Sedimentology of the Late Pleistocene to Holocene Paleolake Merzbacher in the Northern Inylchek Valley (Central Tien Shan, Kyrgyzstan)

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Abstract

During an expedition to the central Tien Shan, Eastern Kyrgyzstan, in 2011, lake deposits in the Northern Inylchek Valley were investigated. Deposits from the following four locations were studied; from West to East, at the Peremitschka plain, which is seasonally flooded by melt waters and then turns into the Lower Lake Merzbacher, which is dammed by the Southern Inylchek Glacier; at the stable moraine-pond-ensemble, and at the glacier front of the Northern Inylchek Glacier.

The development of the Southern- and Northern Inylchek Glacier is quite complex due to the fact that the Northern Inylchek Glacier retreated and advanced at least twice during the Holocene, and hence two fluctuation cycles can be described. The youngest fluctuation cycle has been documented for the last century using remote sensing imageries. In the 1950s a proglacial lake developed which expanded by four kilometres by the 1990s and was then termed Upper Lake Merzbacher. In 1996 the Northern Inylchek Glacier rapidly advanced again, shortening the Upper Lake Merzbacher by 75%.

For analysing the older cycle, which occurred prior to 1900, fine-grained, bedded deposits in the Peremitschka, in the stable moraine-pond-ensemble, and at the front of the Northern Inylchek Glacier, consisting of clayey silt, sandy silt and sandy clay, were investigated. The clay mineralogy of these fine-grained deposits reflects the mineralogical composition of the surrounding Paleozoic bedrock, with the bulk spectrum primarily consisting of potassium feldspar, plagioclase, chlorite, quartz, muscovite, biotite and calcite.

The fine-grained clay- and silt-deposits of the stable moraine-pond-ensemble plot in the field of pelagic suspension in Passegas CM grain size diagram. Soft-sediment deformation of the laminated lake sediments on top of the stable moraine-pond-ensemble comprises microstructures such as asymmetrical and disharmonic folds. The glacio-lacustrine deposits on top of the stable moraine-pond-ensemble are overlain by ground moraine material indicating a glacier advance at the end of the older fluctuation cycle, during which the Northern Inylchek Glacier probably piled up multiple moraine walls east of the Peremitschka plain.

Lining up fine-grained glacio-lacustrine deposits covering the Peremitschka, the stable moraine-pond-ensemble, and the surged Northern Inylchek Glacier, one can delineate a paleolake of approximately 10 kilometres in length, which results in a paleo water level at 3500 m altitude. This lake is termed “Paleolake Merzbacher”, which is inferred to have been dammed by both the Southern and Northern Inylchek Glaciers. Late-glacial to Neoglacial moraines at Poljana, at an altitude of 3530 m above sea level, indicate that the Southern Inylchek Glacier was able to dam Paleolake Merzbacher.

Während der Expedition 2011 in den zentralen Tien Shan (Ost-Kirgistan) wurden an vier Stellen Seeablagerungen im Nördlichen Inylchek Tal untersucht. Es sind dies, von West nach Ost, Ablagerungen in der Peremitschka, einer saisonal durch Schmelzwässer überfluteten Ebene, die dann vom Südlichen Inylchek Gletscher zum Unteren Merzbacher See aufgestaut wird, im stabilen Moränen-See-Ensemble und im frontalen Bereich des 1996 erneut vorgestoßenen Nördlichen Inylchek Gletschers.

Die Entwicklungsgeschichte des Südlichen und Nördlichen Inylchek Gletschers ist komplex, da sich der Nördliche Inylchek Gletscher im Holozän mindestens zweimal zurückgezogen hat und jeweils danach wieder vorgestoßen ist. Luftbild- und Satellitenbilder belegen die jüngste Fluktuation im vorigen Jahrhundert, wobei sich in den 1950er Jahren ein proglazialer See entwickelt hat, der bis 1990 eine Länge von vier Kilometern erreicht hat und als Oberer Merzbacher See bezeichnet wird. 1996 stieß der Nördliche Inylchek Gletscher rasch vor und reduzierte die Länge des Sees um 75%.

Zur Rekonstruktion eines Fluktuationszyklus vor 1900 wurden geschichtete sandig-tonige, sandig-siltige und tonig-siltige Ablagerungen in der Peremitschka, im stabilen Moränen-See-Ensemble und im Frontbereich des Nördlichen Inylchek Gletschers untersucht. Die Tonmineralogie dieser feinkörnigen Ablagerungen spiegelt die Zusammensetzung der paläozoischen Untergrundes wider, denn das Gesamtspektrum umfasst Kalifeldspat, Plagioklas, Chlorit, Quarz, Muskovit, Biotit und Calcit.

Die feinkörnigen Ton- und Siltablagerungen des stabilen Moränen-See-Ensembles plotten im Passega CM-Korngrößendiagramm im Bereich der pelagischen Suspension. Synsedimentäre Strukturen im Hangenden des stabilen Moränen-See-Ensembles umfassen asymmetrische und disharmonische Falten. Da die glazilakustrinen Ablagerungen im Hangenden des stabilen Moränen-See-Ensembles von einer Grundmoräne überlagert werden, wird auf einen neuerlichen Vorstoß des Nördlichen Inylchek Gletschers

geschlossen, der vermutlich zur Bildung der multiplen Moränenwälle östlich der Peremitschka geführt hat.

Verbindet man die Vorkommen der glazilakustrinen Ablagerungen in der Peremitschka, im stabilen Moränen-See-Ensemble mit dem Stirnbereich des Nördlichen Inylchek Gletschers vor seinem rapiden Vorstoß (surge) im Jahr 1996, so lässt sich ein Paläosee-spiegel in mindestens 3500 m Seehöhe rekonstruieren, was einem See von ca. 10-12 km Länge entspricht. Dieser See wird als „Paläo-Merzbacher See“ bezeichnet, der sowohl vom Südlichen als auch vom Nördlichen Inylchek Gletscher aufgestaut wurde. Die spätglazialen bis neoglazialen, linkslateralen Moränen der Poljana auf über 3530 m Seehöhe zeigen, dass der Südliche Inylchek Gletscher eine ausreichende Höhe gehabt haben dürfte, um diesen Paläo-Merzbacher See aufzustauen.

1. Introduction

The system of glaciers and lakes, which came into existence after the retreat of the Northern Inylchek Glacier, is situated in the Central Tien Shan, Eastern Kyrgyzstan. In 1902 the Bavarian alpinist and researcher Gottfried Merzbacher discovered a lake in the Northern Inylchek Valley at 3300 m altitude, which was later named after him (Fig. 1). This lake has become famous for its regular outbursts (Mavlyudov, 1997; Glazirin, 2010), the mechanism of which was studied e.g. by Ng et al. (2007), Hagg et al. (2008), Mayer et al. (2008), and Ng and Liu (2009). The Northern and Southern Inylchek Glaciers were the subjects of many expeditions, both by the (former) Soviet Academy of Sciences and from abroad (Meiners, 1997; Mavlyudov, 1998; Aizen, 2006; Fischer, 2010).

Since the 1950es, two lakes have basically existed in the Northern Inylchek Valley. The lower is at an altitude of 3300 m above sea level, and only comes into existence seasonally. The higher, perennial lake is at an altitude of 3400 m. The two lakes are termed Lower Lake Merzbacher and Upper Lake Merzbacher. South of the former confluence of the Northern and Southern Inylchek Glacier, the Global Change Observatory Gottfried Merzbacher was constructed at “Poljana” (Russian for meadow; also termed green yard camp) in 2009, located at an altitude of 3530 m (Wetzel, 2009). Using the GCO as a base, the glacial geology at the confluence of the Northern- and Southern Inylchek Glacier was investigated. The main aim of studying the Inylchek Glacier system in Central Tien Shan was to investigate the rapid change of glacier dynamics in the Northern Inylchek Valley during the last century compared to the stagnating Southern Inylchek Glacier. Subsurface investigations on the distribution of dead ice at Poljana and Peremitschka were performed during a one-week expedition in 2009 (Häusler et al., 2011). Studies on the tectonic or sedimentological origin of staircase terraces along the Southern Inylchek Valley as well as environmental and sedimentological investigations in the Northern Inylchek Valley were performed during a two-week expedition in 2011 (Häusler et al., 2012 a, b). This paper – on two generations of lake deposits in the Northern Inylchek Valley – is the result of a short-term study of outcrops combined with a remote sensing study of glacier fluctuations of the Northern Inylchek Glacier. Recently published topographic maps from the Alpenverein at 1:100.000 from 0/14 and 0/15 were used for field mapping of the Inylchek region.

