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Geological fingerprints of climate history: a cooperative study of Qinghai Lake, China

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ABSTRACT

In 1985 an EAWAG/ETH limnogeological expedition to China's largest inland lake recovered seismic profiles and piston cores to help calibrate paleoclimate models of monsoon and insolation fluctuations over the northern Tibetan Plateau since the last Glacial maximum.

Qinghai Lake is a closed-drainage lake located at 3,194 m above sea level in an active tectonic basin near the north-west corner of the Tibet-Qinghai Plateau in Central China. It covers 4,635 km^2, up to 27 m deep with a brackish bitter magnesium-sulfate-rich, saline (14 g/l TDS), alkaline brine.

Seismic profiles revealed a complex topography with channels, irregular bedding, tectonic-tilting and desiccation features buried under a uniform 5 m of nearly parellel-bedded Holocene sediment.

Piston cores recovered a record of over 13,000 years with sedimentation rates from 0.25 to 1.0 mm/yr. Calcium carbonate content proved a sensitive monitor of lacustrine subenvironments and ranges from 20–85%. Radiocarbon dates by accelerator mass spectrometry provided a chronological framework.

Preliminary results suggest that sedimentation patterns respond with higher resolution to climate change than vegetation. There are several abrupt steps, but no evidence of overflow during Holocene. We interpret lowest levels in Qinghai during the early Holocene interval which corresponded to times of intensified monsoon activity in Africa.

ZUSAMMENFASSUNG

Wir berichten über die vorläufigen Ergebnisse einer limnogeologischen Expedition der EAWAG/ETH zum grössten See ohne Abfluss in China. Seismische Aufnahmen und Kolbenlotkerne haben neue Anhaltspunkte für die Kalibrierung von paläoklimatologischen und Monsunmodellen über Tibet für das Spätglazial und das Holozän gegeben.

Der Qinghai See ist ein hydrologisch geschlossenes System auf 3194 m.ü.M. in der nordöstlichen Ecke eines tektonisch aktiven Beckens des Qinghai-Tibet Plateaus. Er ist 4635 km^2 gross und 27 m tief. Das Seewasser ist mesosalin (14 g/l Salz) und alkalisch, reich an Magnesium und Sulfat.

Hochauflösende (3,5 kHz) seismische Profile zeigen eine komplexe Beckenmorphologie mit unregelmässigen Rinnen, tektonische Schrägstellungen und Austrocknungserscheinungen unter etwa 5 m parallelgeschichteten holozänen Seesedimenten. Kernprofile zeigen eine etwa 13 500-jährige Geschichte mit Sedimentakkumulationsraten zwischen 0,25 bis 1,0 mm/J. Drei hauptlithologische Einheiten werden anhand eines Typusprofils definiert: A) Bis etwa 11 000 J. vor heute sind lössartige Lehme in einem salinen Sumpf abgelagert. Nach einer Süsswasserperiode mit

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klastischen Laminationen (10 900 bis 10 000 J. vor heute), folgt ein abrupter Übergang, markiert durch Dolomit als Zeichen eines sehr niedrigen Seespiegels. B) Das Frühholozän wird durch niedrige, wechselnde Seespiegel, mit rötlichen, karbonat-reichen Sedimenten gekennzeichnet. C) Seit etwa 6000 J. vor heute wurden aragonitische Sedimente, ähnlich der heutigen, mit deutlich zyklischen Tendenzen, abgelagert.

Das Sedimentationsbild zeigt eine Abfolge von mehreren abrupten Schritten und rhythmischen Schichtungen, die geochemisch-sedimentologisch sehr schnell auf Klimaänderungen reagiert, mit höherer Auflösung als die allgemeine Vegetationsgeschichte. Der Qinghai See blieb offenbar während des ganzen Holozäns ein geschlossenes System. Es scheint, dass die Seespiegel in Qinghai im frühen Holozän am tiefsten waren, während Afrika eine Zeit mit verstärktem Monsoon erlebte.

1. Introduction

We are entering into a new era of environmental research where it is increasingly important to evaluate geological archives in terms of their relevance to the understanding of global changes on scales of decades to centuries. The aim of this paper is to report the preliminary results of a limno-geological study of the unusual and sensitive paleoenvironment of Lake Qinghai, China. The study is part of an international effort to understand how uniform global warming might result in abrupt environmental responses through a series of environmental feedbacks. The present paper is the first of a series, and provides a general framework for Qinghai Lake. Studies in progress (eg. Yu & Lister) will focus more on the higher resolution variability and geochemical stratigraphy.

Lake sediments are one of the high resolution archives that can be used to test various scenarios of climate change on a regional scale. Nature has already carried out many short term experiments. Whereas ice cores store direct atmospheric compositions, lake deposits help us understand feedback responses on a regional scale. In lake sequences, we can look closer at the resulting transitional zones in order to determine the magnitudes and rates of change that are possible in the natural environment. Precision dating and correlations are required to determine the synchroneity of events.

Lithology and sedimentation rates also change in response to environmental shifts. How do we reconstruct past climate? Pollen has been one traditional tool. We now also have a plethora of sedimentologic and geochemical tools which can add higher resolution information. In order to correctly interpret the proxy climatic signal held in lake sequences, it is imperative to understand how environmental signals are stored in lake sediments. Which signals carry what information? How can integration of numerous signals provide a clearer environmental picture or better models? Models generally aim to simulate stable periods; whereas core archives allow us to focus on transitional contacts that represent rare events and dynamic response. Integration of the two is time consuming. Models may produce a global simulation after only hours of supercomputer time. In contrast, a field program and subsequent detailed lab work on cores necessary to test only one grid point consumes several dozen man-years.

