BATHYMETRY AND SEDIMENTARY ENVIRONMENTS OF LAKE ISSYK-KUL, KYRGYZ REPUBLIC (CENTRAL ASIA): A LARGE, HIGH-ALTITUDE, TECTONIC LAKE

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1. Introduction

Lake Issyk-Kul, located in the northern Tien Shan of the Kyrgyz Republic, in the heart of Central Asia, is one of the deepest and largest lakes in the world. Although Kyrgyz and Russian scientists have studied the lake quite intensively since the 1850's, not much of the scientific literature has found its way to the international community. It is only recently that Lake Issyk-Kul has also started to attract international attention, and this is essentially thanks to the fact that the area occupies a potentially interesting location for paleoclimate research as well as for geodynamic studies.

The sediments that have accumulated in the lake are believed to have functioned as accurate "recorders" of the processes that were active during or after their deposition. As such, they potentially hold a record of tectonic events that affected the area and/or of past changes in regional climate. However, sediments in large lakes like Lake Issyk-Kul are not all generated and deposited by the same processes and are far from uniform, and their "recording capacity" is thus highly variable. A thorough knowledge of the sedimentary processes and environments in the lake is therefore indispensable for the selection of sites that are suitable for the collection of sediment cores for such investigations.

Such knowledge is also vital for the assessment of the potential impacts on the lake system of the influx and dispersion of solid contaminants. This is a particularly acute problem for the Lake Issyk-Kul region, which is currently attempting to deal at the same time with plans for a further, sustainable growth of the recreational and tourist industry around the lake shores and with the environmental effects of the intensive gold and uranium exploitation that took or is still taking place in the basin and the nearby mountain ranges and of the increasing agricultural use of the lake shores.

In this paper we will define and characterise the main sedimentary environments in Lake Issyk-Kul. We will do this on basis of the interpretation of existing bathymetry data, of a comprehensive first reflection seismic study carried out on the lake in 1997, and of a series of reconnaissance gravity cores collected from the lake in 1998. All the data presented here were acquired as part of an ongoing Belgian-Kyrgyz-Russian-French research initiative.

2. General characteristics of Lake Issyk-Kul

Lake Issyk-Kul (Fig. 1) is a closed mountain lake, located at about 77º E and 42º30' N, in the northern part of the Tien Shan mountain belt in the Kyrgyz Republic (Central Asia). It is situated at an altitude of 1,607 m above sea level and surrounded by high mountain ranges: the Kunghei Alatau Range in the north with the highest peaks reaching 4,770 m, and the Terskei Alatau Range in the south with peaks exceeding 5,200 m.

The lake has the shape of a trapezium with its base oriented to the north (Fig. 1). It is 178 km long in the E-W direction, its width is about 60 km and it covers an area of 6,236 km^2, making it the second largest high-altitude lake of the world. It is also the world's fifth deepest lake, with a maximum depth of 668 m. The average water depth is 278 m, the length of the coastline is 688 km, and the total water volume is 1,736 km^3 [1] [2] [3].

About 118 rivers enter the lake. They drain an area of 22,080 km^2 and are predominantly fed by melt-water from snow and glaciers, which occupy about 509 km^2 of this drainage basin, at altitudes of 3,000 m and above [4]. The main inflowing rivers are the Djyrgalan River and the Tioup River, entering the lake axially at its eastern extremity.

At present the lake has no outlet. Previously, the Chu River was flowing into and out of the lake at its western extremity. Now, the river changes its course a few kilometers before reaching the lake, and flows into the Boom Canyon towards west. This change in the course of the Chu River and its disconnection from Lake Issyk-Kul is inferred to have occurred at the end of the Late Pleistocene, and most likely resulted from tectonic movements [5]. Since the disconnection, the lake has still been intermittently overflowing via the paleo-outlet of the Chu River during periods of higher lake level; the last of such periods ended about 150 years ago.

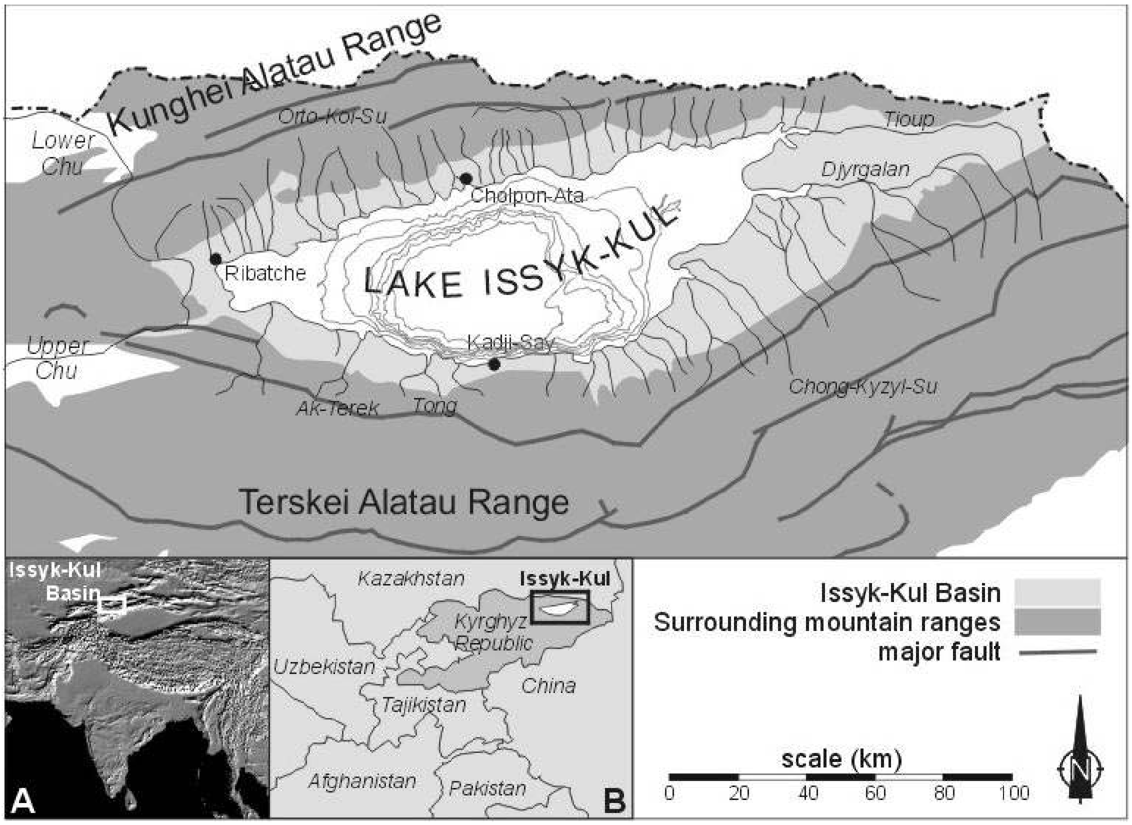

Figure 1. General localisation map of Lake Issyk-Kul, indicating the surrounding mountain ranges, the depth of the lake (with some selected contours), the main towns, rivers and other localities mentioned in the text. Inset A shows the location of Issyk-Kul Basin in the regional context of the Tien-Shan. Inset B indicates the political-geographical location.

The lake surface temperature in January does not drop below 2-3°C, and in July it reaches up to 19-20 °C [6]. At depths of more than 100 m, the water temperature remains constant all the year at 3.5-4.5 °C. Water circulation is counter-clockwise and surface water currents of up to 0.3 m/s occur in the northern part of the lake [7].