A more detailed study of glacier retreat and rapid glacier advance was presented by Kopecny (2014) based on geocoded and enlarged high-resolution remote sensing imageries, namely aerial stereo pairs (1943-1956), KH (1960-1974), Landsat MSS (1975-1990), SPOT 3 (1996), JERS-1 (1996), IRS-1 (1997), Landsat 7 (1999-2002; 2011), Aster (2003) Quickbird (Google Earth, 2005), and RapidEye (2011).

Figure 1: Northern and Southern Inylchek Glacier, central Tien Shan, Eastern Kyrgyzstan. The circle indicates the 2011 investigation area near Dës Valley in the Southern Inylchek Valley and the square indicates the investigation area in the Northern Inylchek Valley (URL1 for overview; section of central Tien Shan changed after map at original scale 1:500.000, Goscartographia 2002). Note that the larger lake (Lower Lake Merzbacher) in the Northern Inylchek Valley is an intermittent lake whereas the smaller lake (Upper Lake Merzbacher) is a permanent lake.

2. Geological and environmental setting

Central Asia consists of a “jigsaw puzzle” of Precambrian terranes surrounded by fold belts originating from the Caledonian-, Hercynian-, and Alpine/Mediterranean orogeny. The Altaids, the Central Asian Orogenic Belt including the study area of the Inylchek region in Kyrgyzstan, is one of the largest accretionary orogenic collages in the world with the highest rate of Phanerozoic continental growth (Xiao et al., 2009;

Kröner and Rojas-Agramonte, 2014; Şengör et al., 2014). The subduction-related orogeny of the Altaids started in the late Precambrian and gradually migrated southward over time. The Southern Altaids include late Paleozoic to Permian arcs, late Paleozoic to mid-Triassic accretionary wedges composed of radiolarian cherts, pillow lavas, ophiolitic fragments, and high pressure/ultrahigh-pressure metamorphic rocks. The northward subduction of the Tarim block in the Cenozoic resulted in the final closure of the Paleoasian Ocean. Due to the fact that Tien Shan is one of the tectonically most active belts on the globe (Kalmetieva et al., 2009; Zubovich et al., 2010) strong earthquakes have also been recorded in historical times.

In 1965 a geological map of the Eastern border region of Kyrgyzstan was printed at a scale of 1:200.000 (Zakharov and Mozolev, 1971). The explanations were published by Zakharov in 1988. More recently, Mikolaichuk and Buchroithner (2008) compiled the geological map 1:200.000 of the Inylchek Valley and Mikolaichuk et al. (2010) published the explanations. Where topographic maps derived from geodetic surveys and aerial photographs from the 1950s are available, changes in glacier size become obvious. For a few Tien Shan glaciers (e.g. in the Ala Archa region), topographic surveys even date back to the 1860s. During Soviet times the glaciers of the Tien Shan were documented in the Glacier Catalogue of the former Union of the Socialistic Soviet Republics (UdSSR; 1968-1982).

Presently, the Southern Inylchek Glacier is about 61 km long. Its glaciated catchment comprises Pik Pobedy (7493 m) and Khan Tengri (6995 m) bordering Kazakhstan and China. The debris-covered glacial tongue of the Southern Inylchek Glacier terminates at an altitude of 2950 m (Fig. 1). Comparing its position to the photo-documentation of Merzbacher (1906) shows the position of the glacial tongue to have remained constant since 1903. Moraines in the Southern Inylchek Valley were dated by Lifton et al. (2014) and reveal stages from the Last Glacial Maximum in the lower to Late Glacial advances in the upper valley.

North of the junction of the Northern and Southern Inylchek Valleys, the Northern Inylchek Valley comprises six morphologically different segments (Fig. 2), namely the bended Southern Inylchek Glacier with its frontal ice-dam, the Peremitschka (A-B), a couple of 25 m high moraine walls, convex in Western direction, the stable moraine-pond-ensemble (C) and Upper Lake Merzbacher, a proglacial lake of the Northern Inylchek Glacier (D). The area between the moraine dams and Upper Lake Merzbacher is termed “stable moraine-dam-ensemble”, because a comparison of the geometry, size and relation of slopes, kettles and ponds behind the frontal moraines remote sensing imageries from the 1940s to nowadays reveals that the geometry, size and relation of slopes, kettles and ponds of this area has not changed significantly (Häusler et al., 2012 b). The Peremitschka is a 4,5 kilometer long, gently south-west dipping plain, situated between the ice-dam of the bended Southern Inylchek Glacier and the walls of the frontal moraine of an older stage of the Northern Inylchek Glacier.

In the summer period, melt waters, predominantly discharging the Northern Inylchek Valley, regularly fill this plain. When the Peremitschka is flooded, Lower Lake Merzbacher starts to form, and is dammed by the bended Southern Inylchek Glacier. As soon as the ice-dam is lifted by buoyancy, the bended Southern Inylchek Glacier advances a few hundred meters into the Northern Inylchek Valley (Mavlyudov, 1997), and the ice-dam calves. As soon as the water level of Lower Lake Merzbacher reaches a threshold, the lake bursts out. After the water of the lake is released through englacial channels of the Southern Inylchek Glacier, the formerly floating icebergs, which calved from the

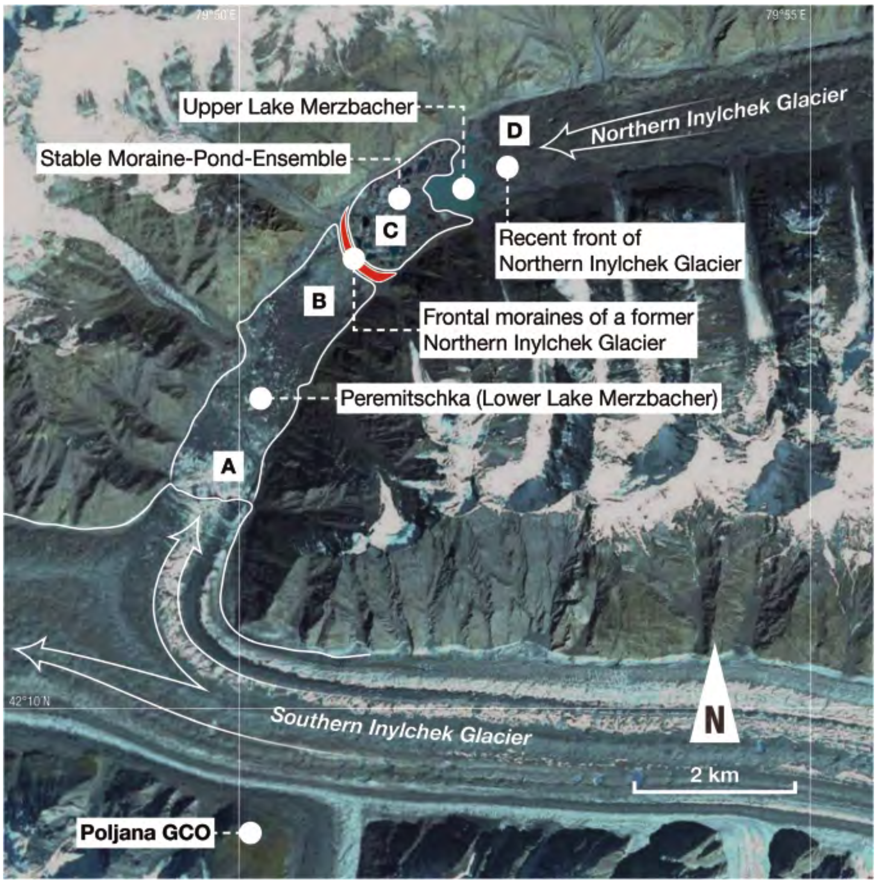

Figure 2: Sections A-D investigated in the Northern Inylchek Valley. The Peremitschka is regularly flooded and then becomes Lower Lake Merzbacher. The Global Change Observatory (GCO) Gottfried Merzbacher was constructed at Poljana (Google Earth). Sections A-D correspond to outcrops presented in Fig. 5.

front of the Southern Inylchek Glacier, are grounded on the Peremitschka. The satellite image of Fig. 2 reveals such white spots of grounded icebergs randomly spread over the Peremitschka. Frontal moraines are missing from the front of the bended Southern Inylchek Glacier.

