al., 1997; Tang et al., 1998; Wang et al., 1999; Jiang and Yang, 2001; Wang et al., 2002; Jing et al., 2004). Thus far, analysis of carbonate-shelled microfossils from the Qaidam Basin used presence-absence data mainly to provide a tool for the biostratigraphic correlation of cores and exposures from different sites. Palaeoenvironmental inferences through the quantitative investigation of aquatic microfossil species from sediment sequences sampled with a high resolution are still missing.

Figure 2 Metric Camera image (Spacelab 1, STS 9, date: 2 Dec 1983) showing the Qarhan playa region in the lowermost part of the Qaidam Basin, foothills of the Qilian Mountains in the north and the Kunlun Mountains in the south as well as the sampled escarpment (Quan Ji section).

Accordingly, one of the escarpments in the eastern central Qaidam Basin was already roughly sampled within the scope of early surveys of China's petroleum industry in the years 1958, 1961 and 1963 by one of the authors (Z.S.). About 40 years later, microfossils from 14 samples of these early surveys were re-examined and a surprisingly high diversity (about 30 species) of mostly freshwater ostracods (Crustacea: Ostracoda) was noticed. To improve the knowledge on the environmental history of the Qaidam Basin with emphasis on the evolution of lakes within the basin, we investigated the sediments of a prominent escarpment in the eastern central Qaidam Basin (Figure 2) which probably correspond to those already roughly sampled in the late 50s and early 60s of the last century.

Material and methods

About 250 samples were collected from the Quan Ji section (36.97°N, 96.26°E, 2734 m asl, Figure 2) and washed through 0.098 mm and 1 mm meshes for fossil analysis. Seven sediment samples were collected for OSL dating at the Philipps-Universität Marburg (Department of Geography, Anja M. Zander). Whereas a successful OSL application on quartz is limited to approximately 100,000 yr, depending on the environmental dose rate and the saturation behaviour, the infrared stimulated luminescence (IRSL) signal of feldspar usually saturates at higher doses and can hence be used to date much older deposits. However, the IRSL signal of feldspar is often

affected by anomalous fading (see e.g. Wintle, 1973; Aitken, 1985), which leads to underestimation of the burial age.

For this study, equivalent dose determination of sand size potassium feldspar and quartz were carried out on a standard Risø TL/OSL reader (Bøtter-Jensen et al., 2002) using the single aliquot regeneration (SAR) protocol (Wallinga et al., 2000; Murray and Wintle, 2000). A 200 s IR stimulation was applied to feldspars and IRSL detection used a blue transmitting filter pack (Schott BG39, Corning 7–59 and Schott GG 400) for the measurements. The dating approach on quartz using the SAR protocol with blue light stimulation and UV detection failed due to large scatter and saturation effects. Fading experiments were carried out on two feldspar samples over a period of 3 months. 41 days after irradiation, the samples lost 9 % – 6 % of their initial IRSL signal and 3 % – 0.5 % within the following 56 days.

Dose rates were determined by neutron activation analysis. Internal potassium contents of 9 ± 1 % and an alpha efficiency of 0.2 ± 0.02 was assumed (Mejdahl and Christiansen, 1994). The sampled sequence mainly comprises lacustrine sediments (see below) but with regard to the escarpment morphology and the present day conditions, a water content of 10 ± 5 % (15 ± 5 % for the lowermost sample) was adopted for age calculation.

Uranium-series measurements using the technique of thermal ionisation mass spectrometry (TIMS) were carried out on a sample of biogenic carbonate at the GEOMAR Research Center for Marine Geosciences Kiel using a Finnigan MAT 262 RPQ2+ mass spectrometer. The biogenic carbonate consisting of shells of gastropods, bivalves and ostracods as well as charophyte gyrogonites was collected from the upper third of the sequence between 10.5 m and 17.5

m below the section's top (Figure 3). For TIMS dating, the sample was divided into two aliquots of smaller and larger carbonate remains. Prior to analysis, the biogenic carbonate was ultrasonically cleaned and subsamples were checked for diagenetic alteration by SEM analysis.