Lake Issyk-Kul is monomictic, slightly saline (6 g/l), oligotrophic to ultra-oligotrophic and it has high values of dissolved oxygen even at the lake bottom [6]. The water chemistry is dominated by Na^+ and K^+ among the cations, and by Cl^- among the anions [8]. The slightly saline waters are oversaturated in calcite, monohydrocalcite and vaterite, minerals which are found in the sediments [9] [10].

The total annual water input by rivers amounts up to 437 mm/yr (about 3,720,000 m^3), and the average annual rainfall is 251 mm/yr. The western part of the lake is slightly drier than the east. With evaporation at about 702 mm/yr, the lake has a negative hydrological budget [11] and the lake level has the tendency to gradually become lower since ± 150 years [7]. This effect appears to be even amplified by the increasing use of river water for human activities and agricultural purposes.

3. Geological setting

The northwestern Tien Shan is characterized by a succession of E-W-trending mountain ranges with elevations of more than 4 km and intervening intermontane basins containing a Cenozoic infill of up to 6 km in thickness. Ranges are generally overthrusted onto adjacent basins [12] [13] [14], and major active fault zones mark the boundary between them.

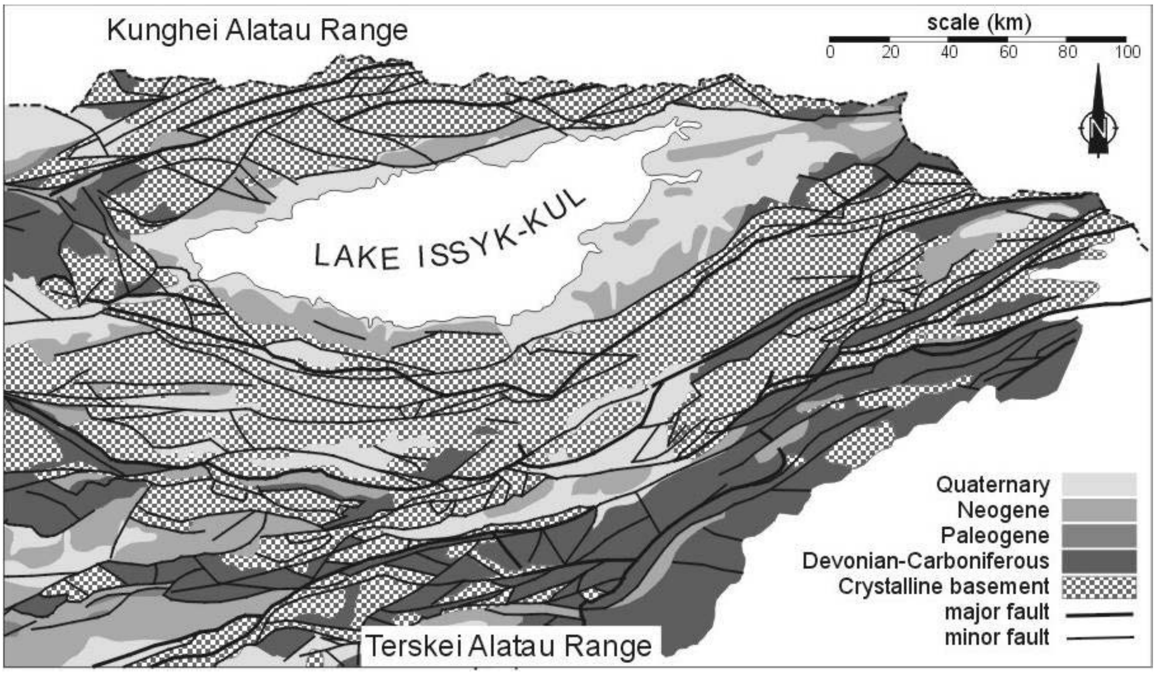

Figure 2. Simplified geological map of Issyk-Kul Basin and surrounding mountains (after [7]).

The Issyk-Kul Basin is one of the largest of these intermontane basins in the Kyrgyz Tien Shan. It has an oval shape, a length of 250 km in the E-W direction and a width of about 145 km in the N-S direction. Lake Issyk-Kul occupies the central part of the basin [15] [16] [17].

The mountain ranges surrounding the Issyk-Kul Basin are the Kunghei Alatau Range in the north and the Terskei Alatau Range in the south. They are composed of crystalline basement rocks of Archean to Middle Paleozoic age, covered by volcano-sedimentary and sedimentary strata of Devonian-Carboniferous age (Fig. 2). Their uplift and exhumation is believed to have started in Oligocene-Miocene times [18], although recent data from the neighbouring Chu Basin point to a Late Miocene onset of mountain building [19].

The mountain ranges are separated from the Issyk-Kul Basin by broad strike-slip zones that have accommodated most of the Late Cenozoic strain and have protected the basin interior from any significant deformation: the Chon-Kemin-Chilik zone in the north and the Pred-Terskey zone in the south [17] (Fig. 2).

The oldest deposits in the basin are thought to date back to Oligocene-Miocene times [12] [18] [15]. Since that period up to 3,500 m of sediments have accumulated in the depression [20]. These comprise a series of continental and lacustrine formations of Miocene to Quaternary age, that witness the initial expansion of the lake and the subsequent shrinking to its present-day size (Fig. 2). Uplifted lacustrine deposits of the Pliocene Djuka Formation are currently exposed in the southern part of the basin, along the southern lakeshore, where they are cut by horizontal Quaternary lacustrine terraces. The northern shoreline of the lake is dominated by glacial and fluvioglacial deposits, which cover older lacustrine deposits and reflect the expansion of the Kunghei Alatau valley glaciers to the foot of the mountain range during Pleistocene glaciations.

The area is tectonically still highly active: some of the largest earthquakes of the last century occurred in the Kyrgyz Tien Shan [14] [21]. Most of the present-day tectonic activity is focused at the margins of the intermontane basins. For example, the Chon-Kemin earthquake of 1911 (Ms = 8.2) has activated a fault within the Kemin fault zone, north of the Issyk-Kul Basin, over more than 200 km [22]. A considerable component of strain is currently also being accommodated by younger fault systems that have propagated into the basin centres during the late Quaternary [19].

4. Methods and data

The bathymetry, seismic and gravity coring information discussed in this study comprise both existing data sets and recently acquired new data.

The 1:100,000 bathymetry map of Lake Issyk-Kul has been digitised at the Royal Museum of Central Africa, and the data were merged with those of digitised 1:200,000 topography maps of Kyrgyzstan and Kazakhstan, in order to create a digital terrain model (DTM) of the entire Issyk-Kul Basin and surrounding mountain ranges [23].

In 1982, a very first reflection seismic survey was conducted on the lake by Moscow University. A total of 31 seismic profiles were collected across the lake, using a single-tip sparker source and a single-channel receiver. Only a few interpreted line drawings of these profiles have ever been published [24].

A second reflection seismic survey was carried out in 1997, by The Renard Centre of Marine Geology in cooperation with the Royal Museum of Central Africa and the Seismological Institute. About 990 km (62 profiles) of seismic profiles were acquired, using a 500 J multi-electrode sparker, a single-channel streamer, GPS positioning and digital recording on a Delph2 acquisition system (Fig. 3). Post-acquisition processing

involved frequency band-pass and spiking deconvolution filtering. The data have a theoretical (Rayleigh criterion) vertical resolution of < 1 m; penetration is highly variable, but in places it exceeds 350 ms TWT.
In 1998, the Royal Museum of Central Africa, the Institute of Geology and the Université de Savoie collected 28 short gravity cores (up to 1.76 m long) from different parts of the lake, along a longitudinal and a latitudinal transect (Fig. 3). The core locations had been selected on basis of the results of the 1997 seismic survey. These cores have been sub-sampled and characterized using gray-scale analysis, magnetic susceptibility measurements, grain-size analysis, x-ray diffraction measurements, thin sections studies and pollen analysis. A chronological framework has been established on basis of ^{14}C AMS and ^{210}Pb dates [25] [10] [26].