The thickness of clayey to silty deposits exposed in the central Peremitschka is at least 10 meters. They are underlain by dead ice, as described from an outcrop in the south-western part of the Peremitschka plain, and also by a high resistivity layer of at least 50 meter in thickness, which Häusler et al. (2011, Fig. 6) interpreted as dead ice of the retreated Northern Inylchek Glacier. A couple of high moraine walls (up to 25 meters) border the Peremitschka to the northeast. A narrow valley discharging Upper Lake Merzbacher cuts the 2-kilometer long, stable moraine-pond-ensemble to the east. Upper Lake Merzbacher is a permanent lake, which, according to the aerial photos available, was formed in the 1940s as a proglacial lake in front of the retreating Northern Inylchek Glacier (Fig. 3). Its size has both increased and decreased during the last 60 years.

2.1 Recent development of Upper Lake Merzbacher

A detailed description of the glacier retreat and advance based on remote sensing imageries of the last 70 years, and the resulting increase and decrease in size of Upper Lake Merzbacher, are not topic of this investigation. For considerations on the sedimentology of Paleolake Merzbacher only major steps of landscape evolution are presented, namely the formation of the Lake between the 1940s and 1990s, and its rapid reduction in size due to advance of the Northern Inylchek Glacier within three months in late 1996 (Kopecny, 2014; see Fig. 3).

An aerial photo taken on April 7, 1943 reveals that an Upper Lake Merzbacher did not exist at that time, but instead abundant sinkholes and small supraglacial ponds covered the front of the Northern Inylchek Glacier. In its frontal part, a proglacial lake came to exist, which can clearly be delineated in the 1956 aerial photo, and the aerial photo taken in 1990 shows that the lake had reached a length of about four kilometres by that time. After a rapid advance of the Northern Inylchek Glacier in late 1996 (Häusler et al., 2012 b), the size of the Upper Lake was once more reduced to its 1956 extent (Fig. 3: satellite scene acquired September 11, 2005). Time series analysis of remote sensing imageries clearly reveals that the relation between ridges and smaller ponds in the stable moraine-pond-ensemble (West of the Upper Lake) remained identical, considering that in 1956 high water conditions caused a higher water level in the lake, which also flooded the depressions of the stable moraine-pond-ensemble (Häusler et al., 2012 b).

Following the original and more descriptive definition of Meier and Post (1969), Häusler et al. (2012 b) described the 1996 rapid advance of the Northern Inylchek Glacier as a glacier surge. Glacier surges are now defined as cyclic phenomena which are not directly triggered by external events, but instead result from internally driven oscillations in the condition of the glacier bed (Benn and Evans, 2010, p. 187). The cause and mechanism of the rapid advance of the remote Northern Inylchek Glacier is still unknown as it is the case for the Mushketov Glacier north of Northern Inylchek Valley, which was described as a "pulsing" glacier when its tongue advanced nearly 5 km during the year of 1957 (Williams and Ferrigno, 2010).

3 Material and methods

In order to characterize and compare deposits of recent lakes, supposed paleolakes, and moraines of the Northern and Southern Inylchek Valley, sediment samples were collected. Samples for grain size analysis and clay mineralogy were taken in August 2011 from two locations, namely from the junction of the Dës Valley with the Southern Inylchek Valley, west of the terminus of the Southern Inylchek Glacier (circle in Fig. 1; samples K2011-00, K2011-40), and from the stable moraine-pond-ensemble in the Northern Inylchek Valley (samples K2011-50 to

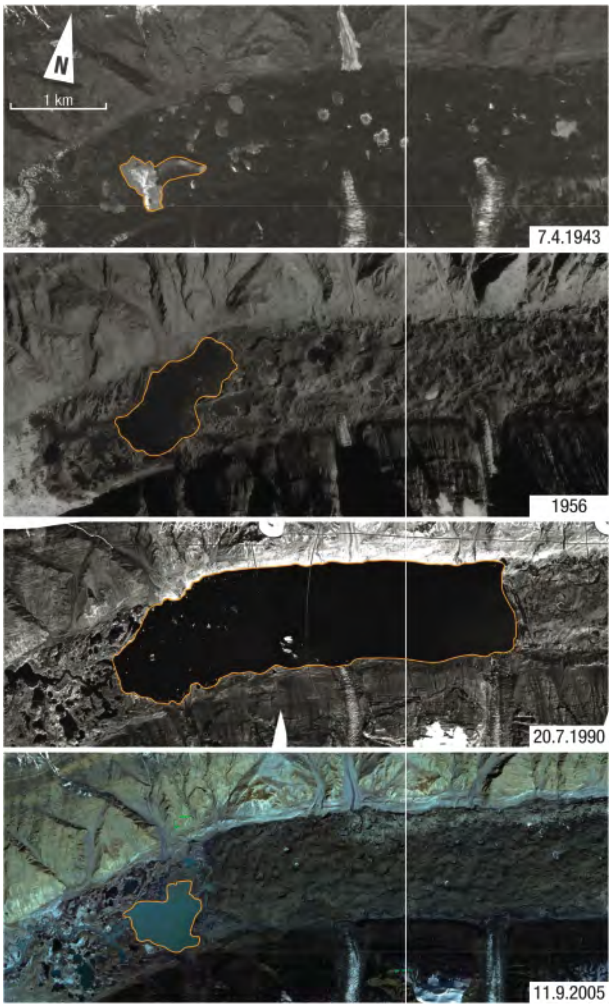

Figure 3: Georeferenced aerial photos indicate increase of Upper Lake Merzbacher from 1943 to 1990, and Quickbird satellite image acquired in 2005 (Google Earth) reveals reduced size of the lake due to 3 km advance of Northern Inylchek Glacier (Häusler et al., 2012 b; aerial photos courtesy of V. A. Kuzmichenok, Kyrgyz National Academy of Sciences, Institute for Water Problems and Hydroelectricity, and S. A. Erochin, Ministry of Natural Resources).

K2011-70; Table 1). Sample K2011-00 represents fine-grained fluvial deposits of the recent Inylchek River. Sample K2011-40 was taken close to the Dës Valley from a massive ground moraine of 10 meters in thickness, containing abundant striated pebbles of dark Paleozoic limestone (Fig. 4).

3.1 Grain size analysis

The amount of material taken for grain size analysis varied between 290 g and 4000 g depending on its visible grain size range and composition. The maximum sample of 4 kg was taken from a moraine (K2011-50) overlying the layered deposits of the stable moraine-pond-ensemble. The coarse material of till containing clasts of up to 20-50 cm in diameter is underrepresented in the diagram because no bigger samples (e.g. up to several tens of kilograms) were taken.

Due to the fact that the organic content of a few samples was very high, organic carbon was eliminated before sieving by adding diluted hydrogenperoxid. Grain size distribution of the sediment samples was analyzed by a combination of two methods. First, the total sample was separated by wet sieving into three fractions: (1) > 2.0 mm mesh size, (2) 2.00 - 0.063 mm, and (3) < 0.063 mm. The sand fraction > 63 µm, was measured by a sediment balance (Macrogranometer), the pelite (silt and clay) fraction was analyzed by Sedigraph (c), based on the X-ray monitored gravity.

Finally the grain sizes were plotted as cumulative grain size curves, various grain size parameters (e.g. Pettijohn et al., 1987) were calculated, and samples were classified in triangle diagrams with weight-% of clay-silt-sand/gravel.

3.2 Bulk and clay mineral analysis

Powdered samples prepared with an agate mill were used for the analysis of the bulk mineralogy with X-ray diffraction. The sample powders were pressed into the sample holders and analyzed. To separate the clay fraction, the samples were treated with H_2O_2 to remove the organic matter. They were treated for 3 minutes with a 400 W ultrasonic probe for further disaggregation. The <2 µm fraction was separated by sedimentation in an Atterberg cylinder (DIN 51033, 1962). About 10 mg of the samples was dispersed in 1 ml of distilled water and sedimented on glass slides. They were dried overnight at room temperature and analyzed with X-ray diffraction. The <2 µm fractions were then saturated with K^+ and Mg^{2+} ions and again sedimented on glass slides. Additionally, they were vapor solvated with ethylene glycol and glycerol at 60°C for 12 hours to differentiate between smectite and vermiculite and were heated to 550°C (Moore and Reynolds, 1997). The bulk mineralogy and the clay fraction were analyzed with a Panalytical PW 3040/60 X'Pert PRO (CuKα radiation, 40 kV, 40 mA, step size 0.0167, 5 seconds per step) diffractometer. The X-ray diffraction patterns were interpreted according to Brindley and Brown (1980) and Moore and Reynolds (1997).