2. Expedition of 1985

In late summer 1985, a 3-year cooperative limnogeology project between the Geology Section EAWAG, the Geological Institute ETH-Zürich and the Salt Lake Research Inst., Academia Sinica, Xining, China commenced with a 6-week expedition to

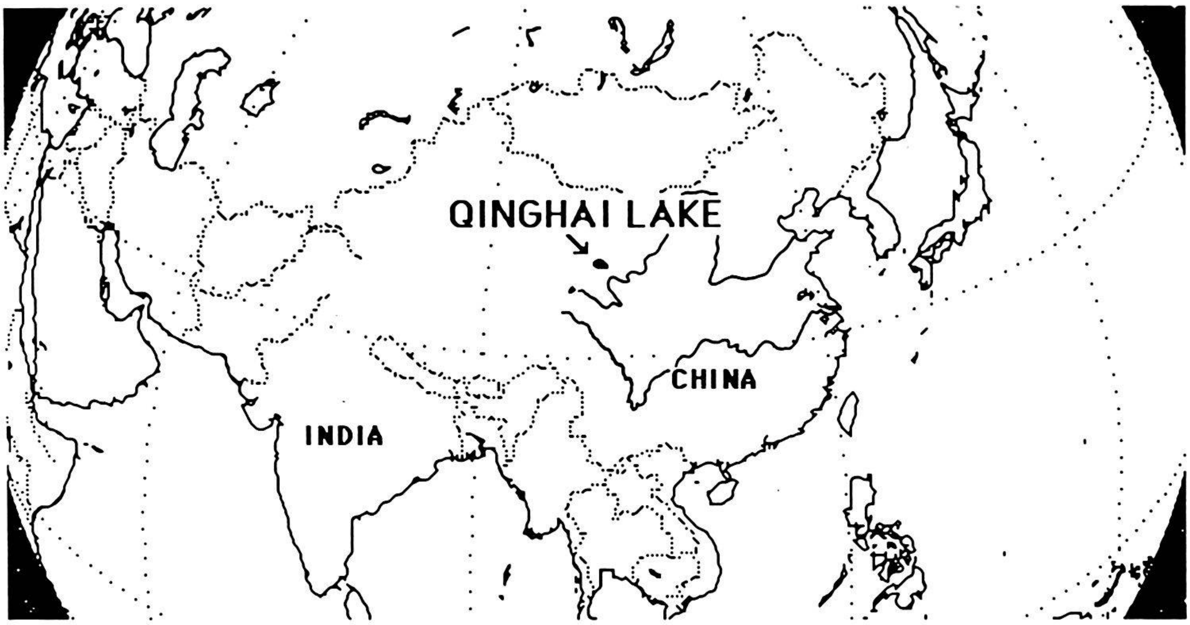


Fig. 1. Location of Qinghai Lake.

Table 1: Physiographic summary of Qinghai Lake and basin. (Mainly based on the years 1960–61 after the report Academia Sinica, 1979 [2] with modifications from our own 1985 observations marked with *)

Location	99°36′ to 110°47′E / 36°32′ to 37°15′N
Elevation*	3,196 m
Max. Length	106 km
Max. Width	63 km
Perimeter	306 km
Lake Area	4,635 km^2
Catchment Area	34,950 km^2
Ratio Catchment/Lake	7.5
Max. Depth*	27 m
Average Depth*	ca. 17.5 m
Volume of Lake	85.45×10^9 m^3
Total dissolved solids*	14.15 g/l (Hypolimnion summer around 6 °C; surface frozen Dec.–May)
Annual runoff-input:	
surface	1.6×10^9 m^3
groundwater	0.6×10^9 m^3 (est)
Annual Precipitation	
north shore	377 mm
south shore	395 mm
Average annual temp.	0.9 to 2.7°
Ann. Evaporation	
north shore	1,433 mm
south shore	1,487 mm
Atm. pressure (annual avg.)	690 mm Hg
Modal wind directions	dominant from W and NW
Average annual sunshine	3,640 hrs (70–80%)

Qinghai Lake (Fig. 1 and Table 1). Approximately 500 kg of ETH limnogeology equipment accompanied us on a 46 hour train journey from Beijing to Qinghai.

More than the initial reconnaissance goals were attained. The Salt Lake Research Institute provided a 90-ton research ship for 22 persons on a 10-day coring cruise as well as a smaller cruiser for seismic surveying. More than 300 km of high-resolution 3.5 kHz seismic profiles (Fig. 2) showed three separate basinal areas with evidence for several high and low lake level stands in the uppermost 30 meters of sediment (Fig. 3). We used the seismic results to select 17 coring sites for our gravity core system (1 meter samples) and another three sites for sets of 6–8 meter piston cores (Kelts et al. 1986).

3. Significance of Qinghai Lake

The Plateau of Tibet-Qinghai is one of the most important continental regions controlling global climate. A stable low pressure center caused by summer heating influences the vital motions of monsoonal winds. Continuous records are lacking for the entire Qinghai region which show how the present climatic patterns fluctuated on decadal to century scales during the Late Quaternary. Some global circulation models predict decreased monsoon activity during the glacial maximum, partly due to lowered sea levels and increased albedo in Tibet. Kutzbach & Street-Perrot (1985), for example show evidence for increased monsoon activity in N-Africa during the insolation maximum around 9000 years B.P.

Chinese authorities are gravely concerned about the rapidly decreasing water levels (2 m in 15 yrs) and increasing salinity of Qinghai Lake. Major fisheries and economic development are at stake. Cores help evaluate the long term trends.

There are several reasons why Qinghai Lake provides ideal conditions for a paleoenvironmental analysis:

- A major study of the lake was made by the Chinese in 1960–62. This comprehensive geological, limnological, and zoological monograph provides a comparative framework (Lanzhou Inst. 1979).
- The presence of an endemic fauna suggests that the lake has been isolated for thousands of years.
- Carbonates occur as a variety of precipitates and benthic ostracods are abundant. The samples thus can be analysed isotopically for palaeo-hydrology, -temperature, and -productivity.
- In spite of the remoteness, the lake has excellent harbour, ship and barge facilities.
- The lake is located within the convergence zone of two climatic belts, and should sensitively register subtle interactions which are not continuously recorded in neighbouring, more arid regions.