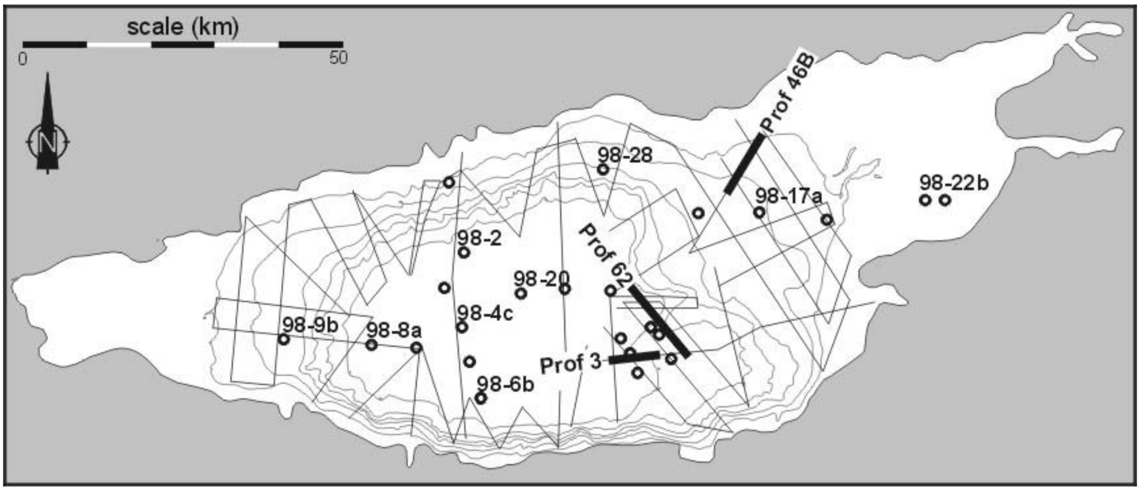

Figure 3. Location map of the seismic profiles (shot in 1997) and sediment cores (collected in 1998) used for this study.

5. Morphology of the lake floor

Lake Issyk-Kul is characterized by a highly unusual lake-floor morphology (Fig. 4). Different distinct morphological “provinces” can be discerned. The most striking ones are two shallow platforms, and a flat-floored central deep, which are separated by very steep slopes.

5.1 THE WESTERN AND EASTERN MARGINS

The western and eastern parts of the lake consist of gently dipping shelf-like areas or platforms that extend over distances of 40 km (west) to 60 km (east) from the shorelines in water depths between 0 and about 300 m (Fig. 4). These platforms represent about half of the total lake-floor surface. They both comprise two distinctly different parts: a shallow part between 0 and 110 m, and a deeper part between 110 and 300 m (Fig. 4).

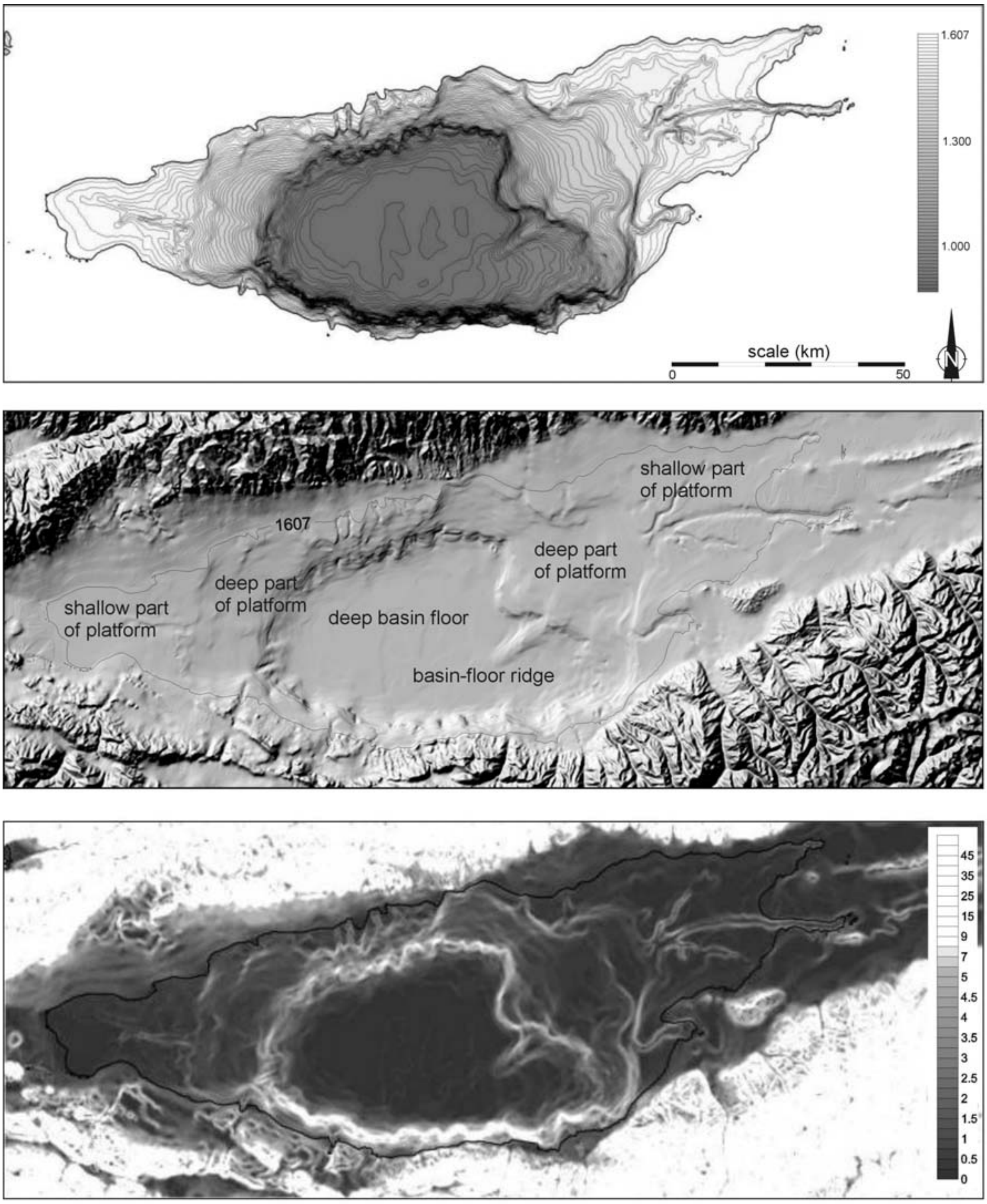

Figure 4. Lake-floor morphology maps of Lake Issyk-Kul, based on DTM [23].
Top: Grey-shaded bathymetric contour map (with isobaths every 100 m, in m above sea-level).
Middle: Shaded-relief map with indication of the main morphological “provinces”.
Bottom: Grey-coded slope gradient map.

The shallow part of the platforms, of which most is shallower than 50 m, has an average dip angle of 0.5º and is incised by a basinward converging system of channels (Fig. 4). These channels are about 2-3 km wide, up to 50 m deep, and abruptly disappear at 110 m of water depth. The main channel in the eastern platform extends all the way to the lakeshore, to the mouth of the inflowing Djyrgalan River; further to the southwest a solitary channel links up to the mouth of the Chong-Kyzyl-Su River. The main channels in the western part become very subdued in water depths of less than 25 m but appear to extend to the former mouths of the inflowing and outflowing Chu River.