4. Results and interpretation

Results from field observations and section logging are presented, in particular sedimentary structures, as well as grain

Sample	Location	UTM / WGS 84 / Zone 44T		Clay	Silt	Sand + Gravel	Total
		Easting	Northing				
K2011-**00**	Recent deposit of Inylchek River east of Gribkov Camp; SIV	378163	4671834	1.6	54,2	43.3	99.1
K2011-**40**	Coarse-grained moraine east of Gribkov Camp; SIV	378163	4671834	20.3	35.2	44.5	100.0
K2011-**50**	Coarse-grained moraine deposit at stable moraine-pond-ensemble; NIV	406184	4674801	19.4	43.7	36.9	100.0
K2011-**55**	Fine-grained matrix of coarse moraine at stable moraine-pond-ensemble; NIV	406183	4674972	26.6	63.2	10.3	100.1
K2011-**60**	Recent lake sediment from small lake within stable moraine-pond-ensemble; with very high amount of organic material (10-15%); NIV	406276	4674988	26.6	72.3	1.1	100.1
K2011-**65**	Fine-grained (lake) deposit at stable moraine-pond-ensemble; soft-sediment deformation; NIV	406457	4675047	13.0	77.5	9.4	99.9
K2011-**70**	Recent lake sediment from Upper Lake Merzbacher with very high amount of organic material (10-15%); NIV	408021	4675365	33.5	66.5	0.1	100.1
		Lon	Lat				
Meiners 1997, (Fig. 9)	Moraine at Poljana (3530 m); SIV	42°10´N	79°50´E	15,0	49,0	36,0	100,0

Table 1: Grain size distribution in weight-% of seven sediment samples from moraines, glacifluvial and glacilacustrine deposits, taken in the Southern and Northern Inylchek Valley in August 2011. Abbreviations: NIV = Northern Inylchek Valley, SIV = Southern Inylchek Valley. For comparison grain size distribution from moraine deposit at Poljana (GCO in Fig. 2) described by Meiners (1997; Fig. 9) is added.

size analysis and clay mineralogy.

4.1 Field observations

In the Eastern Peremitschka abundant depressions have been observed. They are circular to elongate in shape, one to several meters in diameter or extension, display a crater-like morphology and were interpreted as glacier karst by Häusler et al. (2011). Multiple circular to elongated scarps indicate steady active solifluction processes at the rim of the sinkholes. Outcrops of fine-grained deposits were observed in three areas, namely in the Peremitschka (Fig. 5A, B), in the stable moraine-pond-ensemble (Fig. 5C), and at the front of the Northern Inylchek Glacier advance of 1996 (Fig. 5D).

A small river has locally eroded the Peremitschka plain by about 10 metres, in an area where outcrops at two locations were studied. In its western part (Fig. 5A) the brownish fine-grained deposits of at least one meter in thickness overly massive dead ice. In its north-eastern part fine-grained brownish deposits intercalate with dm thick layers of ice and ice lenses (Fig. 5B). No sedimentary structures were observed in the outcrops of the Peremitschka.

Outcrops yielding abundant sedimentary structures were studied in deposits exposed in the stable moraine-pond-ensemble, an area that was not flooded in the 20th century. Along the ridges between smaller ponds, and on top of the ice-free hummocky terrain grey, often tilted, fine-grained silty deposits are exposed which can be mapped on the satellite images of Google Earth due to their bright colour. These layered deposits are obviously not underlain by dead ice (Fig. 5C). Sedimentary structures were observed in this region between the Peremitschka and the Upper Lake Merzbacher (Fig. 6-8). In a few outcrops these sediments are overlain by a till of a few meters in thickness. At the front of the present Northern Inylchek Glacier tilted layers of fine-grained sediments overly huge blocks of dead ice (Fig. 5D).

The sedimentary structures observed in outcrops on top of the stable moraine-pond-ensemble as well as results from grain size analysis and clay mineralogy are presented in the following.

4.1.1 Sedimentary structures

The widespread fine-grained deposits of the stable moraine-pond-ensemble are preserved in few outcrops (see Fig. 5C) where sedimentary structures were studied. The sequence

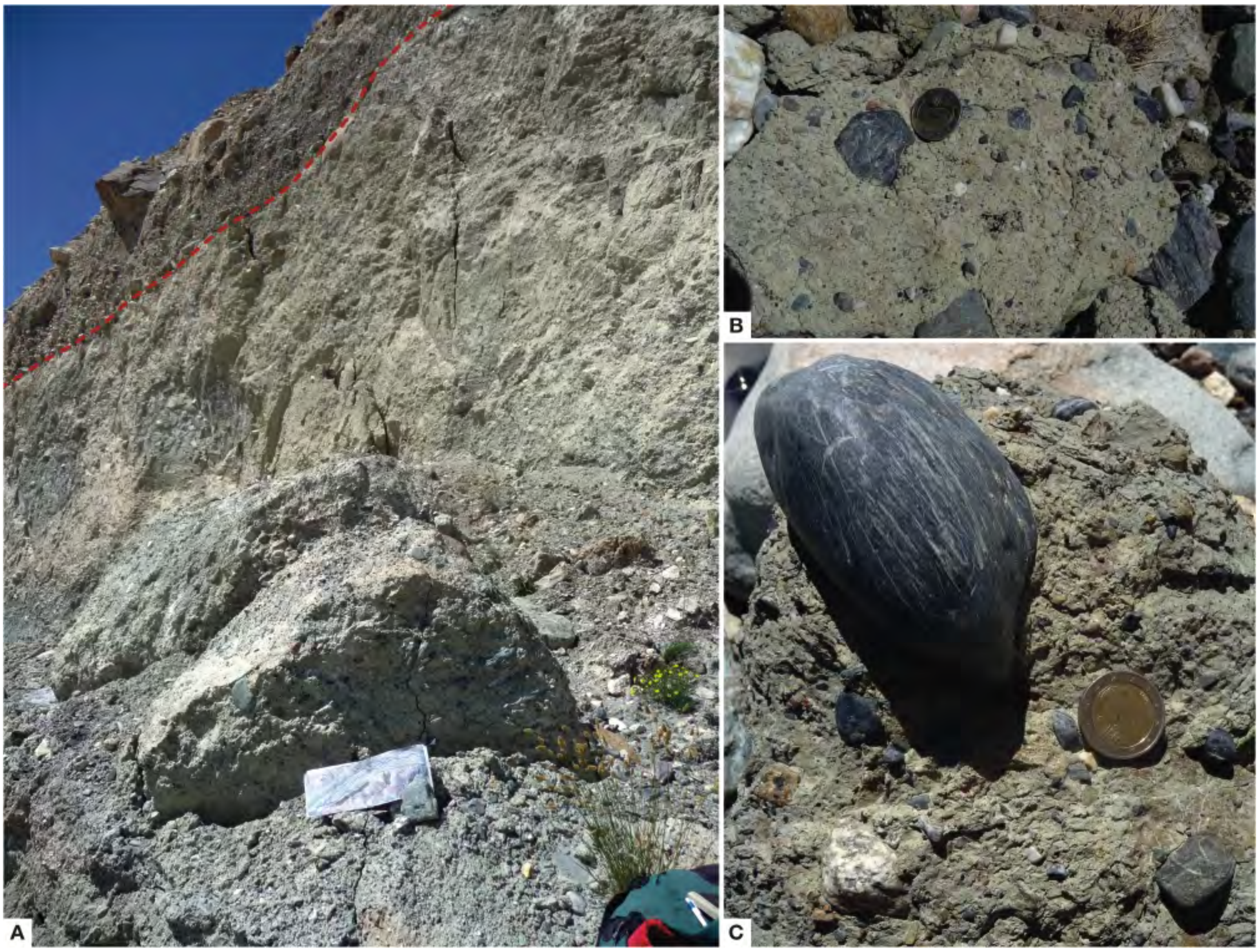

Figure 4: About 10 metres thick matrix supported, unbedded ground moraine (till, sample K2011-40), overlain by 2 metres of fluvial sediments with well rounded pebbles (above red dotted line) east of junction Inylchek Valley – Dës Valley (A). Moraine contains striated coarse debris (B), and striated pebbles (coin for scale; C). Photos by Häusler, 15.8.2011.

compiled from a couple of tilted outcrops at ridges between depressions and smaller ponds is several metres thick in total, and comprises both thin layered fine-grained beds containing single angular clasts and diamict containing angular and rounded debris of dark carbonate rock with clasts of 1-10 cm in size, rich in striated pebbles of dark Paleozoic carbonate rock (Fig. 6).

