Results from the 2009 geoscientific expedition to the Inylchek Glacier, Central Tien Shan (Kyrgyzstan)

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Abstract

The 2009 expedition led to the Inylchek Glacier in eastern Kyrgyzstan, the largest glacier of the Tien Shan with a length of 60,5 kilometers. In this paper we present the results of our investigations in the surroundings of the Northern Inylchek Glacier, namely in the Peremitschka, the seasonally flooded plain situated between the Southern Inylchek Glacier and Upper Lake Merzbacher. During the summer, this plain is flooded by melt water discharged from the Northern Inylchek Valley, creating the up to 120 m deep Lower Lake Merzbacher, which regularly bursts out and releases its water through an englacial piping system of the Southern Inylchek Glacier in. It is due to this unique phenomenon that Lower Lake Merzbacher has been the subject of study by scientists on numerous expeditions during the last century. As a mapping basis for our field works, we used an enlarged scene acquired in September 2005 from the Quickbird satellite with 60 cm ground resolution. For identification of advancing and retreating parts of the Inylchek Glacier system, a pan-sharpened Landsat 7 ETM+ scene (bands 1, 4 and 7) with a ground resolution of 15 m acquired in 2006 was used. A time series analysis of aerial photos dating from 1943 and 1956 was compared to the Quickbird scene from 2005 and revealed first the retreat and later the rapid advance of the Northern Inylchek Glacier along a distance of at least two kilometres. Since neither indications of a glacier lake outburst around Upper Lake Merzbacher nor stretched ogives or erosional scars in the Northern Inylchek Glacier implying a rapid surge could be detected, the mechanism of this fluctuating glacier is subject to ongoing investigations. Our helicopter-supported campaign in the Peremitschka at altitudes between 3300 and 3500 meters lasted only four days. For the glaciogeologic and geomorphologic interpretation of remote sensing imageries we used geophysical methods such as electric resistivity tomography (ERT) and frequency domain electromagnetics (FDEM). The 800 m long ERT-profile crossing the Peremitschka plain revealed resistivities ranging from 6 Ohmmeter (ohm.m) in the near subsurface to 100.000 ohm.m down to a depth of 45 meters. A series of thin, undulated, low-resistivity layers are underlain by a thick high-resistivity layer, which has been interpreted as dead ice from the formerly advancing Northern Inylchek Glacier. A small river flows down the Northern Inylchek Valley, here termed “Merz Rivulet” or “Merzbach”, with a flow of about 30 m^3/second. Along its course it has locally eroded the Peremitschka plain to a depth of 20-25 meters. This steep slope within the Peremitschka reveals an intercalation of silty calcareous lake deposits with ice layers and ice lenses respectively. These outcrops have been interpreted as near subsurface permafrost layers, which can be correlated with the undulated low-resistivity layer of the ERT-profile. Additionally, high resolution mapping of this permafrost zone using frequency domain electromagnetics with 2525 Hertz (Hz) and 5025 Hz revealed cone-like depressions, which were interpreted as glacier karst.

Die Expedition im Jahr 2009 führte zum Inylchek Gletscher in Ost-Kirgistan, dem mit 60,5 km längsten Hochgebirgsgletscher des Tien Shan. In diesem Beitrag geben wir einen Überblick über unsere Untersuchungsergebnisse in der Umgebung des Nördlichen Inylchek Gletschers, der Peremitschka, eine saisonal überflutete Ebene, die sich zwischen dem Südlichen Inylchek Gletscher und dem Oberen Merzbacher See befindet. Während der Sommermonate wird diese Ebene von Schmelzwässern aus dem Nördlichen Inylchek-Tal überflutet und es bildet sich der bis zu 120 m tiefe Untere Merzbacher See. Dieser bricht regelmäßig durch ein im Südlichen Inylchek Gletscher befindliches englaziales Röhrensystem aus. Wegen dieses einzigartigen Phänomens ist der See während des letzten Jahrhunderts von Wissenschaftlern zahlreicher Expeditionen besucht worden. Als Kartierungsgrundlage unserer Feldarbeiten verwendeten wir eine vergrößerte Quickbird-Szene aus dem Jahr 2005 mit 2 m Bodenauflösung. Für die Unterscheidung vorstoßender und abschmelzender Partien des Inylchek Gletschersystems diente eine Landsat 7 ETM+-Szene (der Bänder 1, 4 und 7) aus dem Jahr 2006 mit 30 m Auflösung, die mit Band 8 derselben Szene auf 15 m erhöht wurde. Ein Zeitreihenvergleich von Luftbildern aus den Jahren 1943 und 1956 mit der Quickbird-Szene von 2005 ließ einen Rückzug und darauffolgenden erneuten Vorstoß des Nördlichen Inylchek Gletschers auf eine Distanz von etwa 2 Kilometern erkennen. Da im Umkreis des Oberen Merzbacher Sees weder Hinweise auf einen Gletscherseeausbruch noch im Nördlichen Inylchek-Gletscher spindelförmige Schleppungsstrukturen von einmündenden Seitengletschern identifiziert werden konnten, die auf ein rasches Gletschervorstoßen („surge“) hinweisen würden, bleibt der Mechanismus dieses fluktuierenden Gletschers Ziel weiterer Untersuchungen. Unsere Geländekampagne in Höhen zwischen 3300 bis 3500 m wurde durch Helikopterflüge unterstützt und dauerte nur vier Tage. Als „ground-check“ für die glazialgeologische und geomorphologische Auswertung der Fernerkundungsdaten wendeten wir geophysikalische Unter-