The mid-platform break at about 110 m (corresponding to 1,495 m above sea level) is a very prominent feature in the platform morphology. It is particularly well expressed on the eastern platform, but also clearly visible on the western platform. It occurs at exactly the same water depth around the lake.

The deeper part of the platforms is not incised and has an average dip angle of about 1º (Fig. 4). It is characterized by a series of low-relief terraces (with heights of up to 20-30 m) that exhibit a slight basinward convex shape in map view; these terraces are best developed on the eastern platform.

The platforms transit abruptly into steep slopes (Fig. 4) that extend to central basin floor, at water depths of over 600 m. The slope of the western margin has an average dip angle of 3-6º and its southern part is incised by a number of small canyons. Along the eastern margin, the transition from the platform edge to the slope is more gradual than in the west, and the slope is not incised by canyons. The northern part of the eastern slope has a two-step appearance, with a gradually dipping (2-3º) upper part between 300 and 400 m, and a steeply dipping (4-6º) lower part between 400 and 600 m. The southern part has an average dip angle of 1-5º.

5.2 THE NORTHERN MARGIN

The northern margin of the lake is characterized by a small, shallow-water shelf (Fig. 4). It occupies the central part of the northern shoreline over a distance of about 30 km, and extends for about 3-5 km from the shore in water depths of 25-50 m. It has an average dip angle of 1º. It is incised by a series of short trunk channels that connect to the shoreline, to the mouths of the small rivers draining the nearby Kunghei Alatau Range (e.g. the Orto-Koi-Su River, west of Cholpon-Ata).

In basinward direction, the shelf transits into a two-step slope (Fig. 4). The upper slope extends from 25-50 to 300-350 m water depth, with an average dip angle of 2-4º; the lower slope from 300-350 to 600 m with an average dip angle of 4-9º. The upper slope has an irregular, bumpy morphology, and some of the shelf channels appear to extend down to these depths. Where the shelf is only very small, e.g. off Korumdy (just west of Cholpon-Ata), the upper slope starts virtually at the shoreline. The lower slope is very steep and strongly incised by several canyons.

5.3 THE SOUTHERN MARGIN

The southern margin of the lake consists of a single steep slope, extending from the shoreline to the central basin floor (Fig. 4). It has an average dip angle of 8-10º, and is highly irregular with small terraces and a number of canyons that seem to originate from some small rivers draining the southern part of the Issyk-Kul basin (e.g. the Tong and the Ak-Terek Rivers).

5.4 THE DEEP BASIN FLOOR

The deep basin floor is essentially flat, apart from some minor undulations. Water depths range from 600 m at the foot of the slopes to the maximum depth of 668 m in the central part of the basin (Fig. 4).
The eastern part of the basin floor is characterized by the presence of a ridge-like structure (Fig. 4). It has a SW-NE orientation, a maximum width of 4 km and a length of 20 km. It reaches a maximum height of 150 m with respect to the surrounding basin floor. It is connected to the eastern slope and plunges to the southwest where it disappears as a morphological feature.

6. Seismic profiles of the lake structure and infill

The 1997 seismic data cover most of the above-described morphological “provinces” (Fig. 3). Because of the highly variable penetration of the seismic profiles (due to e.g. the presence of shallow gas or very coarse-grained deposits), the often very steep slopes and the strong lateral variations in seismic facies, it has not been possible to establish a whole-lake seismic stratigraphic framework. Below, the seismic data will thus be discussed per morphological province.

6.1 THE WESTERN AND EASTERN MARGINS

Seismic profiles from the western and eastern platforms usually have a penetration of 100-200 m, except where they are characterized by acoustic blanking, probably due to the presence of shallow gas. Deeper areas show a complex stratigraphy. Sedimentary units of variable thickness (typically up to 40-50 m, but laterally changing in thickness quickly) are separated by distinct unconformities marked by onlap, downlap, toplap, regional erosional truncation or localized erosional incisions. Unconformities typically amalgamate in basinward as well as in landward direction.
Three main seismic facies types can be discerned in the platform strata (Fig. 5). The most common type consists of relatively parallel, continuous reflectors of medium to high amplitude. Packages of these reflectors alternate with units with a much more subdued facies that can be almost reflection-free or contain some weak parallel reflectors. The third facies type, which occurs interbedded between the others, consists of lens- or wedge-shaped units (typically up to 50 m thick and 10-15 km across) characterized by a typical offlap pattern in longitudinal (i.e. east-west directed) cross-section and by bi-directional downlap in transverse cross-section. Topsets are often associated with high-amplitude returns and gas blanking. The wedges have the typical

characteristics of prograding delta lobes, similar to those observed in other large tectonic lakes [27] [28]. Interlobe areas are sometimes highlighted by channel incisions with high-amplitude basal reflectors and limited penetration, suggesting a coarse-grained basal channel fill. Several of such lobes occur at different stratigraphic levels and at different distances from the shores in a complicated stacking pattern. Some of the lobes are virtually at the lake floor, some are completely buried and others are only partially buried and still have a lake-floor expression in the form of the convex terraces in the lower part of the platforms (Fig. 5).

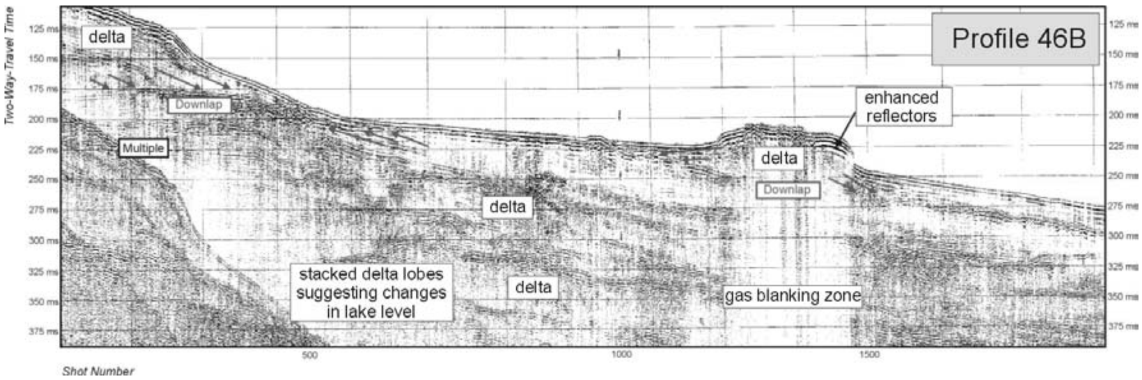

Figure 5. Seismic profile across the eastern platform, showing present-day and buried proximal delta deposits and the various seismic facies associated with it.

Towards the distal parts of the lower platforms, the stratigraphic variability becomes more moderate and the units become more homogeneously stratified, especially in the northern part of the eastern platform. Elsewhere, the units tend to thicken towards the platform edges, where they form large progradational lobes on the upper part of the slope. The steep slopes themselves are difficult to image on seismic records, but they appear to be characterized by chaotic units, suggesting that they are gravitationally unstable.

In the southern part of the eastern platform, strata are locally cut and displaced by a fault that continues up to the lake floor, suggesting it is currently active.