Soft-sediment deformations such as disharmonic and asymmetrical folds are typically encountered (Fig. 7 and 8).

4.2 Grain size analysis

Samples for grain-size analysis were predominantly taken for characterizing the sedimentary environment of deposits on top of the stable moraine-pond-ensemble (see Fig. 5C), where soft-sediment deformation was encountered. They are compared to a few samples of moraine material taken in the Southern Inylchek Valley, east of Gribkov Camp, at Poljana (Meiners, 1997), and on top of the stable moraine-pond-ensemble in the Northern Inylchek Valley (Fig. 2 and Tab. 1). The analyzed samples have Median values between 0.0034 and 0.051 mm (Trask Median values; Pettijohn et al., 1987) and classify as fine to coarse silts. Sorting is generally poor; with samples K2011-40 (moraine near Dës Valley, East of Gribkov camp; Fig. 1) and K2011-50 (coarse-grained moraine on top of stable moraine-pond-ensemble; Fig. 2) being especially poorly sorted.

The samples taken in the Southern Inylchek Valley, East of Gribkov camp, show a clear dominance of the sand/silt frac-

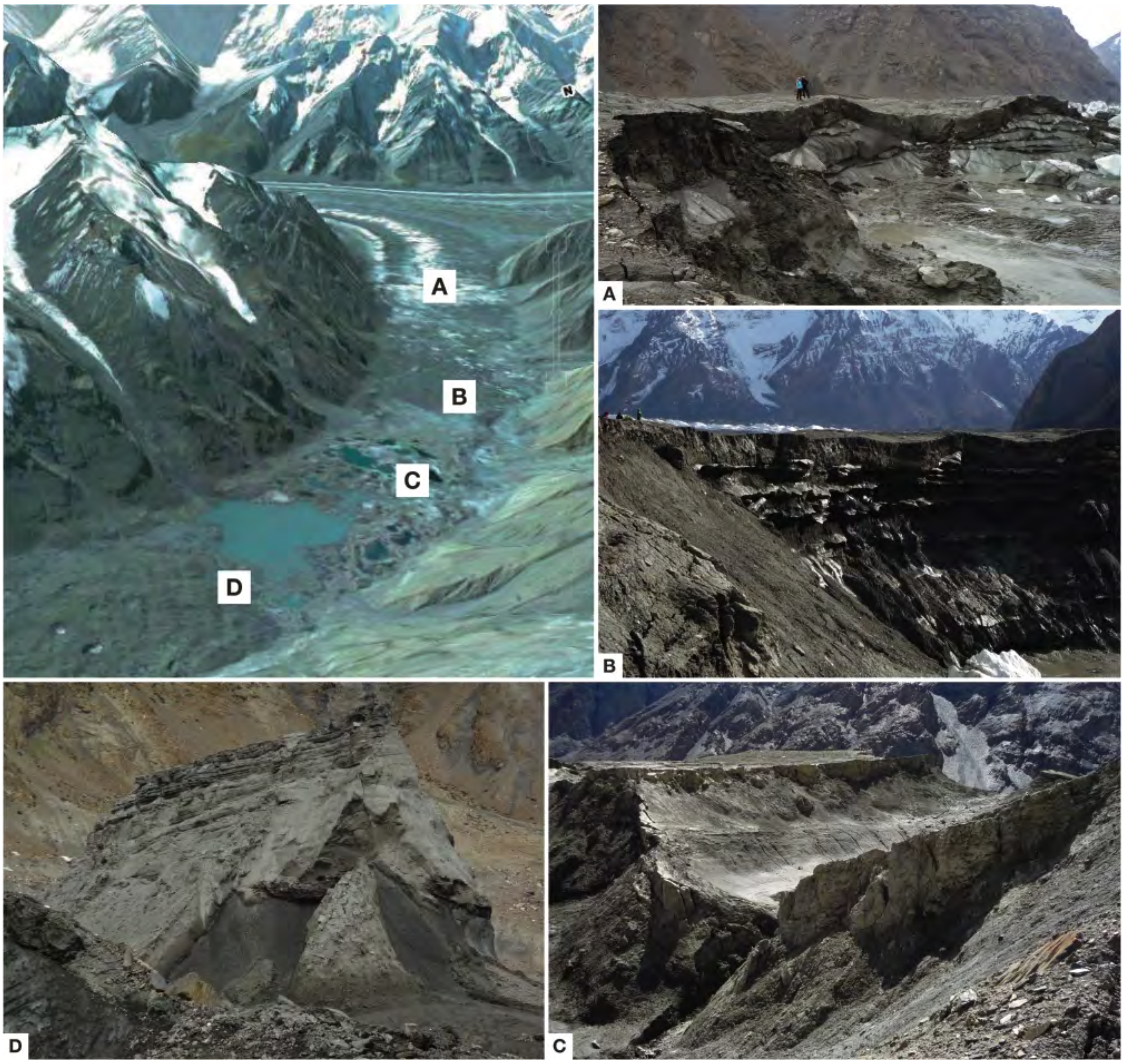

Figure 5: Outcrops of thin-layered deposits in the Northern Inylchek Valley, namely in the Peremitschka (A, B), on top of the stable moraine-pond-ensemble (C), and at the front of the Northern Inylchek Glacier (D). Pictures in the field A-D were taken at locations A-D marked in oblique view of satellite image (Google Earth; view to South-West). For location see also Fig. 2. Photographs taken by Hermann Häusler (A with expedition members for scale: 16.08.2011; B with expedition members for scale: 22.08.2009; C and D: 16.08.2011).

tion with higher amounts of clay. The sample from recent deposits of the Inylchek River (K2011-00) probably represents material from a redeposited till (such as sample K2011-40) with a higher content of sand and silt but without clay, which was washed out and is the cause of the turbid river water (Tab. 1). In the Passega-diagram this sample plots into the uniform suspension field as defined deposit, which was influenced by fluvial transport. Figure 9 shows K2011-40 as a typical till, which can be described as a ground moraine of the former Southern Inylchek Glacier. The high amount of sand/gravel of this till probably represents the high contribution of eroded Paleozoic rock formations, also containing metamorphic rocks, and granites.

Figure 6: In the stable moraine-pond-ensemble few outcrops of thin laminated deposits of several meters in thickness containing smaller clasts are preserved. Coin for scale (left). Debris rich in striated pebbles of Paleozoic carbonate rock was deposited in a diamict, which overlies the thin-bedded deposits (right; Hammer for scale; photographs taken by Hermann Häusler, 16.8.2011).

The grain size distribution of 3 samples taken within the stable moraine-pond-ensemble (K2011-55, K2011-60 and K2011-65) shows a high percentage of clay and silt (Tab. 1). Their clay fraction varies between 13% and 27%, silt varies between 63% and 77% and sand + gravel is low, ranging from 1% to 10%. The recent lake sediments taken from the bottom of Upper Lake Merzbacher (K2011-70) and from the shore of a small pond within the stable moraine-pond-ensemble (K2011-60) are very similar, with a clay content of 26-33%, 66-72% silt and only about 0,1-1% sand/gravel (Tab. 1). These results clearly support the interpretation of the layered deposits studied on top of the stable moraine-pond-ensemble (K2011-65; Fig. 6A and Fig. 7-8) as lake sediments, whereas K2011-55 represents a clay-rich matrix of the hanging wall moraine (Tab. 1; see layer 1 in Fig. 13).

The two samples K2011-60 and K2011-70 were taken from the shore and bottom of recent ponds. The latter were very rich in organic material (up to 30 weight-% of the sample taken) and grain size distribution represents largely eroded and redeposited material from a source which is presently exposed in the stable moraine-pond-ensemble. In particular, samples K2011-60, K2011-65 and K2011-70 represent fine-grained sediments deposited by settling from pelagic suspension as evidenced by the Passega-diagram (Fig. 10). In contrast, samples K2011-40, K2011-50 and K2011-55 plot within field IX, or above, in the Passega-diagram, resembling higher portions of coarse grain-sizes which is characteristic for coarser matrix-supported moraine deposits.

Similar grain-size distribution of deposits in recent ponds and Upper Lake Merzbacher (K2011-60, K2011-70) can either result from surrounding fine-grained moraine material or from relocated older lake sediments.