Results and discussion

Age assignment

IRSL dating yielded ages between $110,000 \pm 17,000$ yr and $144,000 \pm 13,000$ yr for the six OSL samples from the upper 40 m of sediments and $176,000 \pm 17,000$ yr for the lowermost sample. The results obtained for the upper six samples all cover the same age range within standard deviation. Associated equivalent doses range from 318 ± 44 Gy to 437 ± 21 Gy and dose rates show a wide variation in the section. They vary from 2.3 ± 0.2 Gy 1000 yr^{-1} to 3.1 ± 0.2 Gy 1000 yr^{-1} . The highest equivalent dose was obtained for the lowermost sample from the fluvial sand.

Obtained IRSL ages for the feldspar fraction seem to imply a Late Pleistocene burial age sometime between Marine Isotope Stage (MIS) 5e and 5c for the upper 40 m of sediments but with regard to the fading rate of 0.5 – 3 %, these ages represent minimum ages and probably underestimate the true deposition time interval significantly.

Shells and charophyte gyrogonites for TIMS dating showed unaltered ultrastructures and were therefore regarded as suitable dat-

ing material. The two aliquots of the biogenic carbonate sample for TIMS dating yielded ages of $199,000 \pm 4,000$ yr and $216,592 \pm 4,500$ yr, confirming the assessment of the IRSL ages as minimum ages. The TIMS age estimates correspond to the presence of *Candona candida* shells, which are regarded to have appeared in the Qaidam Basin not earlier than $\sim 210,000$ yr BP (Yang et al., 1997). Thus, a late Middle Pleistocene age ($\sim$ MIS 7a) is very likely for the formation of the sampled sediment sequence. A chronological division of the section can not be implemented due to the obtainment of minimum ages by OSL dating.

Sediments and fossils

Sediments of the escarpment display almost horizontally bedded units of predominantly fine-grained silty deposits intercalated with aeolian and fluvial sands (Figure 3). The sediments are laterally continuous over the exposed distance of about 2 km. Most samples yielded large numbers of ostracod shells belonging to 31 species in total. The most diverse subfamily Candoninae comprises eight

Figure 3 Absolute abundance diagram of grouped ostracods (counts per 200 g sediment): (a) ostracods restricted to freshwater s.l. (salinity 0–5 ‰) and the profundal (deep) zone of lakes; (b) ostracods restricted to freshwater s.l. occurring in shallow waters or showing no depth preference (euryplastic); (c) ostracods occurring in a wide salinity range and shallow waters or without clear depth preference. The lithology comprises fine-grained silty sediments (black), well-sorted aeolian sands with tangential foresets (dark grey) and ripple-bedded fluvial or littoral sands (light grey). Grey arrows indicate position of sample for OSL dating and the black arrow with column shows the section of the sequence which has been used to obtain fossil shells for uranium-series measurements. Fish symbol at position of catfish-like skeleton embedded in fluvial sands.

Ostracod taxa: (a) *Cytherissa lacustris*, *Fabaeformiscandona caudata*, *Limnocytherina cf. sanctipatricii*; (b) *Candona weltneri*, *Cypris pubera*, *Eucypris dulcifrons*, *Eucypris afghanistanensis*, *Fabaeformiscandona hyalina*, *Herpetocypris chevreuxi*, *Ilyocypris bradyi*, *Ilyocypris decipiens*, *Paralimnocythere psammophila*, *Potamocypris cf. arcuata*, *Potamocypris smaragdina*, *Prionocypris ganssenensis*; (c) *Candona candida*, *Candona neglecta*, *Cyclocypris ovum*, *Cyprideis torosa*, *Cypridopsis vidua*, *Darwinula stvensoni*, *Eucypris mareotica*, *Fabaeformiscandona fabaeformis*, *Heterocypris salina*, *Limnocythere inopinata*, *Pseudocandona compressa*, *Sarscypridopsis aculeata*.