4. Qinghai basin and Lake

Qinghai (Amdo in Tibetan) is one of China's largest provinces with 720,000 km^2, but sparsely populated. It comprises broad, sediment filled basins, between narrow mountain ranges. It is tectonically active with abundant evidence of major strike-slip faulting, block-tilting, recent folding and rapid uplift (Molnar et al. 1987). Qinghai

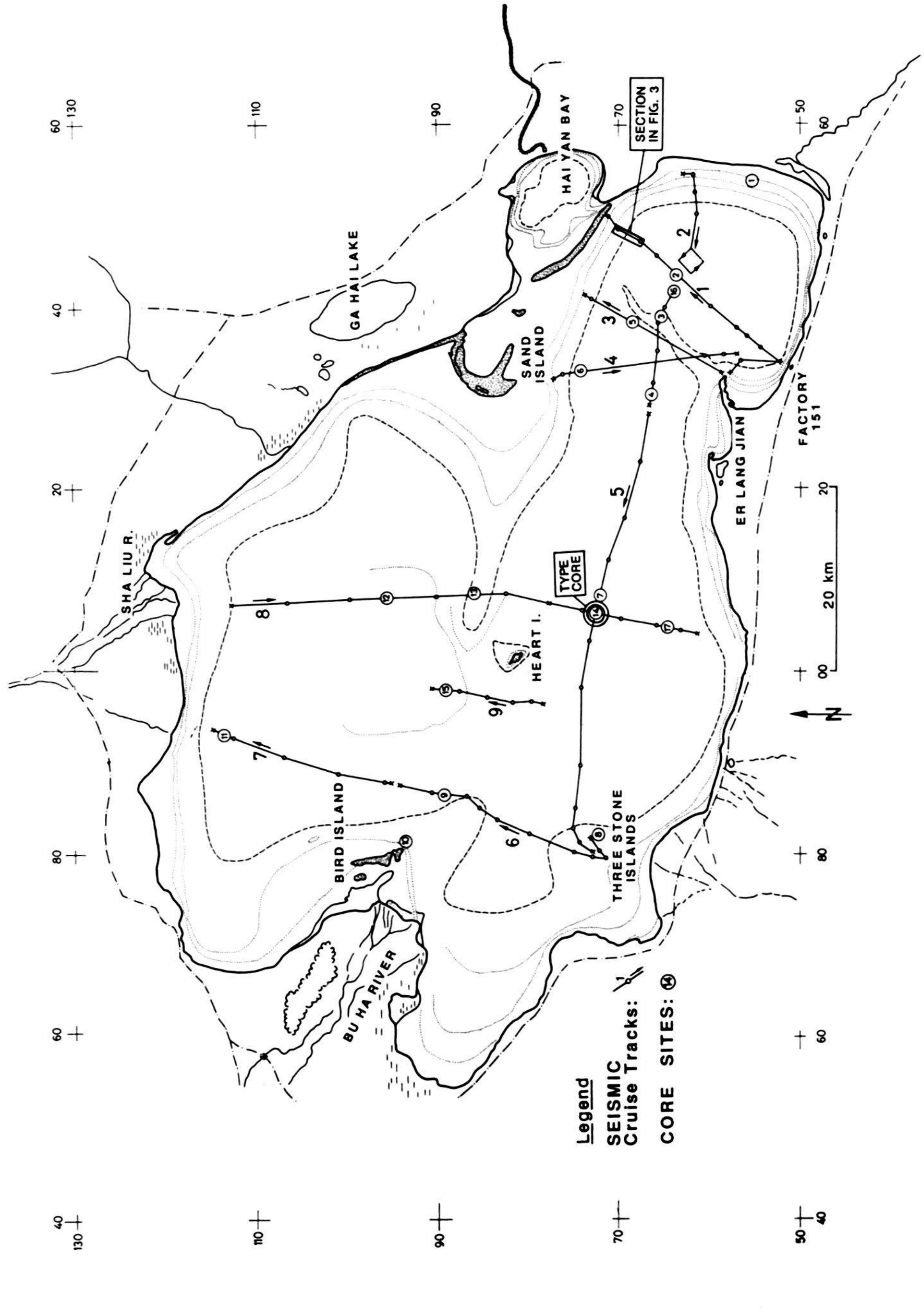


Fig. 2. Qinghai Lake bathymetry with cruise tracks for seismic lines and coring sites of the 1985 Sino-Swiss limnogeological expedition.