Meiners (1997) compared the Lateglacial glaciation to the Holocene fluctuations, and took sediment samples from older moraines located in a higher position at the confluence of the Southern and Northern Inylchek Glacier. The composition of a moraine sampled at Poljana at an altitude of 3530 m, which is supposed to be of Lateglacial to Neoglacial age (sensu Meiners, 1997), is a till made up of 15% clay, 50% silt and 36% sand/gravel, which is basically comparable to the moraine sample K2011-50 from the top of the stable moraine-pond-ensemble.

4.3 Bulk and clay mineralogy

The mineralogy of the fine-grained deposits reflects the mineralogical composition of the eroded bedrock. The bulk mineralogy of the samples taken from the moraines and lake sediments in the Northern Inylchek Valley is very similar. They contain quartz, calcite, dolomite, plagioclase (albite), musco-

Figure 7: Outcrop of soft-sediment deformation in laminated fine-grained deposits, located on top of the stable moraine-pond-ensemble. Sedimentary microstructures reveal disharmonic folds. The lower and upper beds are not deformed. Coin for scale (Photograph taken by Hermann Häusler, 16.8.2011).

Figure 8: Soft-sediment deformation in thin-layered deposits observed on top of the stable moraine-pond-ensemble. The sedimentary microstructures comprise laminated clayey silt with small pebbles and asymmetrical folds, which were sheared off locally. Underlying and overlying beds are not deformed. Location of sample K2011-65; coin for scale (Photograph taken by Hermann Häusler, 16.8.2011).

vite, biotite, chlorite and vermiculite (Fig. 11). The composition of the fine-grained samples differs from the moraine sample taken in the Southern Inylchek Valley (K2011-40 in Fig. 11) near the Dës Valley, East of Gribkov Base, which, in addition, contains K-feldspar, but no biotite and vermiculite. Most interesting in the sample K2011-40 is the occurrence of crossite, a type of amphibole, intermediate between riebeckit and glaucophane. Up to now the only known nearby occurrence is reported from the Chinese side of the Tien Shan (URL2). It is likely that such a formation comprising crossite makes up the Paleozoic rock formations, which extend to the upper catchment of the Southern Inylchek Glacier.

The clay fraction of sample K2011-70 consists of chlorite,

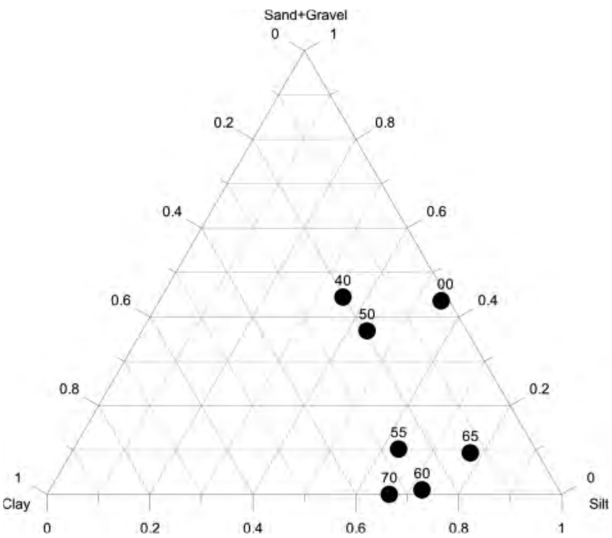

Figure 9: Grain size distribution showing two clusters of sediment samples. Coarser material was taken from river deposits and moraines (samples K2011-00, K2011-40 and K2011-50). Finer material was taken from recent lake sediments (K2011-60 and K2011-70), paleolake sediments sampled in the stable moraine-pond-ensemble of the Northern Inylchek Valley (K2011-65) and from a matrix supported moraine layer (K2011-55).

illite and biotite, and small amounts of vermiculite (Fig. 12). Within all these treatments only a small amount of vermiculite could be identified. No expandable clay minerals such as smectite and no kaolinite are present in these sediments. The vermiculite in the samples (Fig. 11) is rather coarse, it occurs in the fraction >2 µm and is probably a weathering product of chlorite or biotite (Moore and Reynolds, 1997). Clays in lake sediments can be used as an indicator for paleoclimatic conditions (Chamley, 1989). The fact that mostly chlorite and illite are found in the clay fraction indicates that physical weathering prevailed, as would be expected in the study area. Some chemical weathering has occurred for the formation of vermiculite, which was found in the bulk samples. However, the chemical weathering of the Paleozoic rocks must have been minor, because no indicators for heavy weathering, such as mixed layer clay minerals or kaolinite, are present in the clay fraction.

The occurrence of crossite in the clay fraction of a ground moraine deposited in the lower Inylchek Valley (analyzed at junction with Dës Valley, East of Gribkov base) indicates the Lateglacial erosion of a crossite-bearing metamorphic unit in the upper catchment of the Southern Inylchek Valley. Most likely crossite-bearing formations of Precambrian age were squeezed within an accretionary wedge (Xiao et al., 2009) extending from the Chinese side, from where crossite has been reported (URL2), to the west. It is likely that the Atbashi Formation of Early to Late Carboniferous age is a potential source for crossite, which, according to Mikolaichuk et al. (2010, p. 51), represents a polymetamorphic formation of a subduction zone. This formation includes bodies of eclogites and glaucophane shists, belonging to the Paleozoic Structural Complex of the Southern Tien Shan Geological Province (Mikolaichuk and Buchroithner, 2008). Debris from the Atbashi Formation was mapped along the slopes of the main ridge separating the Northern and Southern Valley West of Peak Khan Tengri (6995 m; Mikolaichuk et al., 2010).

5. Discussion and conclusion

The following discusses processes which probably led to soft-sediment deformation of lake sediments in the Northern Inylchek Valley, then continues to reasons for the reconstruction of a larger Paleolake Merzbacher as well as the timing of its formation prior to the beginning of the 20th century.

5.1 Deposits of Paleolake Merzbacher and sediment-deformation triggering processes

According to similar grain size characteristics and clay mineralogy of recent lake deposits in the Northern Inylchek Valley compared with the fine-grained strata on top of the stable moraine-pond-ensemble, these apparently older deposits represent lacustrine deposits from a paleolake that was dammed by the Southern Inylchek Glacier. Grain size indicates deposition from suspension and turbidity flows in a quiet proglacial lake environment together with dropstones falling down from melting ice sheets (Fig. 13, layer 2). Intercalations of fine-grained deposits with lenses of coarse-grained material indicate coarse clastic debris flows from eroded hills made up of Paleozoic shists and carbonate rocks.

The most prominent sedimentary structures encountered in one outcrop of the paleolake sediments on top of the stable moraine-pond-ensemble are folds that can be interpreted as soft-sediment deformation. Slumping and shearing processes causing disharmonic and asymmetrical folds can be interpreted either as resulting from shock-induced liquefaction or from glacio-tectonic processes. As a possible cause, earthquake-induced shaking might have formed these disharmonic and asymmetrical folds (Hoffmann and Reicherter, 2012) but such features represent only one of five criteria for an earthquake-induced liquefaction (Obermeier, 1996). Seismites were described as characteristic features in lake deposits e.g. along the seismically active part of the Alpine thrust and fold belt in Europe (Strasser et al., 2013) as well as within the tectonically active Northern Tien Shan (Zubovich et al., 2010), where Bowman et al. (2004) dated seismites North of Lake Issyk-Kul and within the lake deposits of Late Pleistocene age. However, according to the Kyrgyz atlas of earthquakes (Kalmatieva et al., 2009) the Inylchek region is not prone to strong earthquakes today.

An exposed one meter thick ground moraine which is rich in striated pebbles overlies these glacio-lacustrine deposits (Fig. 13, layer 1). Since synsedimentary folds have not been observed in the lake deposits of the Peremitschka, it is concluded that this layer of ground moraine as well as disharmonic and asymmetrical folds observed in the moraine-pond-ensemble resulted from an advance of the Northern Inylchek Glacier, which terminated east of the Peremitschka, where it piled up frontal moraines. Consequently, the hilly area east of this frontal moraine, termed stable moraine-pond-ensemble, was a central section of a paleolake, overthrusted by the advancing Northern Inylchek Glacier, which now represents an old stage of glacier karst, where the relation of small ponds and moraines has hardly changed over the last 70 years. In conclusion, the former paleolake overthrusted by the Northern Inylchek Glacier must have been larger than the present Lower Lake Merzbacher.