suchungsmethoden, nämlich elektrische Widerstandstomographie und multifrequente Elektromagnetik an. Das 800 m lange Widerstandsprofil quer über die Peremitschka zeigte Widerstände von 6 Ohmmeter (ohm.m) im oberflächennahen Bereich bis 100.000 ohm.m in Tiefen bis etwa 45 m. Eine gewellter oberer Profilanteil mit geringen Widerständen wird in größerer Tiefe von einem hochohmigen Körper unterlagert, der als Toteiskörper des früheren Nördlichen Inylchek Gletschers interpretiert wird. Ein kleiner Bach mit einer Wassermenge von etwa 30 m^3/Sekunde entwässert das Nördliche Inylchek Tal, der in der Folge als „Merzbach" bezeichnet wird. Südlich des Oberen Merzbacher Sees erodiert er die Peremitschka 20-25 m tief und die steile Böschung zeigt eine Wechselfolge siltiger kalkhältiger Seeablagerungen mit Eislagen und Eislinsen. Diese Aufschlüsse werden als Permafrostlagen interpretiert, die der obersten gewellten niedrigohmigen Lage im Widerstandsprofil entsprechen. Eine hochauflösende elektromagnetische Kartierung einer 320 m^2 großen Fläche in diesem Permafrostbereich mit Frequenzen von 2525 Hertz (Hz) und 5025 Hz zeigte lokale trichterartige Strukturen, die in Oberflächennähe Durchmesser von mehreren Metern aufwiesen. Im Vergleich mit den in der Umgebung angetroffenen konzentrischen Einbruchstrukturen werden diese trichterartigen Strukturen geringerer Widerstände als Thermokarst („glacier karst") interpretiert.

1. Introduction

At the beginning of the 20^{th} century the Tien Shan Mountains were subject to many expeditions. When the Bavarian alpinist and researcher Gottfried Merzbacher tried to reach Khan Tengri, a mysterious peak with an altitude of 7.010 m meters located in the Inylchek Valley bordering Kyrgyzstan, Kazakhstan, and China (Merzbacher, 1905; Figure 1), he discovered a lake at 3300 m a.s.l. This lake was later named after him. Due to the fact that two lakes have existed in the Northern Inylchek Valley since the 1950ies, one at an altitude of 3300 m above sea level (a.s.l.) and the second at an altitude of 3400 m a.s.l., these are now termed Lower Lake Merzbacher and Upper Lake Merzbacher. Lower Lake Merzbacher is dammed by the Southern Inylchek Glacier. Since being discovered in 1903, this lake has become famous for its regular outbursts (Glazirin, 2006). Glazirin (2010) documented about 40 outbursts since the beginning of the 20^{th} century. By chance, the members of an expedition of the (former) Soviet Academy of Sciences were able to eye-witness such an outburst in 1990, which is described in detail by Fischer (2010).

In summer 2009 the German Research Center for Geosciences (Deutsches GeoForschungsZentrum, Potsdam) together with the Central Asian Institute of Applied Geosciences (CAIAG, Bishkek) initiated a new station integrating an international network within the initiative "Global Change Observatory Central Asia", named the Global Change Observatory Gottfried Merzbacher (Häusler et al., 2010; Figure 1, Figure 2A). The high mountain observatory network "Inylchek Glacier" comprises a local seismological network, gauge stations, a permanent GPS station as well as hydro- and meteo-sensors. Very small aperture terminals (VSAT) are used for the transmission of data. The main station is installed south of the former confluence of the Southern and Northern Inylchek Glaciers, directly opposite Lower Lake Merzbacher, at "Poljana" (Russian for field) and enables the monitoring of global change in general and geohazards induced by climate change in particular.

2. Study area

2.1 General description

Kyrgyzstan covers an area of nearly 200.000 km^2 and the mountain region of the Tien Shan covers 80% of the country. About 8200 glaciers belong to the summer accumulation type and are fed by snow. The Inylchek Glacier system in the east of Kyrgyzstan comprises glaciers that are between 200 and 300 m thick, and which are heavily debris-covered. The length of the Southern Inylchek Glacier is 60,5 km, and the length of the Northern Inylchek Glacier is 32,8 km (Williams and Ferrigno, 2010; Figure 1).

During recent decades these glaciers have been either strong-

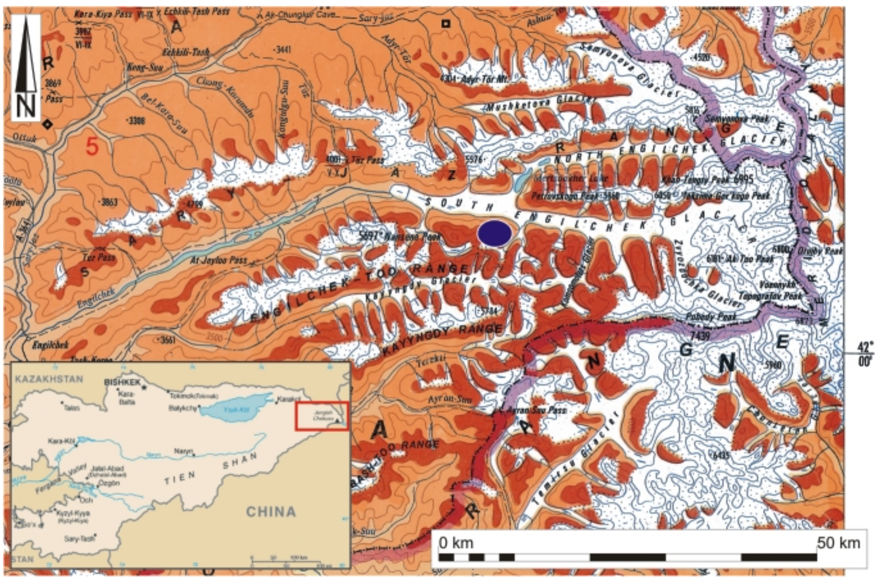

Figure 1: The Central Tien Shan borders Kyrgyzstan, Kazakhstan, and China. The Inylchek Glacier, the largest mountain glaciers in the Tien Shan, is located in the Upper Inylchek Valley, in the east of the Kyrgyz Republic (detail of topographic map of Ysyk Köl Province 1:500.000, Goscartografia, 2002). Blue dot indicates location of Global Change Observatory Gottfried Merzbacher.