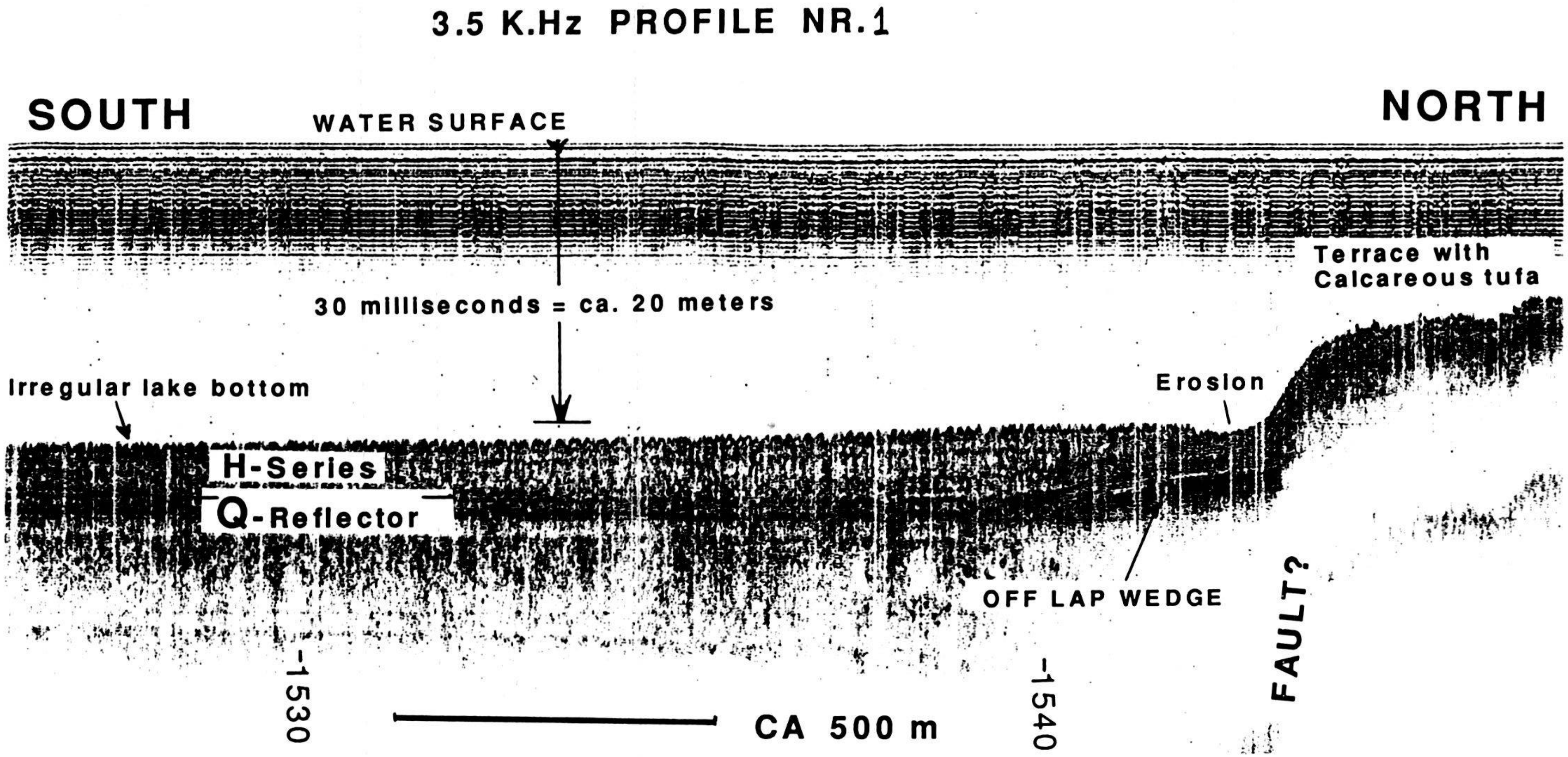


Fig. 3. Seismic profile Nr. 2 across site 14b showing the Q-reflector at 5 m depth, and recently- tilted, offlapping beds below.

Lake lies in one intermontane basin at the northeastern corner of the Tibet-Qinghai plateau, about 1,800 km inland from Beijing (Fig. 1). Geomorphologic fault scarps are prominent features, along with large alluvial fans and sand dunes along the NE margin.

Most of the region has an alpine, continental climate with intense sunshine and a short frost-free season. Temperatures can vary 40 °C between day and night. The drainage basins are treeless and arid with 100 to 550 mm annual precipitation (TANG & SHEN 1981). The Qaidem Basin (2,899 m a.S.L.) to the south, is a large, (200,000 km^2), extreme playa desert with a vast, windswept salt crust (CHEN & BOWLER 1986) and includes rich potassium chloride brines in Dabuxin Lake. The capital, Xining City (2,244 m a.S.L.) has about 400 mm precipitation per year, 2,600 mm evaporation and extended hours of sunshine with a low-humidity continental climate.

The Qinghai Lake (Blue Sea) is also called Koko Nor (Mongolian) and "bright pearl." It sits at 3,194 m elevation, surrounded by statley snow-capped mountains up to 5,000 m a.S.L. The current lake covers about 4,635 km^2. We measured a maximum water depth of 27 meters. Most of the lake is more than 16 m deep, with only a thin littoral rim. The water is brackish mesosaline (14.1 g/l TDS), alkaline (pH = 9.3) and undrinkably rich in magnesium and sulfate (see Table 2). Sodium and chloride are dominant ions (Na-Mg-CI-SO_4 type brine). Summer epilimnion temperatures reach 12–15 °C (rarely to 19 °C) with a hypolimnion of less than 6 °C. The lake has meter-thick ice cover for up to 5 months and is thus dimictic with brief stratification in high summer and in winter (under the ice). Strong winds from NW are common. The total dissolved solids have increased irregularly from 11 g/l measured in the 1920's (GRABAU 1924) to the current 14.1 g/l.

The following briefly summarizes the limnological findings of the Academia Sinica study of 1960–1962 (LANZHOU INST. 1979 and after MELACK 1983 and HAMMER 1986):

Table 2: Water Chemistry of Qinghai Lake.
(After Academia Sinica, 1979 [2] for 1961, and Chen KeZao and Tang, per. comm. 1986)

	1986 (July)		1961	
pH	9.21		9.1–9.4	
Total dissolved solids	14,150	mg/l	12,489	mg/l
Na	3,750	mg/l	3,258	mg/l
K	157	mg/l	146	mg/l
Ca	13	mg/l	9.9	mg/l
Mg	798	mg/l	821	mg/l
Mg/Ca	798/13	mg/l	821/9.9	mg/l
CO_3^-	518	mg/l	419	mg/l
HCO_3^-	689	mg/l	525	mg/l
SO_4^{--}	2,380	mg/l	2,034	mg/l
CI^-	5,847	mg/l	5,274	mg/l
Br^-	2.7	mg/l		
Li	4.65	mg/l	3.7	mg/l
SiO_2			0.35	mg/l
HBO_3^-			12.8	mg/l
Sr^{++}			0.37	mg/l
PO_4^{--}			0.02	mg/l
NO_3^-N			0.036	mg/l

Transparency ranges from 1 to more than 10 m. The lake contained 35 phytoplankton genera (15 Bacillariophyta, 4 Chlorophyta, 4 Pyrrophyta, 6 Cyanophyta, 2 Chrysophyta, and 1 Euglenophyta). Pelagic diatoms (*Cyclotella* dominant) accounted for 32–89%, mainly in summer, followed by dinoflagellates 3.5–50%, dominant in winter.

Protozoans form 80% of the zooplankton in fall with *Strombidium, Strobilidium, Arcella, Difflugia, Didinium* and *Vorticella* in concentrations of 420/liter. Rotifers include *Pedalia, Brachionus, Colurella (dom), Mytilina* and *Notholca*. Cladocera include *Moina, Daphina* and *Chydorus*.

Macrophytes include abundant sessile *Cladophora fracta* colonies with *Rhizoclonium* which together form long green patches 0.5 m thick, 1 m wide and 100 m long. Biomass reaches more than 50 g/m^2 wet weight. Algae have profound effects on the bottom morphology and sediment trapping. Chara are rare whereas *Potamogeton pectinatus* forms minor fringing swamps.

Gelatinous, mucilaginous and filamentous microbial mats are common along the rocky shores of Qinghai Lake. These are probably responsible for the thin aragonite crusts on most beach pebbles.

Nematodes are reported from Qinghai as are the Oligochaetes *Nais sp., Paranais sp.*, and *Limnodrilus helveticus* estimated as 1.68% of the biomass. Shells of gastropods, bivalves or other bioclastics are notably lacking from the modern shorelines although reports include some gastropoda: *Radix ovata, R. lagotis, Glabe pervia, Gryaulus groleri* and Choanophalus sp. [2].