5.2 Landscape evolution

Merzbacher (1905) described a lake of one by four kilometers in size, which was mapped by his team, and which is documented in the topographic map of his expeditions published posthumously by the Bavarian Academy of Sciences (Bayerische Akademie der Wissenschaften, 1928). Therefore it is concluded that the size of the Lake observed in 1903 was more or less identical with the maximum size of the current Lower Lake Merzbacher when it came into existence.

Consequently, at the beginning of the 20th century, a lake significantly larger than four kilometers in extension, covering the stable moraine-pond-ensemble, did not exist. Therefore, a larger lake, as reconstructed from lake deposits of several sections in Northern Inylchek Valley, must have existed prior to 1900. It is inferred that before the westward advance of the Northern Inylchek Glacier, which piled up moraine walls east

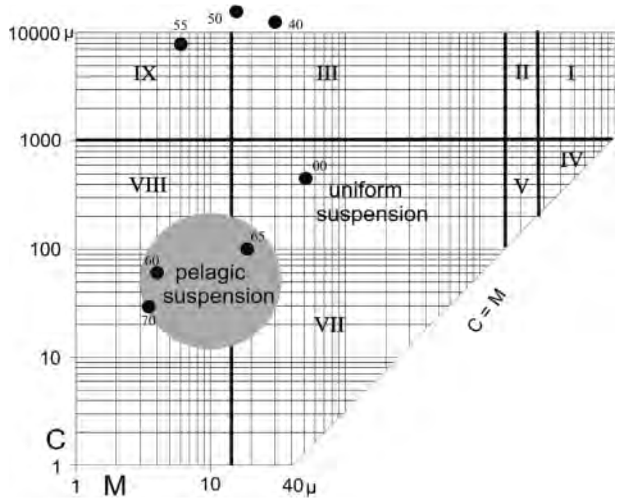

Figure 10: Position of samples in Passegas CM-diagram (coarse 1% vs. median 50%). Samples from recent lakes (K2011-60, K2011-70) and sample from thin-layered bed on top of stable moraine-pond-ensemble (K2011-65) plot in the field of pelagic suspension (modified from Passega, 1964).

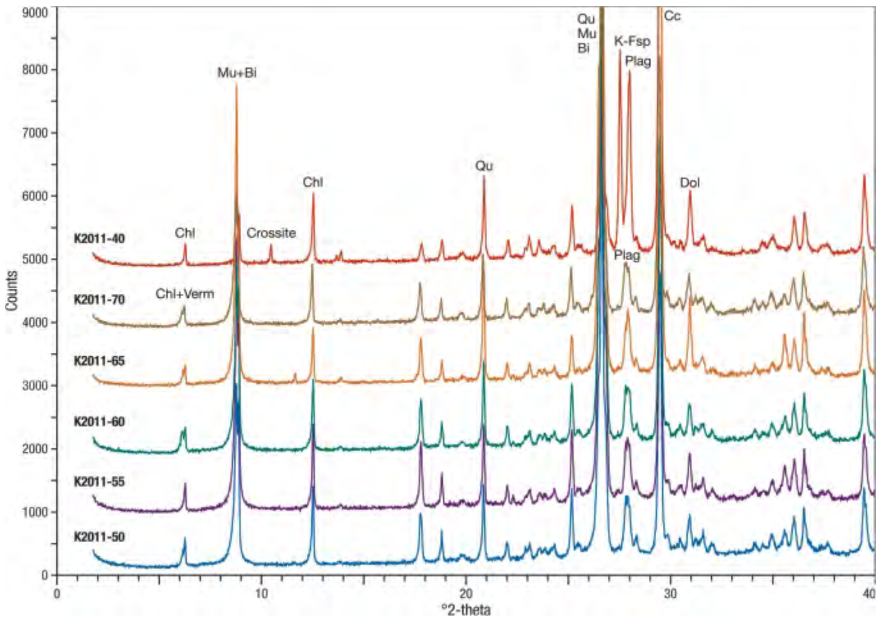

Figure 11: X-ray diffraction patterns of all bulk samples listed in Table 1. The bulk spectra contain quartz (Qu), calcite (Cc), dolomite (Dol), plagioclase (Plag), muscovite (Mu), biotite (Bi), chlorite (Chl) and vermiculite (Verm), and reflect the composition of the weathered surrounding Paleozoic formations. Potassium feldspar (K-fsp) and crossite were only found in sample K2011-40 from the moraine studied close to Dës Valley (Fig. 4).

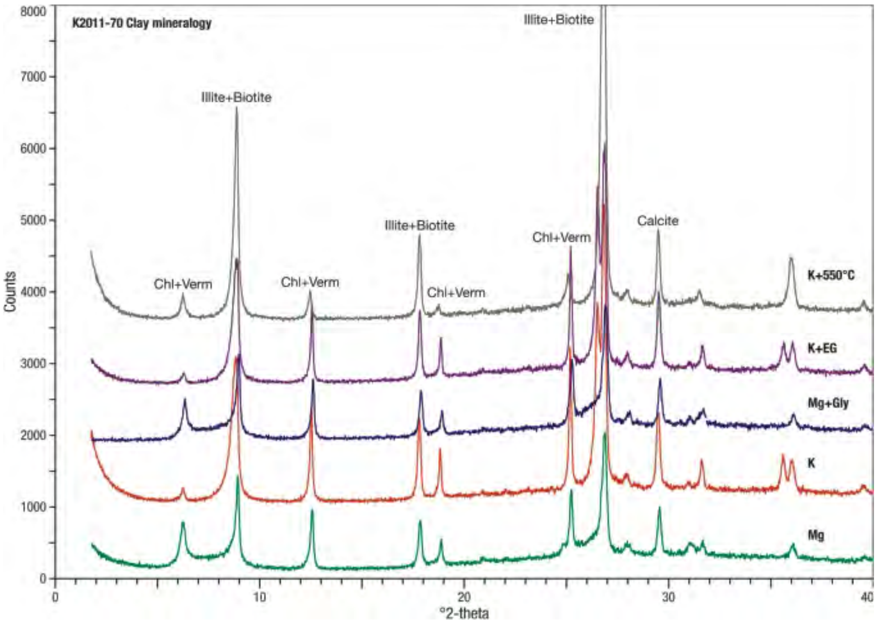

Figure 12: X-ray patterns of the clay fraction of sample K2011-70, taken from recent shore of Upper Lake Merzbacher. Sample was treated with Mg-, K-ions, Mg+glycerol (MgGly), K+ethylene glycol (KEG) and heated to 550°C (KT).

of Peremitschka, the area of the stable moraine-pond-ensemble, was located several kilometers to the east. According to the lake deposits studied, this paleolake comprised the area of the Peremitschka about 4,5 kilometers in length (section with outcrops Fig. 5A-B), a section camouflaged by the advanced front of the Northern Inylchek Glacier including the stable moraine-pond-ensemble at an unknown distance, presumably only a few kilometers, the stable moraine-pond-ensemble of about 2 kilometers in length (section with outcrop Fig. 5C), and lake deposits at the frontal area of the present Northern Inylchek Glacier (outcrop Fig. 5D), which itself surged by at least 3 kilometers in 1996.

Even when the easternmost lake deposits of the 1996 surged Northern Inylchek Glacier (outcrop Fig. 5D) are interpreted as local remnants of downwasting processes on top of the retreated Northern Inylchek Glacier, it is concluded that prior to 1900 a large lake of about 10 kilometers in length in the Northern Inylchek Valley was dammed by the Southern Inylchek Glacier. Due to arguments presented below it is difficult to date this period of paleolake development by comparing glacier fluctuations of the Northern Inylchek Glacier with glacier fluctuations in the neighboring Tien Shan range.

Following the considerations of Koppes et al. (2008) on climatic factors controlling the regional maximum of glacier advances and retreat in Tien Shan mountain belts, a direct comparison of glacier stages in the Inylchek region in the eastern Central Tien Shan with other well dated stages in northern and western Tien Shan is highly hypothetic. Lifton et al. (2014) investigated crystalline boulders spread at kame terraces west and east of the Dës Valley (see Fig. 1), and cosmogenic exposure ages there ranging between 15.000 and 20.000 years before present (YBP) indicate Lateglacial glacier fluctuations.

For further discussion on Holocene glacier fluctuations the terminology of Meiners (1997) was used, who attributed the period between 5500-1700 YBP to Neoglacial, the period between 1700 to 400 YBP to historical phases, and the period of cooling between the 15th and 19th century to Little Ice Age (LIA; 1350-1850 AD; Savoskul and Solomina, 1996).