6.2 THE NORTHERN MARGIN

Seismic profiles from the northern margin generally have a very limited penetration. This is partly due to the steep slopes, but also profiles across the rather flat small shelf and the less steep upper slope show strongly reduced penetration. A number of irregular wedges with a variable, chaotic to roughly basinward prograding facies can be discerned, stacked on top of each other. Their seismic facies and the limited penetration suggest they are composed of very coarse-grained deposits. They downlap onto the upper slope, or prograde across the slope edge.

The presence of irregularities in the slope morphology and of mounded chaotic units further downslope indicate that intensive slope failure is taking place.

The structuration of the margin into a shelf and an upper and lower slope appears to be structurally controlled.

6.3 THE SOUTHERN MARGIN

The southern margin is characterized by very limited seismic penetration due to the high slope angles. Locally, there are some small mid-slope terraces, which are most probably fault controlled and have accumulated small patches of sediment.
The accumulation of chaotic units near the foot of the slope indicates that also the southern margin is subject to intensive slope failure.

6.4 THE DEEP BASIN FLOOR

Seismic profiles from the central deep basin floor typically have a penetration of 200-300 m. They generally show a uniform seismic facies, consisting of parallel, laterally very continuous reflectors, without apparent unconformities. These reflectors occur in 15-30 m thick packages with alternating higher and lower amplitudes. At the foot of the slopes, individual reflectors or groups of reflectors show a slight thickening in the direction of the margin.

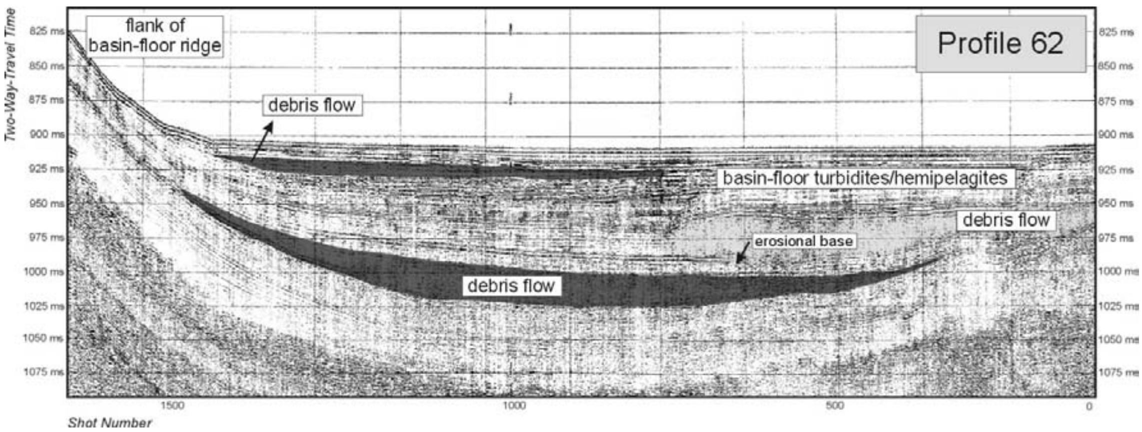

Figure 6. Seismic profile across the deep basin floor,
showing a series of superimposed debris-flow deposits north of the basin-floor ridge.

In the eastern part of the basin floor, several large lenses with an acoustically transparent seismic facies occur in between the conformable, stratified units (Fig. 6). These lenses may reach up to 30 m in thickness, and are up to 3-5 km across. They usually have a basin-filling, ponding appearance, with smooth upper and lower boundaries, although sometimes they may also display irregular, erosive basal unconformities or have a mounded appearance with a convex-upward upper boundary. The lenses have the typical characteristics of debris-flow or other mass-flow deposits that have been observed in other lakes [29] [30]. Their occurrence appears to be

restricted to the area just downslope from the major progradational lobes on the eastern platform edge.
Just south of the area with the debris flow lenses, seismic profiles reveal the internal structure of the basin-floor ridge, which consists of anticlinally folded basin-floor strata, transected by a gently dipping fault parallel with the fold axis. The ridge thus appears to be a structural feature, rather than a depositional or erosional one.

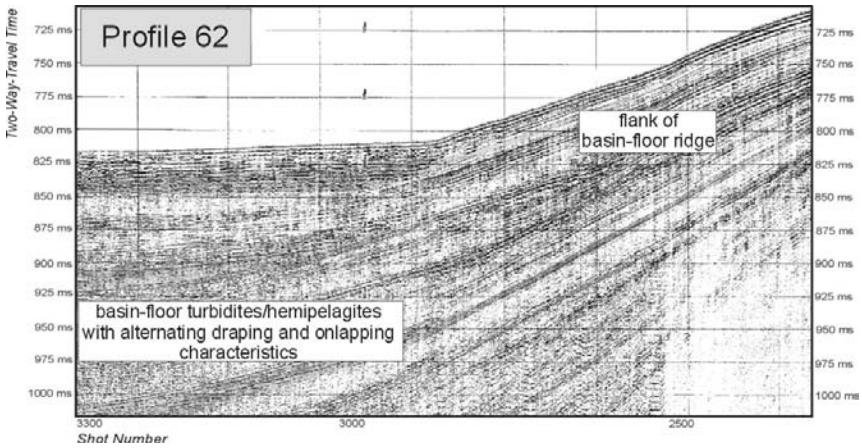

Figure 7. Seismic profile across the deep basin floor,
showing the onlapping turbidites against the flanks of the basin-floor ridge.

In the vicinity of the ridge, the basin-floor strata have a slightly different appearance: they consist of an alternation of higher-amplitude reflector packages (typically about 15 m thick) that onlap and thin towards the ridge, and of lower-amplitude reflector packages (about 20-30 m thick) that maintain their stratigraphic thickness across the ridge (Fig. 7).

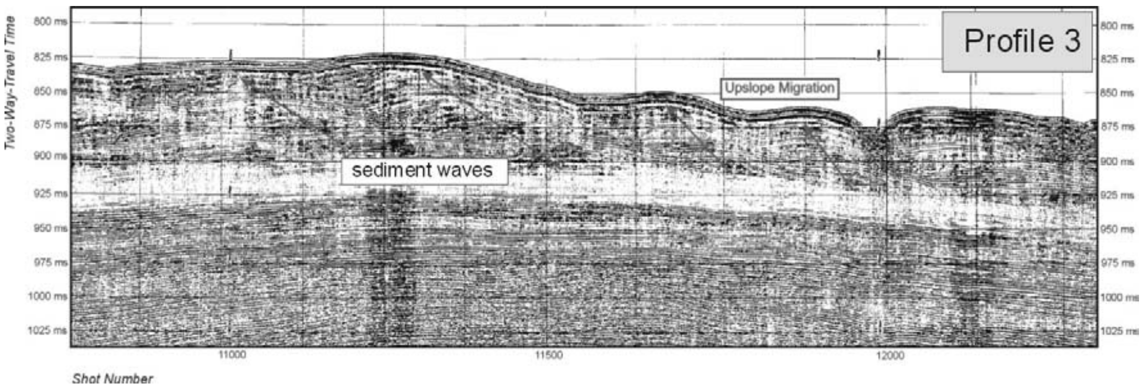

Figure 8. Seismic profile across the deep basin floor,
showing the sediment waves occurring at the nose of the basin-floor ridge.

At the nose of the ridge, the uppermost 50 m of the basin-floor strata are characterized by the presence of large wavy structures, overlying horizontally-bedded strata. The waves are typically about 10 m high, they have a wavelength of about 800-900 m and appear to be migrating up-slope, towards the crest of the ridge (Fig. 8). They resemble sediment waves, typical for current-controlled deposits. Similar features have been observed in other large lakes and are attributed to the effects of bottom currents [31] [32] [33].