Ecological preference according to Hiller (1972), Hammer (1986), Neale (1988), and Meisch (2000, and refs therein).

species of the genera *Candona*, *Fabaeformiscandona* and *Pseudocandona*, which are commonly regarded as typical freshwater sensu lato (s.l., salinity range 0–5‰) and oligothermophilic or cold-stenothermal taxa (Meisch, 2001; and refs therein). Three species of *Ilyocypris* (*I. bradyi*, *I. decipiens*, *I. sebeiensis*), *Limnocythere inopinata*, *Leucocythere dorsotuberosa*, *Candona neglecta*, *Heterocypris salina*, and *Sarscypridopsis aculeata* are the most abundant species starting with the most abundant taxa. The species of *Ilyocypris* were not routinely differentiated under a low power binocular since a scanning electron microscope is necessary for a proper identification.

All of the 27 species with known salinity tolerance ranges (e.g., Hiller, 1972; Hammer, 1986; Neale, 1988; Meisch, 2000) can thrive in freshwater s.l. whereas only 12 of these taxa can occur at higher salinities too. Accordingly, the majority of shells from ostracods with known salinity tolerance ranges belong to freshwater s.l. species (Figure 3). Furthermore, only three species from the section (*Cyprideis torosa*, *Eucypris mareotica* [a senior synonym of the more widely used *E. inflata*], *Heterocypris salina*) can tolerate the hyperhaline conditions (salinity > 40‰) of the present-day salt lakes in the Qaidam Basin.

Whereas most of the ostracod taxa are known from freshwater s.l. habitats of relatively shallow depth only, species such as *Cytherissa lacustris* (Figure 4), *Fabaeformiscandona caudata* and *Limnocytherina sanctipatricii* are restricted to the profundal zone of deeper lakes and dilute waters (Danielopol et al., 1993; Meisch, 2000). Although usually exhibiting low population densities, the occasional presence of these species clearly hints at lake periods of greater depth (Figure 3a). In addition to microfossils, a catfish-like skeleton (*Siluridae*, identification T. Klose, Humboldt-Universität Berlin) embedded in sands of fluvial origin points towards a perennial water body as well.

Thus, the ostracods from the section indicate the existence of a large freshwater lake of several metres depth at least in the Qaidam Basin. Periods of greater depths probably in the range of several decametres can be inferred too. Using the elevation of the shoreline deposits at 2800 m (i.e. 65 m above the section) identified by Chen and Bowler (1986) as a very tentative assumption to infer the former lake extent, an area of about 60,000 km² or the size of Lake Huron (USA), the fourth largest lake of the world arises. The shoreline deposits at about 2950 m mentioned by Hövermann and Süssenberger (1986) probably do not correspond to the sediments of the Quan Ji section due to their much higher position 215 m above the sampled exposure. However, unless an age determination and detailed geomorphological work has been done, a correlation of shoreline deposits with our lake sediment sequence can not be performed.

Assuming a correct age assignment of the section to MIS 7, possibly MIS 7a, the sediments of the former freshwater lake were accumulated during a period of high sea levels and interglacial conditions (e.g., Imbrie et al., 1984; Karner et al., 2002; EPICA, 2004). The strength of the Southeast Asian and Indian Monsoons was probably at maximum during the late MIS 7 (Liu et al., 1988; Clemens and Prell, 1991; Bloemendal et al., 1995). However, the climatic conditions or other hydrologic characteristics within the catchment

Figure 4 Scanning electron micrograph of *Cytherissa lacustris*, a typical freshwater inhabitant of the profundal zone of a lake (left shell, external view, length 758 μm).