Ostracods are the most important component of the benthic community with over 12 species that include several endemic varieties (eg. *Qinghaicypris crassa, Potamocypris reticulata, Zonocypris oliviformis*). Qinghai Lake has dense populations in the bottom waters with up to 15 individuals/liter. Cm-thick sediment layers comprising mainly ostracod shells are common in cores and probably result from gentle winnowing of bottom sediments.

Chironomid insecta are very cosmopolitan. Seven species of Tendipes (Chironomus) occur in Qinghai. *C. gr. reductus* is most common (70%) with *Psectrocladius, Procladius, Psilotanypus, Cryptochironomus, Heptagia* and *Cricotopus gr. silvetris*. In terms of biomass, chironomids also form a significant part of the benthos.

Fish are abundant but dominated by a single, bone-rich, naked-carp *(Gymnocypris grzewalski)* which is endemic in the system and forms the basis of commercial fisheries. In addition there are minor quantities of three types of loaches *(Nemachilus sclaropterus, N. alticeps* and *N. dorsonatalus)*. The islands provide welcome roosts and protected breeding grounds for Cormoran and a wide variety of fowl migrating long distances in Asia. Overall, total productivity of the Qinghai Lake waters seems low, in concert with low nutrient concentrations and a short growth season (Melack 1983).

5. Preliminary results

Seismic investigation

We used the ETH-Geology 3.5 kHz ORE seismic profiler with an EPC 1,600 digital recorder. Sound pulses were transmitted at one second intervals with ship speeds of about 10 km/hr. The profiles display high resolution (ca. 15 cm) and penetration up to about 30 m. The lake bottom has a broad, flat, basinal morphology with a narrow, abrupt littoral zone (Fig. 2 and Table 3). In some basinal areas, rills and mounds about 50 cm high, and on the order of 20–50 m by 100 m, occur aligned E-W with the dominant wind directions. Wave cut benches were found at about 4 m depth.

Profiles show the lake divided into three main basins (N-, S-, & E-basins) by ridges uniformly at about 16 m water depth, which are capped with calcareous tufa (Fig. 2). The Er Lang Jiang Peninsula extends NE underwater as one typical, strongly asymmetric ridge with a sharp cliff to the west. Cliffs also occur along the E-W ridge that extends from the Buhar river mouth along the northern edge of the East Basin. These cliffs are thought to represent fault scarps because they can be linked with geomorphological expressions of active tectonics along the foothills.

Profile 1 (Fig. 3) provides a N-S cross-section of the East Basin that displays seismic stratigraphic features typical of the lake. The uppermost 6–10 milliseconds (4–6 meters) comprises generally parallel, closely-spaced reflectors. On close inspection some of these pinch and swell, but in general, the series (H-Series) seems to represent dominantly pelagic deposition in a perennial lake. A strong, planar reflector (we call the Q-reflector) defines the base of the H-Series. This widespread boundary appears to correlate with an unconformable layer of hard mud which stopped piston core penetration, and which represents a period of very low lake levels. It is possible evidence of a playa or desiccation horizon that was swept planar by high winds. These winds may also have driven the large sand dunes along the northeast edge, cutting off Hai Yan Bay.

Beneath the Q-reflector, echoes are more diffuse. Irregular steps in two horizons suggest the presence of some channeling, possibly in an ancient soil or tundra cover. Although echoes are weak, there are also some intervening layers with parallel reflectors that may derive from older lacustrine deposits.

Our seismic profiles provide important documentation of neotectonic tilting of the basin, and a tool for eventual dating of the most recent movements. Beds dip progressively towards the fault scarp along the northern basin boundary. The scarp ridge displays evidence of current erosion along its base. Progradation of the lake depo-center towards the north clearly shows that the main movements predate the formation of the Q-reflector. Due to the low angle unconformity, a complete sedimentary section below the Q-reflector can only be expected along the main central scarp.

Table 3: Depositional subenvironments of calcareous chemical and biochemical deposits in Qinghai Lake Basin; a hydrologically-closed, mesosaline, perennial lake

Supralittoral:	
	Relict beach ridges with aragonite coated cobbles and pebbles. Rare calcareous shell debris.
Intralittoral:	
	Beach-rock: aragonite cemented sands to gravels. Beds dip gently from shorelines beneath the lake. Recent origins as shown by cemented anthropogenic relicts.
	Calcareous silts and muds with crust fragments and ostracodes. In some restricted lagoons evidence for recent dolomite, hydromagnesite and magnesite.
Eulittoral:	
	Laminated or bioturbated muds. Rare tufa.
Pelagic plain:	
	Laminated aragonite muds with abundant calcitic ostracode shells. Massive aragonite tufa crusts along ridges.

Piston cores

We chose Site 14 (Fig. 2) as an initial type locality because this site displays characteristic seismic features correlative over long distances. Triplicate sets of piston cores up to 5.5 m long were taken in plastic core liners, cut into 1 m sections and sealed for