7. Interpretation of depositional environments

The sediments in Lake Issyk-Kul are either generated in situ by chemical precipitation of several carbonate phases, or they are terrigenous in origin and brought into the lake by inflowing rivers [9]. The main source of terrigenous sediment is presently the Djyrgalan River, which drains the basin axially and flows into the lake at its easternmost end. Much shorter rivers drain the northern and southern margins and carry a much less significant sediment load. The upper Chu river is larger than the Djyrgalan River and when it was flowing into the lake, it should have been a major source of sediments in the lake, at its westernmost end.

Depositional environments within the lake are thus controlled by the interplay between authigenic formation and terrigenic input, and by dispersion and redistribution processes under the influence of currents and along steep slopes.

Based on the interpretation of our seismic profiles and bathymetry data, and supported by sedimentological evidence from shallow gravity cores (Fig. 9), we distinguish up to 6 main depositional environments: proximal delta deposits, distal delta deposits, glacial outwash deposits, mass-flow deposits, basin-floor turbidites/hemipelagites and basin-floor current-controlled deposits (Fig. 10).

7.1 PROXIMAL DELTA DEPOSITS

We interpret the strata making up most of the western and eastern platforms as proximal delta deposits, consisting primarily of delta plain deposits and of prograding delta lobes exhibiting the characteristic topset-foreset-bottomset configuration. Angles of foreset slopes are around 1.5º. The delta-lobe strata are deposited out of the bedload and the coarser-grained component of the suspended load from rivers entering the lake. The main tributaries are those entering the lake at the eastern side and draining the basin axially, i.e. the Djyrgalan River and the Tioup River. Delta lobes in the western platform have probably been deposited by the Chu River, which was the main tributary at the western part of the lake before it was deflected to the west. Delta lobes are typically about 5 km^3 in volume, and each represents a significant period of sedimentation under relatively stable conditions.

The position of the individual lobes within this succession has switched laterally, due to autocyclic processes, and longitudinally, due to allocyclic processes that are primarily driven by changes in lake level or significant changes in sediment load of the tributaries. During periods of high lake level, delta lobes developed high up the platforms, while during periods of lake-level lowering these deposits got cannibalised and re-deposited on the lower-lying parts of platforms.

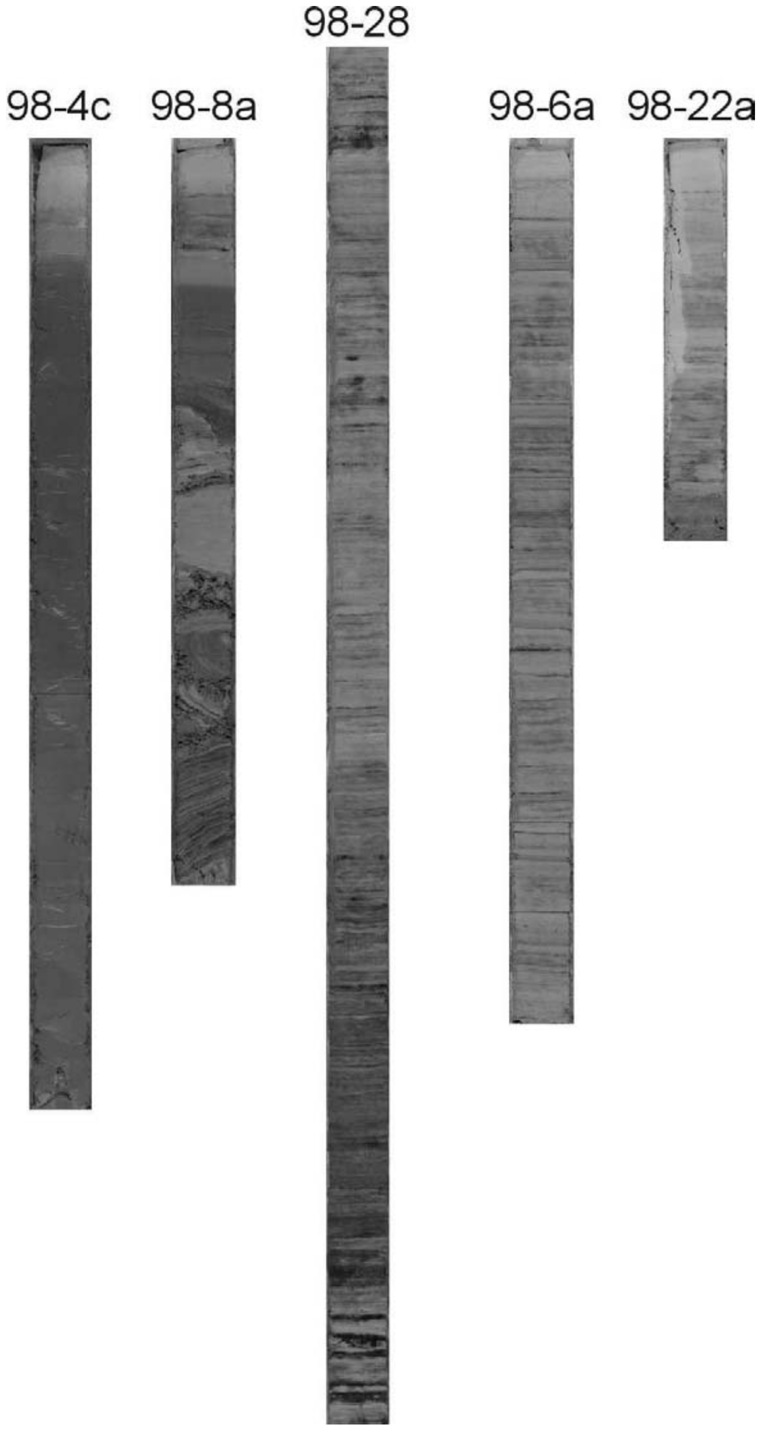

Figure 9. Some of the sediment cores discussed in the text. See Fig. 3 for location.

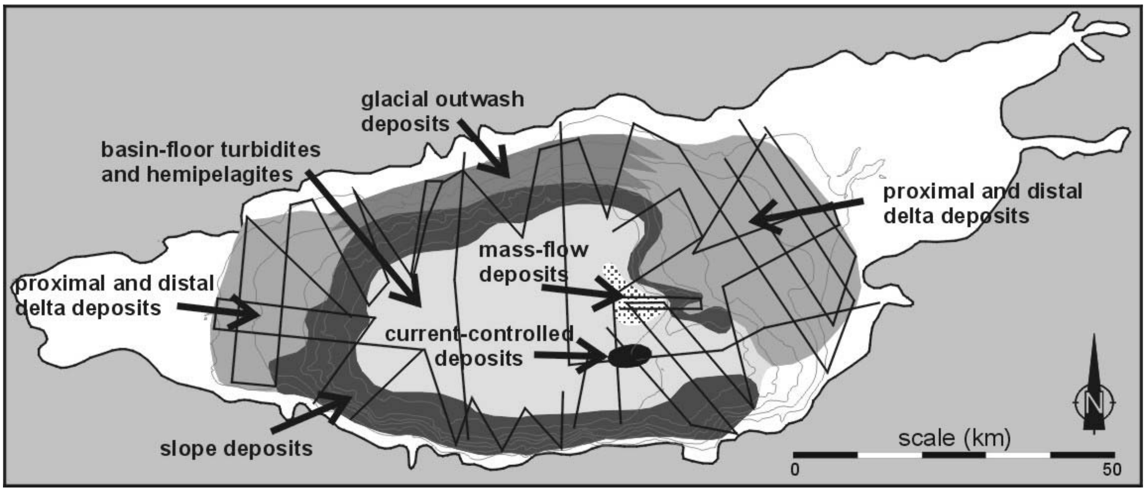

Figure 10. Morphosedimentary map of Lake Issyk-Kul showing the main depositional environments as interpretated from the seismic profiles, bathymetry data and shallow sediment cores.