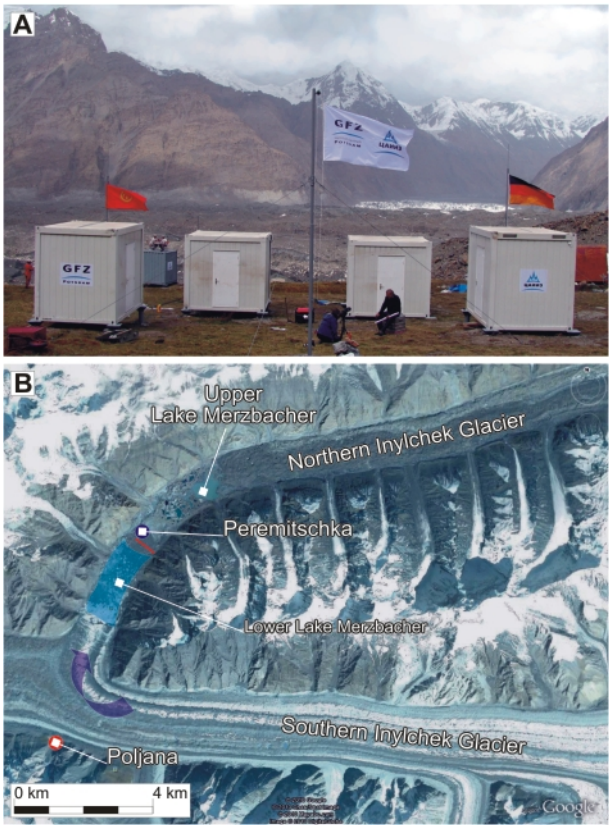

Figure 2: The Global Change Observatory Gottfried Merzbacher is located south of the former confluence of the Northern and Southern Inylchek Glacier ("Poljana", view to north; Wetzel, 2009; A). Satellite image acquired after an outburst of Lower Lake Merzbacher (Google Earth, B). Transparent blue area is maximum size of Lower Lake Merzbacher, when full. Arrow indicates northward bended advance of Southern Inylchek Glacier. Red line indicates geophysical profile at Peremitschka (Figure 6).

ly retreating or at least stagnating. For the neighboring Ak-Shirak Glacier a reduction of 20% in area was calculated between 1977 and 2001 (Khromova et al., 2003).

In 2009, geoscientific field work-based research was conducted at the Poljana, close to the Observatory, and at the Peremitschka (Figure 2B). The Russian term Peremitschka means "area between", and is used to describe the approximately three square kilometre area between the Southern Inylchek Glacier and Upper Lake Merzbacher. The slightly southward dipping plain borders the terminal moraine of the Northern Inylchek Glacier. The Merzbach drains the Northern Inylchek Valley and flows towards the ice-barrier of the still advancing Southern Inylchek Glacier (Figure 3A). Over the summer, it flows toward this glacier at about 30 m^3/s (Mavlydov, 1997) and backs up, forming Lower Lake Merzbacher. Once Lower Lake Merzbacher is full, the Peremitschka is flooded. The bended Southern Inylchek Glacier then presses forward into the Lake and the calving icebergs float on the water. When the hydrostatic pressure of the growing lake reaches a threshold, the englacial piping system of the Southern Inylchek Glacier becomes unblocked and the lake bursts out (Figure 3B).

Lower Lake Merzbacher is drained after a period of several days and most of the icebergs become grounded on the Peremitschka plain. For more details on the bursting mechanism, we refer to Mavlyudov (1997), Ng and Liu (2009) and Glazirin (2010). After an outburst of the Lake, the plain is covered only by these melting icebergs and is therefore more or less dry enough for field campaigns.

The Vienna team's expedition to the Inylchek Glacier in 2009 was for the most part to perform investigations on surface and subsurface structures as a basis for the interpretation of glacial and paraglacial features in remote sensing images. The second main reason for the expedition was to acquire insight into glacier retreat and advance in the Upper Inylchek Valley by performing time series analysis of aerial photos.

2.2 Geologic setting

The terms for the geological division of the Tien Shan Mountains differ from the geographical terms because they are more reflective of the geologic development since the Paleozoic. A geologic map of the eastern border region of Kyrgyzstan was printed at a scale of 1:200.000 by Zakharov and Mozolev (1971). The explanations were published by Zakharov in 1988. Basically, systematic geologic mapping has been carried out in Kyrgyzstan since 1970, and geological maps at a scale of 1:50.000 are theoretically available for more than 80% of the Kyrgyz territory. Although these maps are no longer classified as confidential, they unfortunately are archived in various Kyrgyz institutions and therefore hardly accessible (e.g. Mikolaichuk et al., 2004). More recently, the geological map 1:200.000 of the Inylchek Valley and the explanations of the Khan Tengri Massif were updated by Manfred Buchroithner and Manfred Strecker within the scope of a GIS-project funded by the International Science and Technology Center of the Kyrgyz-Russian Slavic University (ISTC), and published in English by Mikolaichuk et al. (2006), and Mikolaichuk et al. (2009), respectively. According to Mikolaichuk et al. (2009), marine Paleozoic formations of the Khan Tengri Massif comprise folded schists, partly intercalated with fossiliferous calcareous schists, siltstone and sandstone Devonian to Lower Carboniferous in age. The coarse clastic material of the terminal moraine of the Northern Inylchek Glacier and the fine clastic material of the lake deposits of Lake Merzbacher (in the Peremitschka) therefore mainly consist of weathered Paleozoic metasediments, predominantly slates, calcareous schists, siltstone and sandstone.

2.3 Glaciation changes

The Central Tien Shan is characterized by both continental and subpolar climates. Yearly mean precipitation amounts to only 300 mm, even at altitudes above 3000 m. The yearly mean temperature in the Northern Tien Shan is about 9°C, but diminishes to -4°C at an altitude of 3400 m in the Central Tien Shan (Bolch, 2006).

As with other regions in the Central Tien Shan Mountains, the youngest major advance of the Inylchek Glacier took place during the Little Ice Age (LIA; Solomina et al., 2004; Kargel et al., 2005; Aizen, 2006). Global analysis of glacier regimes reveals widespread wastage since the late 1970s, with a marked acceleration in the late 1980s; this is also true for the Tien Shan (Narama et al., 2008; Niederer et al., 2008). The wasting of the Ak-Shirak Glacier system, situated about 100 km northwest of the Inylchek Glacier system, features a significant decrease in average glacier size and an increase in the area of outcrops. A small shrinkage during 1943–1977 was followed by a reduction of at least 20% from 1977–2001 in response to an increase in summer- and annual air temperature and congruent decrease of annual precipitation (Khromova et al., 2003). Bolch (2006) published an excellent analysis of glacier retreat related to climate change in the Northern Tien Shan.