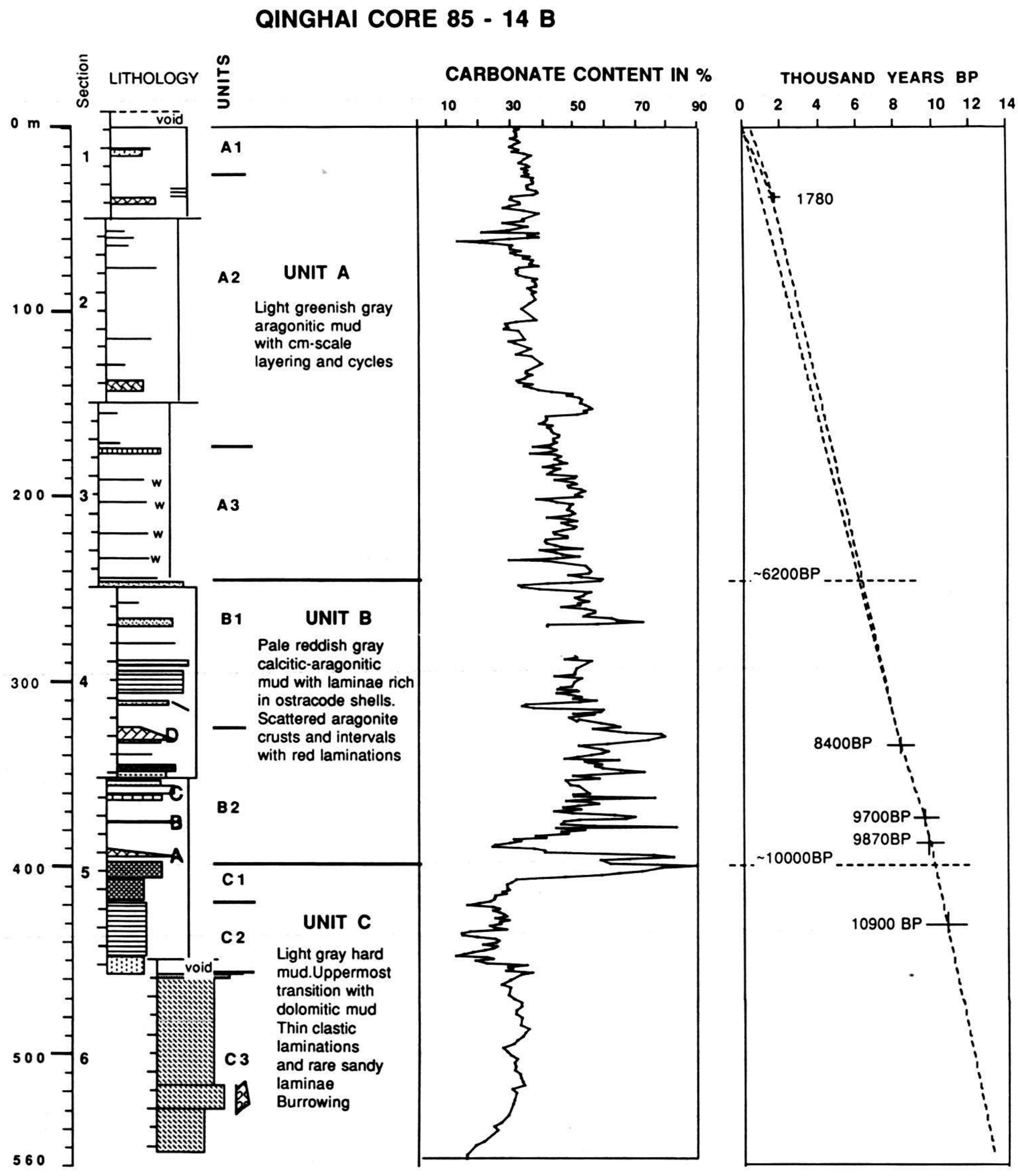


Fig. 4. Type-core Nr. QH-14b with combined logs for lithostratigraphy, calcium carbonate contents and radiocarbon chronology from accelerator mass spectrometry. White layers of aragonite (w). A–D, are aragonitic crusts in subunit B1.

transport. After whole core measurements of magnetic properties, the core sections were cut, photographed and described. Coulometer analyses of calcium carbonate provided one of the most rapid and sensitive records of the environmental state of a lake. Therefore, a continuous strip was subdivided into 1 cm samples for a high resolution carbonate profile (Fig. 4). Other samples were selected for stable isotope, mineralogical and dating analyses. Detailed pollen, biota, mineral and geochemical analyses are underway in China.

A precise dating framework is the key to a reliable paleoclimate reconstruction. Sediment samples of 2 to 20 g were selected and sieved at 63 microns after gentle disaggragation. Fresh-looking seeds (mostly of the aquatic plant Ruppia) or algal threads were hand-picked under a binocular microscope and cleaned. Graphitization in HTP capsules followed the procedures of LISTER et al. (1984). The paucity of well-defined organic matter provided only 5 samples to date. Samples were mounted on copper targets and measured at the Accelerator Mass Spectrometry facility at the ETH Institute Middelenergy Physics. Results are given in Fig. 4 and Table 4.

Table 4: Results from AMS radiocarbon dating from core QH85-14b. (ETH-AMS Facility)

Section/cm	Sample depth interval cm	mean depth cm	Material	Age years B.P.
1. 1/47.5-49	47.5-49	48.3	Algal	1,780 ± 23.2
2. 4/81.5-83	339.5-341	340.3	Seeds	8,400 ± 130
3. 5/21-22.5	382-383.5	382.7	Seeds	9,730 ± 130
4. 5/26-34	387-395	395	Seeds	9,870 ± 170
5. 5/77-79	438-440	439	Seeds	10,900 ± 250

Lead-210 was analysed at EAWAG from short cores representative of each basin in order to determine sedimentation rates for the last 200 years (YU et al. 1987). The results varied from 0.3 mm/y (0.022 g/cm^2/y) in the North Basin to about 0.6 mm/y (0.033 g/cm^2/y) at the type locality in the South Basin and a somewhat higher 1.09 mm/y (0.062 g/cm^2/y) in the East Basin where high winds pile up waters and cause return flow.

Three main sedimentary units, (A, B & C) are distinguished in core 14 (see Fig. 4 and Plate 1):

Unit C: (S. 6/103 cm to S. 5/43 cm; 396 to 553 cm) (more than 13,000 to 10,000 years B.P.) is characterized by the general medium gray color, firm consistency and overall lack of laminations, although 3 subunits are distinct.

Basal subunit (C3) of hard, gray, homogenous mud with 30% carbonate contents. Iron sulfide pigment and pyrite occurs below S. 6/60 cm as burrow fills and splotches. Most of unit C3 is bioturbated. At S. 6/9 cm (450 cm), a thin, coarse gray sand lag infills a burrow, suggesting that this is an erosion contact. The age assignment for this subunit remains uncertain.

C3 is interpreted as an arid, cold-period, with loess-derived sediment deposited in a shallow swampy, fresh to mesosaline environment.

Subunit C2 is 40 cm thick (S. 5/104 cm to S. 5/65 cm), characterized by clastic laminations. Coarser grained fractions include bits of carbonate crust, and ostracods, but comprise mostly silico-clastics. There is considerable variability among the types of laminations, with some levels showing incipient burrowing. Carbonate values are highly variable, but below 25% and only about 10% in coarser sand laminae.

C2 is interpreted by seasonal input of melt- or freshwater during a wetter episode from about 12,000 to 10,500 years. Lake salinities were low.