Several sub-environments can be distinguished in the proximal delta deposits. Inter-lobe channels funnel parts of the coarser bedload/suspended load further across the platform in basinward direction, where it is deposited on the lower platform. There is thus an important amount of sediment bypass in the delta area. Core 98-17a from the lower platform area, about 100 m deeper than the mouth of the main channel consists of a layer of fine sands at the bottom, which progressively changes upwards to a centimetric to millimetric alternation of light and dark layers of clays and silty-clays. Delta plain deposits are characterised on seismic records by toplap, high-amplitude reflection returns and gas blanking. This is probably due to the presence of shallow gas, originating from the biogenic disintegration of organic material in the coarse proximal delta deposits, i.e. most likely soils that developed in the delta plain area as this prograded and gradually became sub-aerially exposed. Core 98-22b shows the presence of very compact clayey, sandy to gravelly deposits [26].

These proximal delta deposits thus essentially consist of coarse-grained bedload sediments, intermixed with slightly finer-grained suspended load sediments deposited out of interflows. These deposits may have been sub-aerially exposed one or several times after their formation, and they may have been often reworked as a result of lake-level fluctuations and of autocyclic or allocyclic switching of channel courses.

7.2 DISTAL DELTA DEPOSITS

On the outer parts of the western and eastern platforms, more homogeneously stratified deposits locally occur, intermixed with the proximal delta deposits. We interpret these deposits as distal delta deposits, consisting primarily of the fine-grained component of the suspended load from rivers settled out on the delta fronts. This fine-grained material has been transported across the platforms as interflows, at the level of the thermocline during summer stratification. The suspended particles get carried along with the counter-clockwise-moving currents and deflected to the right by the Coriolis force and finally settle out in the distal parts of the platforms, at the right-hand side from the downstream direction of the inflowing rivers. The most important accumulation occurs in the northern part of the distal eastern platform (originating from the main inflowing Djyrgalan River). Core 98-28, which consists of a rhythmic alternation of light and black silty-clay sediments [10], confirms that these distal delta deposits are essentially fine-grained suspended load sediments that have settled from the water column (Fig. 9). They have accumulated continuously through time controlled by the current regime, the thermal stratification characteristics of the water column and the suspended sediment load of the inflowing rivers, and are virtually undisturbed.

7.3 GLACIAL OUTWASH DEPOSITS

By comparison of the seismic facies with onshore outcrops, we interpret the acoustically chaotic, generally prograding sediment wedges on the small shelf and upper slope of the northern margin as fluvioglacial outwash deposits. Onshore, the whole north-central part of the shoreline is dominated by sandur deposits, consisting of very coarse-grained, poorly sorted sediments, containing blocks of several dm in diameter. Such deposits are believed to have been generated by the breaching of the enormous terminal moraines at the foot of the Kunghei Alatau Range (i.e. well developed above Cholpon-Ata, at 2,500 m altitude) and subsequent drainage of formerly dammed proglacial melt-water lakes. These melt-water outbursts probably extended into Lake Issyk-Kul, where the sediment load was quickly deposited on the small shelf due to rapid deceleration of the flow.
Presently, the rivers draining the Kunghei Alatau Range carry very little sediment and only a thin layer of suspended load fall-out covers the fluvioglacial outwash deltas in the lake.

7.4 MASS-FLOW DEPOSITS

The steep fault-controlled walls of the deep basin are evidently prone to slope failure. This is particularly true for the slopes that receive larger amounts of sediment, such as those of the western and especially the eastern platforms. The fault-controlled slopes of the northern and southern margin are extremely steep and have not allowed large quantities of sediment to accumulate, but also here are indications for slope failure. Mass-flow deposits are evident from the seismically chaotic mounded heaps (slumps) at the foot of the northern and southern slopes, and from the seismically transparent debris-flow deposits along the platform-edge delta fronts of the eastern margin. The debris-flow deposits appear to not have had long run-out distances as they occur close to the foot of the slopes. Nevertheless, it is not excluded that they may have partially developed into turbidites, which may have extended much further in the basin. Sediment cores 98-09b, located at the upper part of the delta front, and 98-08a (Fig. 9), located at the foot of it, contain inversely graded gravels and sands, together with slumped and folded laminated sediments overlying an erosive base [26] [10]. They confirm that these foot-of-slope mass-flow deposits may contain quite coarse sediments, which thus most likely find their origin in the failure of proximal prograding delta deposits or basinward funnelled channel deposits.

Slope failure may have occurred simply as a consequence of rapid sediment accumulation due to delta progradation onto the slopes, or it may have been triggered by external factors. Earthquake triggering seems a likely cause for generating slope instabilities in a region of active mountain building like the Tien Shan. Our records indicate the presence of 5 major debris flow units incorporated in the upper 200 m of basin-floor strata along the eastern margin [34]. Assuming an average sedimentation rate of 0.3 mm/yr, as deduced from sediment cores from the basin floor [26], this means 5 large-scale slope failures in about 670 kyr.

7.5 BASIN-FLOOR TURBIDITES/HEMIPELAGITES

The seismic facies on the basin floor strata, with the distinct alternation of intervals with higher and lower reflection amplitudes, is typical of deep-water depositional environments, e.g. a mixture of biogenic or fine terrigenous hemipelagic deposits and terrigenous sediments transported to the basin floor by turbidity currents. This is confirmed by our sediment cores from the deep basin, which invariably consist of gravels and sands in fining-upward sequences (near the steep slopes, such as in cores 98-02 and 98-06b) representing a proximal turbidite facies, or of homogenous dark muddy sediments with sub-millimetre-scale sand lenses (at the centre of the lake, such as in cores 98-4c and 98-20; Fig. 9) representing a distal muddy turbidite facies or a homogenite facies [35]. These central basin-floor deposits may thus represent run-out turbidites resulting from gravitational slope failures (seismically triggered or not) along the steep slopes or they may represent underflow deposits resulting from sediment charged melt-water input (mainly from the northern margin, as can be deduced from the magnetic susceptibility records) in a thermally not stratified lake during spring. In any case, the cores indicate that all these sediments are heavily re-worked.

The configuration around the basin-floor ridge in the eastern part of the deep basin, offers the possibility to estimate the relative proportions of turbidites and hemipelagites in the basin-floor sedimentation. The anticlinal ridge has functioned as a topographic feature during sedimentation. Around the ridge, the basin-floor deposits are characterised by an alternation of higher-amplitude reflector packages that onlap and thin towards the ridge, and of lower-amplitude reflector packages that maintain their stratigraphic thickness across the ridge. The latter most probably represent essentially the draping hemipelagite component of the basin floor deposits, while the former are more likely to represent essentially the ponding and onlapping turbidite component. The seismic data thus indicate that there have been alternations of periods with increased turbidite input and of periods with predominantly hemipelagic sedimentation. These alternations may reflect climatically driven changes in underflow intensity (precipitation changes or periods of enhanced glacier melting), and/or tectonically driven pulses of increased slope failures (higher seismicity). Assuming an average sedimentation rate of 0.3 mm/yr for the basin-floor sediments [26] and for the sake of simplicity disregarding the evident differences in sedimentation rates between turbidites and hemipelagites, the observed facies alternations suggest that the periods of enhanced turbiditic activity had a duration of about 50 kyr and a recurrence rate of about 117-150 kyr.