3. Methods

For analyzing the activity of the Inylchek Glacier and as an actual base map for our field survey, we used enlarged copies of high resolution satellite images. For time series analyses of the retreat and advance of the Northern Inylchek Glacier we compared recent satellite images with older aerial photos. For referenciation and image processing we used the ERDAS IMAGINE-software. The multispectral bands 1-5 and 7 of Landsat 7 Enhanced Thematic Mapper Plus (ETM+; Figure 4) with a ground resolution of 30 metres were pan-sharpened using the panchromatic band 8 from the same image at 15 metres resolution. The RGB information from the combination of band 1 (blue; used for differentiating water, soil and vegetation), with band 4 (near infrared; used for enhancing coastal lines) and band 7 (near infrared; used for differentiating water content of soils) led to a very good result for differentiating active and stagnating parts of the glacier in the same scene.

In both the Poljana and Peremitschka test sites we applied geophysical methods for differentiating between debris-covered glacier, lake sediments and permafrost layers. In this paper we present only the results from the Peremitschka, where we applied electrical resistivity tomography (ERT) and electromagnetic mapping. The ERT-profiles were acquired using the standard Wenner-Schlumberger array with 2 m electrode spacing. The measurements were performed with a GEOTOM-4MK100 manufactured by the GEOLOG2000 Company with 100 electrodes connected to a 200 m multi-core cable using the roll-along technique with 50% overlap. The 800 m long profile produced a total number of 2487 apparent resistivity measurements which were displayed in the field in an apparent resistivity pseudosection. The data was eventually filtered and inverted with the RES2DINV software (Loke, 2008). For the inversion process the software calculates a model solving smoothness constrained least-square method. The difference between the initial model (apparent resistivity) and the calculated model is given by the root mean square error (RMS). In the profile of Figure 6, the RMS comes to 3,9%, indicating an accurate model. For the topographical correction of the profile we did a fine leveling survey. Hence it was possible to incorporate the topographic data to the model using the option of the inverse Schwartz-Christoffel method (Loke, 2010; Spiegel et al., 1980) resulting in a slight curvature of the surface topography. This topographical correction achieves the most accurate layer thickness for flat gradients.

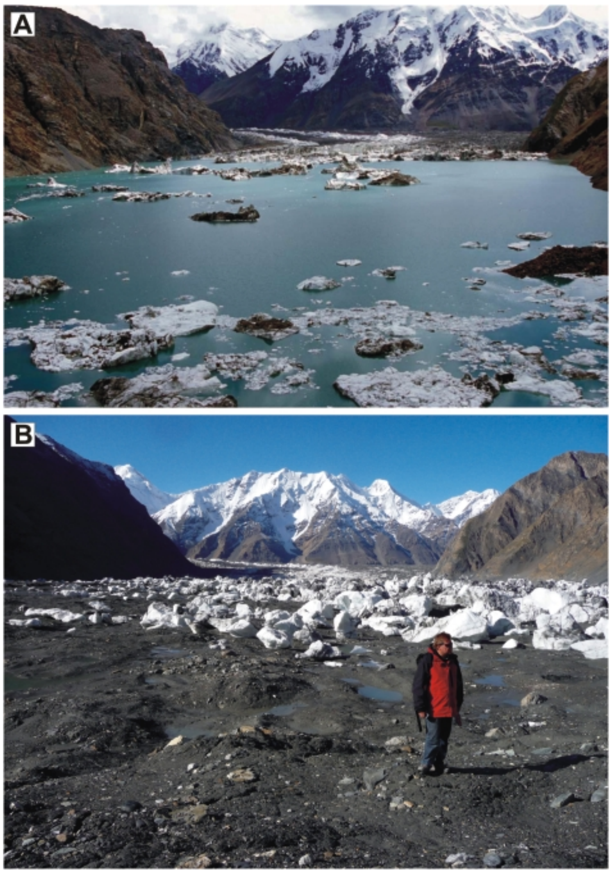

Figure 3: Oblique view of Lower Lake Merzbacher to the south. Icebergs which have split off the forwarding and calving Southern Inylchek Glacier are floating on the Lake (Roussel 2010; courtesy of Marc Roussel, A). After an outburst, the former bottom of Lake Merzbacher turns into the Peremitschka, where the grounded icebergs are exposed to the high solar radiation and melt (photo by Häusler, 24 August 2009; B).

In addition to the ERT survey, we carried out a multi-frequency domain electromagnetic (FDEM) survey in the Peremitschka (Figure 7), close to the ERT-profile, to compare the results of the two complementary geophysical methods. The FDEM survey involves generating a time-varying field (the primary field) from the transmitter coil, which induces eddy currents in the subsurface. These currents, which result in a magnetic field (the secondary field) are measured together with the primary field by the receiver coil. Subsurface features and properties can be deduced from these measurements of the magnetic field, which consists of the in-phase and the quadrature-phase. For the measurements we used a multifrequent GEM-2 (frequency range: 300 Hz to 30 kHz), manufactured by Geophex Ltd. of the USA. The advantage of this instrument is its portability and fast surveying speed, as the simultaneous acquisition of several frequencies (up to five, in this study we used three at a time) enables the imaging of the subsurface at different skin depths. Direct contact with the ground is not needed since induction is used to generate an electromagnetic field in the ground. For this survey we investigated an area of 320 m^2, using a grid of 0,5 m and a data acquisition of three measurements per second adding up to 33.340 conductivity measurements. The data was then converted from the original data format “ppm” to the apparent conductivity in “mS/m” and filtered using WinGem and Surfer software. For the further display of the data we used the apparent resistivity data of the quadrature signal.