Subunit C1 is a mottled, grayish to white, 20 cm transition zone, that progresses across two bands from less than 30% to 85% carbonate (Fig. 4), and from mainly calcite-aragonite to almost pure dolomite (GAO, in prep).

C1 must represent the drawdown and concentration of a large water body, without overprint from clastic inflow. Dolomite may have formed on a broad carbonate playa apron.

Unit B: (S. 5/43 cm to S. 3/96 cm; 246 to 396 cm) (ca. 10,000 to ca. 6,000 yrs B.P.) is characterized by a reddish cast to numerous layers, by various types of fine laminations to bands and 4 or 5 algal crusts. Sediments are mainly calcareous types (60–95% $CaCO_3$), rich in diverse carbonates including dolomite and aragonite mud and aragonitic crusts, winnowed ostracod laminae, and rhythmic algal couplets characteristic reddish organic laminae. Two subunits are distinguished.

Subunit B2 contains the cm-scale, aragonitic algal crust layers marked A-D on Fig. 4. These have a sharp base, then nodular, to tufa-like hard aragonite embedded in micritic gray, dolomitic mud layers. There are levels with some patchy evidence of burrowing, but more commonly, sets of coarser, mm- to cm-scale sands, some with low angle cutouts. These are in fact pure ostracod hash, with almost no quartzose detritus. Carbonate content peaks over 70% are from zones with crusts and dolomite; the host sediment ranges near 50%.

Subunit B1 has a more regular character of laminations, bands and thin beds grouped on a decimeter scale. There is evidence of preservation of fine carbonate couplets such as in Sec. 4/39–42 cm. Sedimentation takes on a cyclic appearance and coarse ostracod hash layers diminish in abundance with the exception of the reddish layer at the uppermost contact. Carbonate contents are around 50% and fluctuate with a rhythmic pattern.

Unit B is interpreted as deposits of a warmer, but humid period with shallow lake levels showing rapid changes from fresh to brackish to saline lake conditions. B1 may represent overall deeper water, with intervals of stratification or persistent bottom water anoxia.

Unit A: (S. 3/96 to S. 1/0 cm; 0 to 246 cm) (ca. 6,000 B.P. to present) comprises overall greenish-gray, banded aragonite muds (30 to 50% $CaCO_3$). Organic content increases, and layers with scattered filamentous organic matter appear. Three subunits are distinguished.

The subunit A3 interval (246 to 173 cm) displays 7 well-developed, multiple upward-shallowing cycles. These are striking, and marked by mm-thin, white aragonite laminae that recur on a 10 to 20 cm scale. An ideal cycle begins with a cm-scale, dark gray mud layer with lower carbonate and scattered black bits of land-derived organic debris. The body may be massive to banded, and commonly shows faint, well-developed laminations towards the top. The thin white aragonite termination is commonly capped by a drape of reddish brown algal filaments.

Subunit A2 (32 cm to 173 cm) is more uniform, with ocasional thin laminae. An overall faint character of decimeter cyclic banding persists. Carbonate contents are lower than A3, with a pulse at 130 to 140 subbottom over 50%. Low carbonate spikes at the top of section 2 are related to layers rich in algal fibers.

Subunit A1 represents the recent history, with bands of sulfide pigmented aragonitic mud and episodes that show low angle unconformities due to bottom currents. Carbonate contents show a minor decreasing trend within a fairly uniform band around 31 to 40%.

Unit A is interpreted as representing brackish-to-saline lake conditions similar or deeper than the lake of today.