area of the Qaidam Basin must have been very different from the present-day interglacial conditions which are by no means favourable for the establishment of a larger lake in the basin. On the contrary, massive sequences of halite were accumulated

since about 30,000 yr in the centre of the Qaidam Basin, most probably formed in shallow salt lakes and playa environments (Sun et al., 1995; Wang et al., 1996; Wang et al., 2003). It may be speculated that larger areas in the south of the Qaidam Basin may have contributed to the basin's water budget which are drained by the Yellow River at present. Possibly, the Yellow River source area around the large Erling and Zaling Lakes (= Gyaring and Ngoring Lakes in some maps, Figure 1) or even the Zoige Basin (= Rouergai Basin) belonged to the catchment area of the Qaidam Basin. Li (1991) reported that the Longyang Gorge (Figure 1) south of the Qinghai Lake was not cut by the Yellow River before the end of MIS 6 and that the present-day Yellow River source area was captured by the river only in the Holocene. Large hydrological changes had occurred on the Tibetan Plateau as a response to the uplift and glaciation history and may have had a large impact on the environmental evolution of the Qaidam Basin too.

On the other hand, climatic conditions may have been significantly different from the present-day conditions and may have caused the formation of a large freshwater lake in the Qaidam Basin. According to Jiang and Yang (2001), the climatic conditions of the Qaidam Basin were generally more humid between 500,000 and 130,000 yr in comparison to the period afterwards.

Our inference of a large freshwater lake in the Qaidam Basin may possibly reactivate the controversy of the existence of an ice sheet in the Yellow River source area in the Middle or Late Pleistocene. Already in 1908, Tafel (1908; cited by Trinkler, 1930) proposed that the Yellow River source area has been covered by a large local ice sheet. Further proponents of an ice sheet which would have been a source of large meltwater amounts flowing to the Qaidam Basin discussed the timing of the ice-sheet formation (Hövermann, 1987; Li et al., 1991). Estimations of the area which has been covered vary between 50,000 and 70,000 km². Contradicting, Zheng and Rutter (1998) stated that there has been no large local ice sheet in the upper reaches of the Yellow River.

To conclude, large abundances of ostracod shells from laterally wide-spread sediments suggest that a large lake has existed in the Qaidam Basin corresponding to earlier inferences based on shoreline relicts. TMS-uranium series measurements and supporting OSL minimum ages allow an age assignment of the large lake to the MIS 7a in the late Middle Pleistocene for the first time. Furthermore, freshwater to oligohaline conditions can be inferred from fossil ostracod assemblages and salinity tolerance ranges of modern species. These are in clear contrast to the massive halite formation which predominates in the central Qaidam Basin since the MIS 2. Based on our study and available literature, we can not conclude whether much elevated precipitation levels and/or a large meltwater supply from surrounding mountain ranges or even a large local ice sheet led to the formation of the large freshwater lake. Thus, the differences between the interglacial climatic conditions which gave rise to the establishment of the large lake and the present-day conditions remain unclear and should be addressed in further studies. In addition, the role of the Late Quaternary tectonic uplift of the surrounding mountain ranges which affects the degree of shading from incoming moisture and the degree of water storage as snow and ice has to be investigated in the future.

Acknowledgements

We are indebted to an anonymous referee for helpful comments. Funding was provided by the Deutsche Forschungsgemeinschaft (DFG) and the Deutscher Akademischer Austauschdienst (DAAD).

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Hutchison 'Young Scientist' Fund

William Watt Hutchison, "Hutch" to his many friends around the world, was a Scots-born Canadian geologist who served Canada and the IUGS in myriad dynamic and creative ways. Most notably, he served as the IUGS Secretary General (1976-1980) at a pivotal time in its history, and as IUGS President (1984-1987). The same boundless energy, enthusiasm, skill in communications, and ability to foster teamwork that characterized his work with the IUGS also carried him to preeminent scientific administrative positions in the Canadian Government, where he served as Director General of the Geological Survey of Canada and as Assistant Deputy Minister of Earth Sciences. His distinguished career was terminated in 1987 by his untimely death at the age of 52, following a painful struggle with cancer.

One of Hutch's last wishes was to establish under IUGS auspices a memorial foundation intended to promote the professional growth of deserving, meritorious young scientists from around the world by supporting their participation in important IUGS-sponsored conferences. The first 3 beneficiaries of the **Hutchison "Young Scientist" Foundation** attended the 28th International Geological Congress (IGC) in Washington, D.C., in 1989.

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