In order to interpret processes forming the surface morphology of the Peremitschka plain and to distinguish between older and younger depressions visible in both the satellite images as well as in the aerial photographs, we studied sink holes at various stages of their development.

To sum up, the enlarged high resolution remote sensing imageries from the LANDSAT enhanced thematic mapper (ETM+) served for mapping the local geomorphology of the Peremitschka test site. The genetic interpretation of the geomorphological features helped to interpret the resistivity patterns of the measured electrical resistivity tomography profiles.

The AMS (accelerator mass spectrometry) technique was used for radio-carbon dating and the ^{14}C analysis was performed at the Vienna Environmental Research Accelerator (VERA).

4. Results from the Peremitschka test site

This section comprises first results of time series analyses of remote sensing images as well as surface and subsurface investigations, focusing on the Upper Lake Merzbacher and the Northern Inylchek Glacier. This glacier can be termed a fluctuating glacier since it has advanced and retreated several times. Near-surface geophysical investigations provided a first insight into the subsurface layers of lake sediments probably covering remnant dead ice of the former Northern Inylchek Glacier. Local geomorphologic observations support the interpretation of melting permafrost layers, which were identified in the resistivity tomography profiles as well as in local mapping using high frequency domain electromagnetics. Since the lake was first documented by Merzbacher (1905), the Northern Inylchek Glacier must have retreated considerably before that time. Efforts at dating the lake sediments by pollen failed, but radiocarbon dating of juniper roots indicated the minimum time for the existence of an ice-free environment in the Northern Inylchek Valley.

4.1 Remote sensing

The behaviour of the Northern and Southern Inylchek Glacier during the last century is quite interesting because at the same longitude, latitude and altitude of the Central Tien Shan, the mass balance of the Southern Inylchek Glacier differs considerably. Contrary to the major southern and western parts, which are stagnating and retreating, its northern part is advancing (towards the Peremitschka). The use of the bands 1, 4 and 7 of the pan-sharpened Landsat 7 ETM+ imagery (Figure 4) enabled a very good differentiation of the stagnant or retreating parts of the Southern Inylchek Glacier (shown in red) as compared to the active flow of tributary glaciers (displayed in blue). At the former confluence of the Northern and Southern Inylchek Glacier the bending active part of the southern Glacier as well as the calving glacier and the icebergs also show up in blue. According to Mayer et al. (2008) image cross-correlation of two ASTER (Advanced Spaceborne Thermal Emission and Reflection Radiometer) scenes acquired in June 2003 and June 2004 allowed for offset tracking of the Southern Inylchek Glacier, which resulted in a surface displacement map showing the bended part of the Southern Inylchek Glacier advancing at about 150 meters/year compared to only 9 meters/year for the more or less stagnating area close to the west. The typical surface velocities at the centre of the advancing glacier were calculated in the order of 90-130 meters/year, which was exactly the distance validated by field measurements of stake profiles with a differential GPS in 2004 (Mayer et al., 2008).

Time series analysis of airborne and spaceborne images offers a sound basis for assessing the glacier dynamics during the last 70 years. Between 1990 and 2000, an advance of the

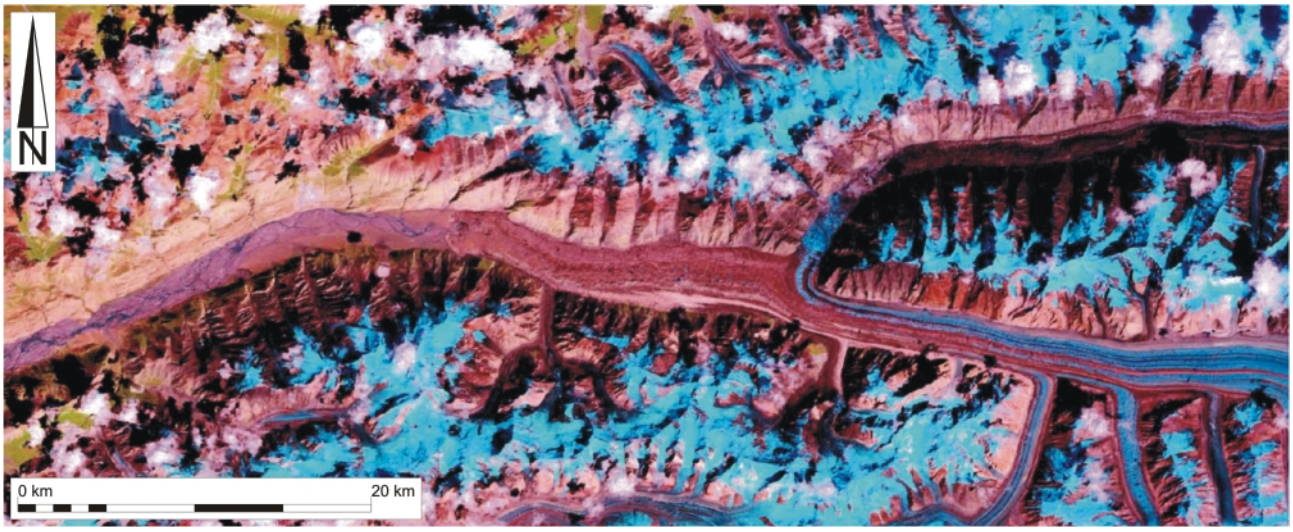

Figure 4: Landsat 7 ETM+ of the Inylchek Glacier (acquired August 2006; pan-sharpened; bands 1, 4, 7; ground resolution 15 m. Source: Global Land Cover Facility – GLCF, Maryland/USA).