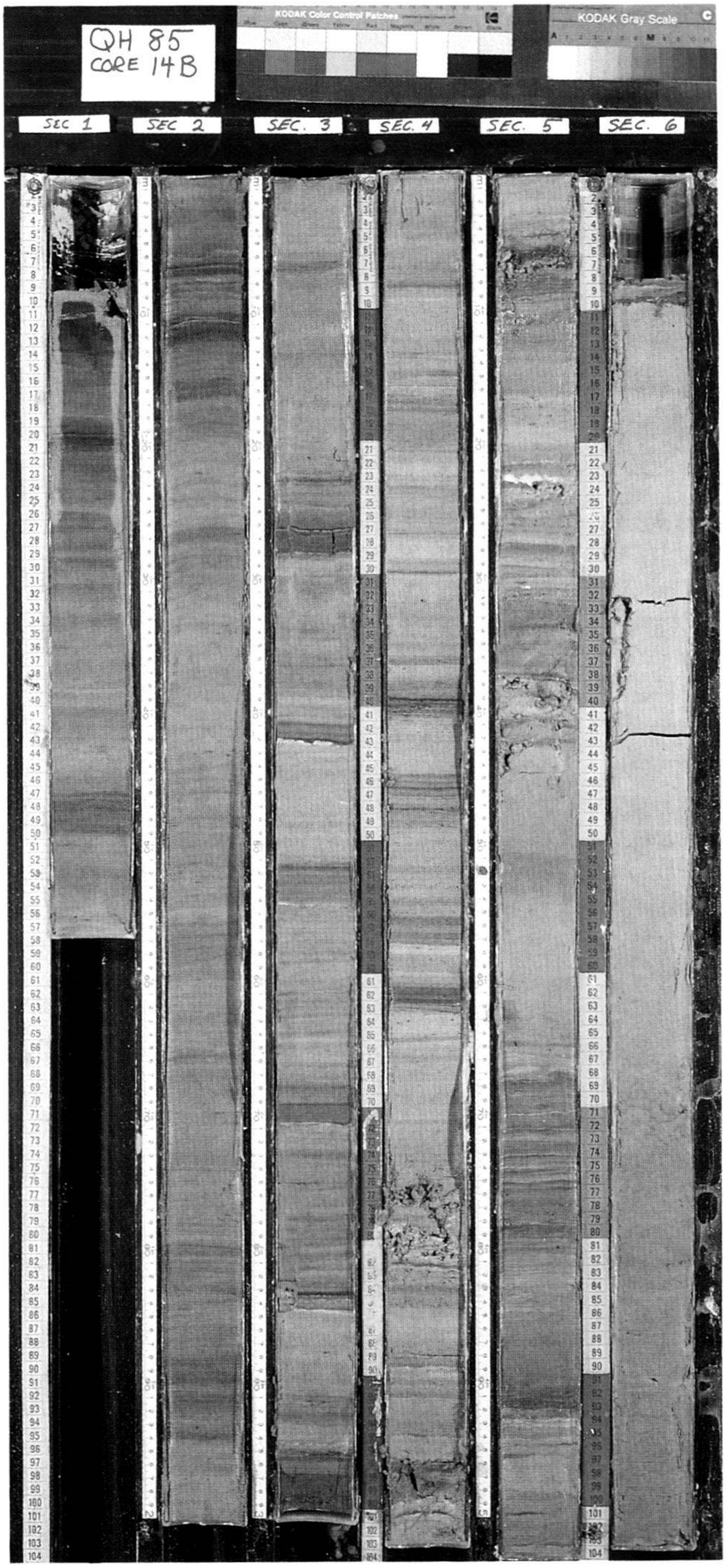
6. Discussion

Qinghai Lake sediments appear to hold the intact record of this large region. On a millenial scale, the chronological and sedimentary framework allows some general conclusions partly based on comparisons with other, more punctuated records of paleoclimate from the Qinghai Plateau. The resolution of century-scale variation must await further detailed analyses.

The present cold, dry climate is mainly a result of Quaternary tectonic uplift of the plateau and Himalaya mountains. During the glacial maximum, worldwide drops in sea level put the shorelines along outer shelf edge, for example, in the South China Sea.

Plate 1

Color photograph of Qinghai type core 14b. Sections (numbered S. 1 to S. 6 from left to right) of the 552 m long piston cores are top left and bottom right.


QH 85
CORE 14B
KODAK Color Control Patches
KODAK Gray Scale
SEC 1
SEC 2
SEC. 3
SEC. 4
SEC. 5
SEC. 6

This limited the possible sources of moisture transfer to the already arid Qinghai Plateau (ZHENG & SHI 1985). The deepest sediments penetrated by our cores are estimated at more than 13,500 years B.P., but these do not show evidence of meltwater from major ice masses. Instead, they possibly document cold saline swamps receiving wind blown dust. During equivalent times, sedimentation in Swiss lakes was still dominated by proglacial varves. We suggest that the flat Q-reflector in Qinghai Lake may stem from planation by high winds during a cold arid Late Glacial that also contributed to loess deposition.

From 12,000 to about 10,500 years B.P., the conditions of the lake freshened, and we assume the lake levels rose. Coarser grained, rhythmic clastic laminations are explained by a stronger seasonal meltwater signal which suggest higher inflow rates. Europe at that time was experiencing a sudden climatic set-back known as the Younger Dryas (eg. RIND et al. 1986). If this wet Qinghai episode is linked to the European record then the current model of a regionally-limited, Younger Dryas impact may require revision (RIND et al. 1986).

Around 10,500 years B.P. conditions changed radically with a sudden increase in carbonate content and presumedly salinity. Lake levels dropped. Sand and silt was replaced by fine carbonate mud with a bioturbating bottom fauna. The abundance of dolomite is a problem. As a large water body concentrated, the already high magnesium to calcium ratio would have further increased and presumedly promoted the precipitation of dolomite in concert with a highly alkaline environment.

Since 10,000 years B.P. the lake has remained a closed hydrological basin. For the period 10,000 to about 6,000 years B.P., sediment structures, reworked sediment, and the presence of several carbonate crusts indicate that the lake went through near-desiccation cycles several times.

While lake levels were very low, the effect of seasonal precipitation was concomitantly higher. Ostracods and lack of evaporites suggest that even during low stages the water chemistry remained mainly fresh to mesosaline. Indeed a tolerant ostracod population suggests that frequently conditions during the early Holocene were brackish. Reddish, ferric mineral coloration of algal and clastic laminae may derive from weathering conditions in the basin that were different than today; for example, higher summer humidity. The interpretation remains speculative because this color could also derive from reworking of older red beds that outcrop in some local areas. Warmer mid-Holocene climates are however documented in southern Tibet by increases in Quercus (oak) pollen (ZHENG & SHI 1985) and greater abundance of tree pollen in our Core 14. Many lakes in northern Tibet were closed basins, with salt lakes around 9,000 years B.P. followed by higher levels in mid-Holocene.

From 6,000 years B.P. to the present, the sediment character suggests relatively steady conditions that do not differ greatly from today. The carbonate content curves however show the presence of a high frequency variability and some events that must be deconvolved with high resolution dating. For example, there are 7 cyclic drawdown-units of 20 cm each between about 6,000 and 4,000 B.P. that could represent periodicity on a multiple century scale. A positive around 4,000 yrs B.P. and a negative carbonate excursion around 2,000 yrs B.P. may be linked to superregional events.

The recent, steady lowering of lake levels is reflected in the uppermost few centimeters of core by distinct oxidation near the sediment water interface. The seismic records also suggest some scouring by bottom currents. Weather patterns suggest decreasing temperatures over the last decades but little increase in precipitation (Zheng & Shi 1985). This instrumental record is however very short. Banding patterns on a 10 cm scale in short cores suggest that present trends may be part of a natural cycle which may have been noted in ancient historical records.

Significance for global lake level fluctuations

Numerous studies have shown that African basins have experienced large fluctuations in area, level and hydrology during the Late Quaternary-Holocene (Kutzbach & Street-Perrot 1985). The most striking feature is a generally parallel development in many basins, with aridity between 17,000 and 12,500 years, and extensive lakes between 12,500 and 5,000 years. A south to north shift in moisture transport from 12,500 to 9,000 years, is thought to respond to Milankovitch insolation patterns (i.e. Kutzbach & Street-Perrot 1985). The reliability of many C-14 dates remains however insufficient to link specific horizons into a synchronous global network.

Qinghai hydrology is also thought to reflect some monsoon influence. On a millenial scale, the sediment record of Qinghai lake would appear out of phase with Africa with low levels during early Holocene. However, this is consistent with Kutzbach & Otto-Bleisner (1982) who predicted that a strengthening of monsoon over Asia would narrow the zone and leave Qinghai with a slight moisture deficit. A transect is needed to test these predictions.

The preliminary results confirm that the Qinghai Lake archives a promising record of high-resolution environmental change. Further work in progress will focus on the detail of episodic climate and hydrological anomalies.

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