7.6 BASIN-FLOOR CURRENT-CONTROLLED DEPOSITS

We interpret the large sediment waves that affect the basin-floor deposits in the vicinity of the ridge as induced by bottom-current activity. In agreement with existing views on deep-ocean current-controlled or “drift” sedimentation, we believe that deep-water currents in the central basin depression are responsible for the deflection and entrainment of hemipelagic particles causing them to accumulate in the down-current direction. Similar drift deposits are increasingly being identified in large lakes: i.e. the East African Rift lakes [31] [32], Lake Baikal [33]. Their formation, and more particularly the nature of the currents causing them, remains however still poorly understood.

8. Lake-level changes

The channel incisions, terraces and buried delta lobes that characterize the western and eastern platforms clearly demonstrate that the lake has witnessed several important fluctuations in lake level. Morphological steps, such as those associated with terraces and delta lobes, may thus be abrasive or depositional in nature, or a combination of both, but do point to a lower-than-present lake level.
The shape and pattern of the incised channels in the upper part of the platforms, the fact that they visibly connect to the mouths of inflowing rivers and their sudden disappearance at the edge of the upper part of the platforms at about 110 m of water depth (1,495 m above sea level) indicate that they were generated by fluvial incision during a time when the lake level was about 110 m lower than present. The age of this lake-level lowstand has been dated variably, ranging from Late Pleistocene [11] [5] to Middle Holocene [36].
Older terraces, at about 18 and 40 m above the present lake level, are also well preserved along the south-western part of the lake, and especially between Kadji-Say and Ribatche. The lowest one corresponds to the altitude of the overflow level of the lake into the lower Chu River (1,622 m above sea leavel). This level was reached by the lake in the first half of the 19th century. A major terrace is also visible at an altitude of 1,645-1,650 m above sea level. It corresponds in the field to the limit between low smoothed slopes and higher rugged badlands. This terrace can be interpreted as an abrasive/depositional scarp of a stable lake-level highstand, the age of which is also debated and ranges from Late Pliocene [11] to Middle Pleistocene [37].
Lake-level changes can be due to two main causes: climate (changes in precipitation/evaporation conditions, changes in temperature leading to increases or decreases in melt-water production) and tectonics (diversion of inflowing rivers due to surface deformation, closure of outflowing rivers due to margin uplift, deepening or

shallowing of the basin). The 110 m lowstand of Lake Issyk-Kul is generally attributed to tectonic processes. Some authors postulate that these tectonic processes are related to and coeval with those that caused the deflection of the Chu River and its disconnection from Lake Issyk-Kul at about 13-18 kyr BP [5]. Trofimov [36] attributes the lowstand to a major tectonic event causing a.o. the assumed collapse of the central part of the lake (see below).

The presence of other terraces and delta lobes in the lower part of the underwater platforms, at water depths below 110 m, suggests that there have been periods of even lower lake level earlier in the Pleistocene: i.e. at 150 m, 250-270 m and 380-400 m.

The terrace at 40 m above lake level, attributed to a stable lake-level highstand, is also interpreted as resulting from compressional tectonic activity along the Chon-Kemin fault zone that crosses the Lower Chu River, which was previously outflowing from the lake.

9. The myth of the central basin collapse

Based on morphology and on information from seismic profiles [24], Trofimov [36] interpreted the central flat-floored basin deep with its steep and evidently fault-controlled margins as resulting from a sudden tectonic collapse, over a height of about 200 m, during the middle Holocene. He invokes this collapse as the cause of the 110 m lake-level lowstand.

In retrospect, this collapse scenario seems, however, a rather unlikely hypothesis. A 200 m tectonic subsidence of the central basin floor since the middle Holocene (i.e. 5 kyr) would imply tectonic subsidence rates of at least 4 cm/yr, assuming the process has continued up to present, and even much higher if the collapse is considered as a shorter-lived event as proposed [36]. These are extremely high deformation rates for extension in an intracontinental environment and difficult to reconcile with the present-day, geodetically determined shortening rates in the area, which are in the order of 1 cm/yr [14].

The new seismic and core data also bring no evidence in support of the collapse hypothesis. Although the seismic profiles across the steep northern and southern basin slopes confirm their fault-controlled origin, they do not provide clues as to the timing of the main fault activity. However, most of the slope-controlling faults are covered by significant amounts of relatively undeformed deposits, suggesting they have not been very active in recent times. Also, a major tectonic event as a basin-floor collapse would have a basin-wide impact on the sedimentary infill, visible on seismic records and in sediment cores: slumping, sliding, in-situ deformation, faulting, seiche development... Our data show no evidence of such basin-wide synchronous effects. Given the penetration depth of our seismic records on the central basin floor of about 350 m and average sedimentation rates of 0.3 mm/yr [26], we postulate that the subsidence of the central part of the basin – if catastrophic at all – must be older than about 1.2 Myr, and thus much older than previously believed. Multi-channel, deep seismic profiling would be required to solve this problem…

10. Tectonic deformation of the basin interior

Current models for the structural evolution of the northern Tien Shan [14] [21] [19] indicate that most of the Cenozoic strain has been accommodated by the broad deformation zones separating the intermontane basins from the surrounding mountain ranges, and that the basin interiors have been largely protected from tectonic deformation. However, field data indicate that since the late Quaternary younger fault systems have started to propagate into the basin centers where they currently absorb a significant amount of the deformation.

Our reflection seismic data bring clear evidence for recent compressive deformation in the centre of the Issyk-kul Basin [34]. The ridge affecting the eastern part of the deep basin floor consists of anticlinally folded basin-floor strata, transected by a gently dipping fault parallel with the fold axis. The fact that the anticline still persists in the lake-floor morphology suggests that it is a relatively young feature. If not, it would already have been buried as a result of the ponding and onlapping behaviour of the turbidite component of the basin-floor deposits. In fact, detailed analysis of the lap-out patterns of this turbidite facies against the flanks of the ridge indicates that the onlap limit does not gradually approach the crest of the anticline as would be expected with a gradual burial (Figure 15). This suggests that the anticline is still actively growing [34] [26].

Up to present, the anticlinal fold is the only indication for recent or active tectonic deformation in the lake basin. Ongoing studies are currently investigating the relationship of this fold with a series of recent strike-slip and reverse fault structures that have recently been discovered along the southern shores of the lake. Similar anticlinal structures are also well expressed in the onshore part of the basin-floor topography towards the eastern termination of the basin.

11. Conclusions

Integrated interpretation of existing bathymetry data, new high-resolution reflection seismic profiles and new short sediment cores that were collected from Lake Issyk-Kul over the past years allows us to define and characterise the main sedimentary environments in the lake. They consist of proximal and distal delta deposits on the eastern and western shallow platforms, glacial outwash deposits along the northern margin, mass-flow deposits, basin-floor turbidites/hemipelagites and basin-floor current-controlled deposits on the flat deep basin floor. A good understanding of the distribution of these sedimentary environments is necessary before collecting sediment cores for paleoclimate studies or environmental investigations.

The seismic data confirm that the lake has been subjected to severe fluctuations in lake level during most of the Quaternary (up to several hundreds of meters below the present level), and that active compressive tectonic deformation is locally affecting the central part of the Issyk-kul Basin. Our data, however, do not bring any evidence in favour of the hypothesis of a mid-Holocene central basin collapse, which is often invoked in order to explain the peculiar lake-floor morphology.

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