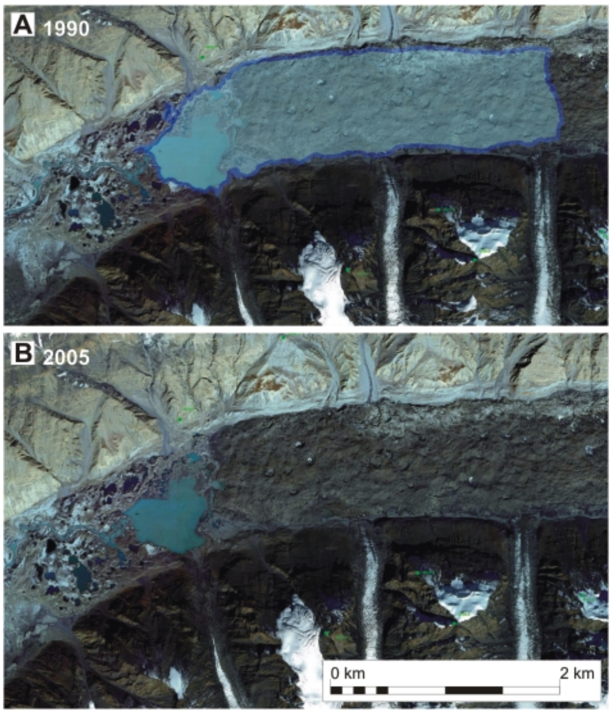

Figure 5: Comparison of Upper Lake Merzbacher between 1990 and 2005. The small lake visible in the Quickbird scene acquired in September 2005 (Google Earth; image 5B) has been draped over the geo-referenced aerial photo taken in 1990 (image 5A). The size of the elongated lake visible in the aerial photo taken in 1990 has been draped over the Quickbird scene from September 2005 (B).

Northern Inylchek Glacier of at least 2 kilometres can be assumed from change detection of the glaciers. The size of the former Upper Lake Merzbacher (which in 1990 equalled the size of the present Lower Lake Merzbacher when full) was then drastically reduced. This rapid advance was interpreted as a glacier surge by Mavlyudov (1998), and probably happened in late 1996.

The interpretation of all remote sensing imageries revealed however, that no surge characteristics such as areas of stretched ogives, erosional scars, transverse crevasses or breaching structures exist around the Upper Lake Merzbacher or in the Northern Inylchek Valley. From a series of frontal moraines of the former Northern Inylchek Glacier visible north of the Peremitschka in all images since 1943, we can also exclude that a glacier lake outburst flood from the Upper Lake Merzbacher has occurred since that time.

The long shoreline of the “black” Upper Lake Merzbacher mapped in the georeferenced aerial photo of 1990 (Figure 5A) was draped over the glacier in the 2005 Quickbird-scene (Figure 5B). This clearly shows how Upper Lake Merzbacher has decreased in size due to the Northern Inylchek Glacier advancing by approximately 2000 metres. Vice versa, the shoreline of the diminished Upper Lake Merzbacher was mapped in the 2005 Quickbird scene and draped over the 1990 aerial photo (Figure 5A). The western and southern shorelines of Upper Lake Merzbacher have remained nearly identical for the past 15 years despite the advance of the Northern Inylchek Glacier. We interpret the bright trim lines on the right lateral (northern) side of the glacier (Figure 5B) not as erosional scars, but as a result of down wasting of the Northern Inylchek Glacier.

To sum up, we found no characteristics indicating a sudden surge, but the comparison of an aerial photo dating 20 July 1990 with a Quickbird scene acquired in September 2005 evidences the fact of a glacier advance, which in the future will be investigated in more detail.

4.2 Geophysical investigations

In the Peremitschka test site we acquired several long profiles in both an east-west and north-south direction using electrical resistivity tomography (ERT). In addition we mapped smaller areas using frequency domain electromagnetics.

4.2.1 Electrical resistivity tomography (ERT)

The almost 800 m long, W-E striking profile shows resistivities to a depth of roughly 45 m below the Peremitschka plain. In total, three differing resistivity layers (a-c) can be distinguished (Figure 6):

a) Upper layer: This 3-5 meter thick undulated layer consists of low resistivities between 0-100 ohm.m. Since the whole surface of the test site is covered by fine grained lake deposits, we interpret this sediment composition as representative for the upper zone. Whereas very low resistivities (<50 ohm.m; silt) prevail in the very near subsurface, slightly higher resistivities (? sand) from running meters 300-370 m and 630-680 m show the undulated base of the upper layer.

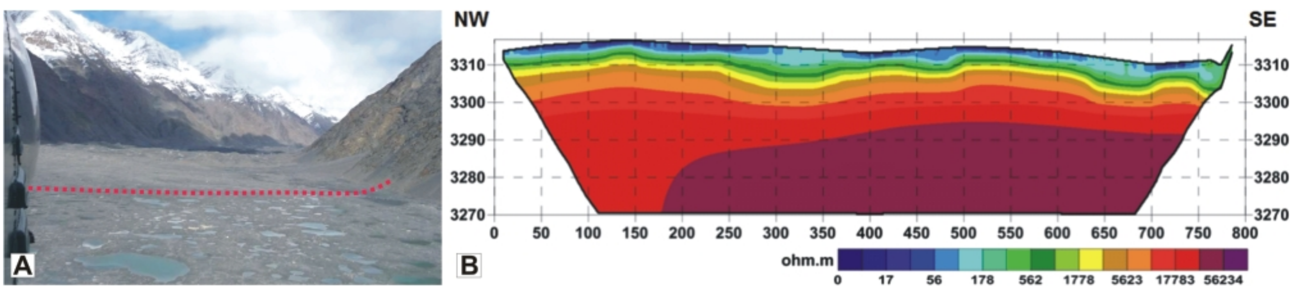

Figure 6: Oblique view of the Peremitschka to northeast (photo taken by Häusler from helicopter on 8 May, 2009). After the outburst of Lower Lake Merzbacher, glacier karst features and countless depressions filled up with water from melting icebergs are visible (A). The ERT profile crosses the Northern Inylchek Valley in a northwest-southeast direction at an altitude of 3320 m a.s.l, and shows resistivities of up to 100.000 ohm.m (B).

b) Sandwich layer: This undulated layer with an average thickness of about 10 m (down to 3300 m a.s.l.) shows resistivities ranging between approximately 200 ohm.m and 10.000 ohm.m. We interpret this "sandwich layer" as the "active zone" of the Peremitschka permafrost zone, the layer, which thaws during summer and freezes again during the autumn. This interpretation matches the observation of alternating thin layers of ice and silt sediment as exposed at the western flank of the Merzbach (Figure 6).

c) Lower layer: High resistivities exceeding 10.000 ohm.m can be correlated with dead ice remaining from the former Northern Inylchek Glacier (below the fine grained lake sediments). This layer shows a thickness exceeding the maximum 30 m penetration depth of the ERT profile. As can be seen in Figure 6, the lowest and highest resistivity layer is bent down to the west. We interpret this geometry of the assumed dead ice body as influenced by the warmer thermal regime caused by the deeply incised Merzbach during the warmer season. For a more sound interpretation a borehole drilling would be necessary.