Comparing Lateglacial to Holocene moraines in the Tien Shan, Meiners (1997) found out that recent ice margins, historical and Neoglacial phases were spatially close to one another, and established a relative system of timing based on the altitude of moraine deposits. Meiners interpreted the left lateral moraines of the Southern Inylchek Glacier at Poljana at an altitude of 3530 m as Lateglacial to Neoglacial stages (Meiners, 1997; moraine levels highlighted in photo 11), and interpreted the historical left lateral moraine walls in the Northern Inylchek Valley at 3500 m altitude as corresponding to the latest glacial maximum (Meiners, 1997; moraine levels highlighted in photo 12).

Solomina et al., (2004) estimated the magnitude of glacier retreat of 293 glaciers in the Tien Shan Mountains from the Little Ice Age (LIA) maximum to the 1980s on the basis of aerial photographs using historical data to control the results, and lichenometry to estimate the age of LIA moraines. They concluded that, on average, the Tien Shan glaciers have retreated by 989 ± 540 m since the LIA maximum. Savoskul and Solomina (1996) investigated the moraines of the Semenov Glacier, ten kilometers north of Northern Inylchek Valley. A sequence of seven lateral moraines was dated by lichenometry (L) as 30, 40, 60-70, 100-110, 160-200, 500 and 1600 L-years ago. The highest lateral moraine M7, at an altitude of 3500 m, is associated with an end-moraine at a distance of about 3 km from the glacier, which is 40 m lower in altitude than the lowest point of the glacier at present. All other moraines are seemingly related to fragments of end-moraines lying on the forefield of the glacier within a distance of 1 km from the tongue. Therefore, during the historical period, the Semenov Glacier experienced fluctuations of rather small magnitudes compared to its enormous dimension.

Visualizing Paleolake Merzbacher northeast of the junction of the Northern and Southern Inylchek Valley in a topographic map at a distance of 10 kilometers results in a lake water level at an altitude of 3500 m. Such a paleolake could have been dammed by the Southern Inylchek Glacier, the crest of which exceeded a height of 3500 metres, when passing Poljana from Lateglacial to Neoglacial times. Such a lake could only have come into existence after the disintegration of both the Northern and Southern Inylchek Glaciers, when the Northern Inylchek Glacier had wasted down, and the valley was flooded by meltwater from the retreating Northern Inylchek Glacier, ice dammed by the Southern Inylchek Glacier. Due to the fact that moraines in the Northern Inylchek Valley have not been dated so far, and that according to Meiners (1997) Neoglacial and historical phases can be located close to one another, there remains a long time span for piling up moraine walls of the advancing Northern Inylchek Glacier bordering the Peremitschka to the east, basically lasting from Neoglacial times to the Little Ice Age.

It is likely that the retreat and advance of the Northern Inylchek Glacier in the second half of the 20th century were controlled more by glacier/lake-interaction after the formation of Upper Lake Merzbacher than by a change of mass balance of

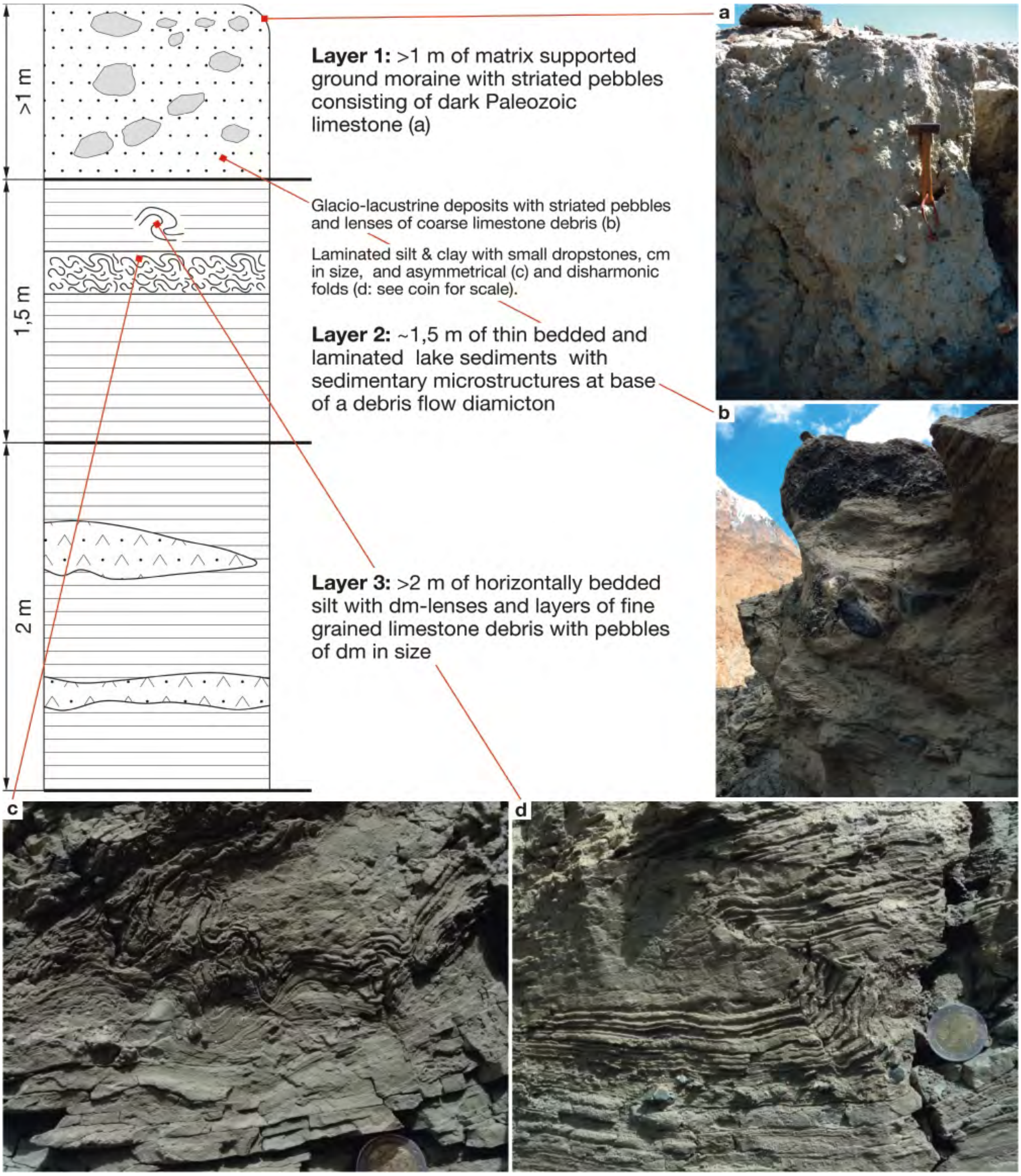

Figure 13: Schematic sedimentological profile of glacio-lacustrine- and moraine deposits, compiled from outcrops (photos a-d) on top of the stable moraine-pond-ensemble. Fine-grained and thin-bedded glacio-lacustrine beds with intercalations of lenses of coarse-clastic beds of in total about 3,5 meters in thickness are overlain by moraine deposits.

the Northern Inylchek Glacier since the 1950s. In this respect, recent fluctuations of the Northern Inylchek Glacier cannot be compared to the fluctuations of the Semenov Glacier (Savoskul and Solomina, 1996), nor can the 1996 surge of Northern Inylchek Glacier be compared to the 1957 pulsing of the Mushketov Glacier (Williams and Ferrigno, 2010; page F 25), because proglacial lakes have never developed in front of either the Semenov or Mushketov Glaciers. In turn it is concluded that the fluctuation of Northern Inylchek Glacier after the decay of the Lateglacial ice stream net was also controlled more by an interaction of Paleolake Merzbacher with a glacier front of the retreating Northern Inylchek Glacier than by a changing glacier mass balance.

Since a first approach of dating lake deposits in the Peremitschka failed (Häusler et al., 2011), and no other dating of moraines or lake deposits in the Northern Inylchek Valley is reported in the literature, it is concluded that Paleolake Merzbacher was formed in the late Holocene, perhaps during a warmer period of the Little Ice Age. Further investigations on the age of lateral and frontal moraines in the Northern Inylchek Valley using optically stimulated luminescence (OSL) for dating fine-grained glacial sediments, and cosmogenic radionuclide (CRN) for dating exposition of crystalline boulders will therefore be of essence.

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