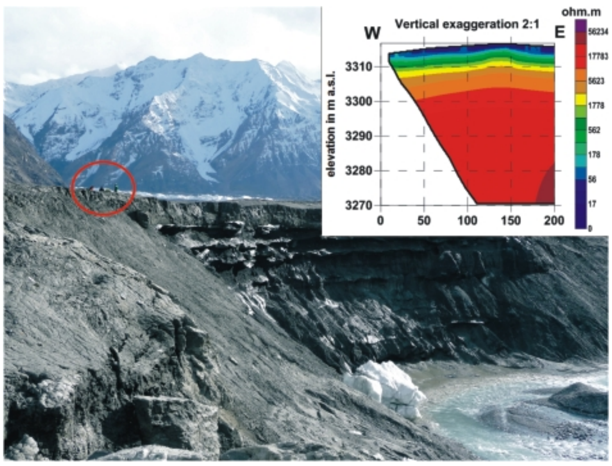

Figure 7: The Peremitschka plain is deeply eroded by the Merzbach. The silty lake sediments, which are intercalated with ice lenses, match the low resistivity layer of the uppermost 15 meters of the ERT-profile. Note crew on top of Peremitschka for scale (photo by Häusler, 22 August 2009).

We use the term glacier karst (Benn and Evans, 2010) to refer to characteristic landforms which result from the thawing of ice-rich permafrost or the melting of massive ice. Sink holes at the Peremitschka with diameters ranging from a few meters to several tens of meters indicate the melting of such ice lenses below. Ice lenses can be seen cropping out of the slope eroded by the Merzbach (Figure 7).

The high resolution ERT measurements are a good tool for the investigation of the near subsurface, giving insights to the general layering as for the identification of small features such as the micro-geomorphology of the Peremitschka. However, the spatial resolution is too low to identify smaller ice lenses of permafrost layers. For this purpose high frequency domain electromagnetic measurements were performed.

4.2.2 Frequency domain electromagnetics (FDEM)

This survey in Figure 8 was taken at the western Peremitschka, in the vicinity of the steep slope, which was eroded by the Merzbach (Figure 2B), in order to detect high conductivity zones (equal to low resistivities of the ERT-profile).

Figure 9 shows the apparent conductivity of the area investigated at two frequencies: 2525 Hz and 5025 Hz. The conductivity revealed in a layer at a certain depth by using one of the frequencies is termed skin depth (Huang, 2005). It describes the distance in which the amplitude of a wave decays to 1/e of its value in a homogenous (and conductive) medium and can be used for an estimation of the effective depth of an electromagnetic wave in the subsurface (Spies, 1989). According to this estimation the penetration depth of these maps is approximately 4-5 meters at 5025 Hz and 7-9 meters at 2525 Hz. Therefore the display of the apparent conductivity map primarily gives a qualitative insight to the variation of the electrical conductivity in the shallow subsurface.

In general, both maps show a similar conductivity pattern. The 5025 Hz-map consists of a very homogenous and low conductive background of 0,25 to 0,4 Millisiemens/ Meter (mS/m) which can be compared to the abundant ice layers exposed in the nearby creek, and which is interpreted as permafrost (Figure 7). The lower frequency map (2525 Hz) shows larger background conductivity of about 1 to 1.5 mS, and since the scale is logarithmic, the difference is about a factor four. This increase in conductivity can be compared to the layered fine grained sediments, which are intercalated with ice lenses down to a depth of approximately 20 meters, as can be seen in the nearby outcrop in Figure 7. Additionally, three high conductivity zones (4 to 8 mS/m) can be distinguished in the 5025 Hz-map and have been tagged as anomaly zones A01 to A03. These three zones are of ellipsoid shape and approximately 20-30 m^2 in size. They show that the core is highly conductive, but that the conductivity decreases gradually towards the rim of this structure. Furthermore, comparing these anomaly zones with the lower frequency map, we see that they are in the exact same position but smaller in extension and lower in conductivity. If these two maps were to be stacked in a three dimensional model, three cone-shaped structures would be the result. These high-conductivity (and therefore low-resistivity) cone-like structures can be interpreted as glacier karst filled with fine grained lake sediments (compare to Figure 11 A).

4.3 Geomorphological observations

As already described for the study area, Lower Lake Merzbacher has been undergoing regular outbursts for one century (Glazirin, 2010), allowing the Peremitschka to fall dry. When the amount of melt water from the Northern Inylchek Valley increases and the Merzbach floods the slightly south dipping Peremitschka plain, the Lower Lake Merzbacher comes into existence and increases in size. Then the forward moving terminus of the bending Southern Inylchek Glacier is raised by the water and begins to calve into the Lake. Close to the calving glacier the lake reaches its maximum depth of about 120 meters and therefore expands three kilometres to the north, to the northern flat shores of the Peremitschka.

Due to the fact that an outburst of Lake Merzbacher lasts for several days, the water level sinks relatively slowly and therefore most of the floating icebergs ground close to the deepest part of the Lake, in the south of the Peremitschka. As the water level sinks, countless depressions with a diameter of one to several tens of meters in diameter remain spread randomly all over the Peremitschka, partly dry and partly filled with water or ice (Figure 10). These depressions can be interpreted twofold. Where a constant deepening of sink-holes is obvious, with stationary depressions, these are probably caused by the melting of ice lenses in the subsurface (Figure 11 A).

Different terms such as “thermokarst”, “glaciokarst”, “cryokarst”, and “glacier karst” are used for these morphological structures. Essentially, these pitted surfaces resemble those formed by solution in some karst areas of limestone, which is how they came to have “karst” attached to their name without the presence of any limestone. Wikipedia, the Internet-ency-encyclopaedia, describes “thermokarst” as a land surface characterized by very irregular surfaces of marshy hollows and small hummocks formed as ice-rich permafrost thaws. The Open University Geological Society Mainland Europe extends “thermokarst” to include both thawing structures in permafrost and the melting of glaciers. In Russian literature the term “thermokarst” is used for the typical morphology of stagnant, downwasting and retreating glaciers. “Glaciokarst” is a term coined by Hans Fischer in a German textbook on exogene morphodynamics (Fischer and Embleton-Hamann, 1992, p. 51). In this textbook the term cryokarst is synonymously used for thermokarst. In another sense, however, the Internet-encyclopedia Wikipedia defines the German term “Glaciokarst” as used for karstified limestone regions which were glaciated during the Pleistocene, and where after their deglaciation the karstification of the limestones continued. In the following we use the term “glacier karst” (Benn and Evans, 2010) to refer to forms developed on wasting debris-mantled glaciers.

The glacier karst of the stagnating and downwasting lower Northern and lower Southern Inylchek Glaciers belongs to the mature type of abla-

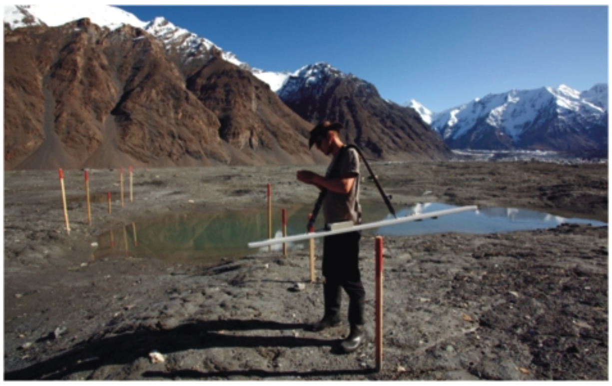

Figure 8: FDEM-measurements in the Peremitschka test site cross water-filled depressions (photo courtesy of Marc Roussel, 24 August 2009).

ting debris-mantled glacier. As can be seen in Figure 4, there are no parallel stripes indicating active ice flow along a distance of about 20 kilometres from the glacier terminus of the Southern Inylchek Glacier. Nor are there such stripes along a distance of 12 kilometers from the front of the Northern Inyl-

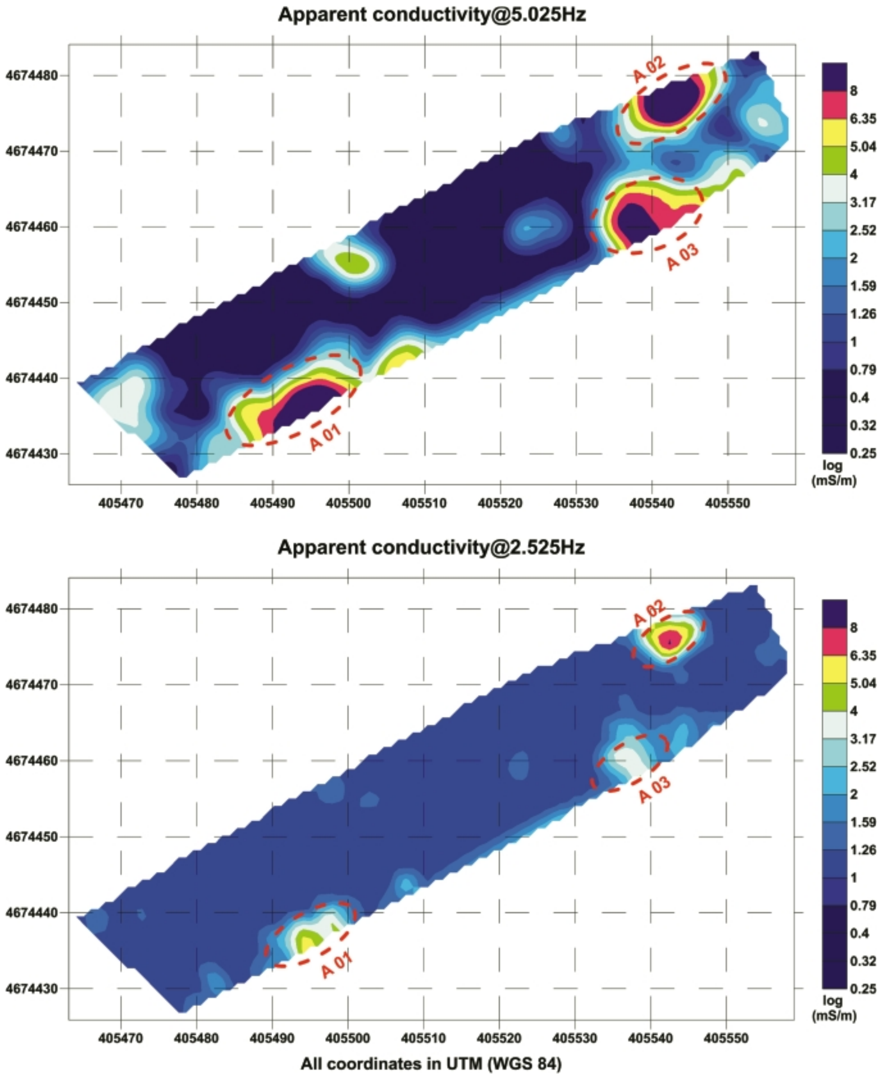

Figure 9: Anomalies A01 to A03 in the apparent conductivity maps (mS/m) for the frequencies 5025 Hz and 2525 Hz reveal high conductivity cone-shaped structures in the subsurface.

chek Glacier. The debriscovered surface consists mainly of sinkholes, lakes at different heights with backwasting margins, and subglacial conduits.

The features of glacier karst, ranging from a few meters to tens of meters in diameter and depth, were observed in the northern part of the Peremitschka only. It is supposed that the northern Peremitschka, consisting of dark moraine- and lake sediments and covered by scarce vegetation, absorbs more solar radiation in late summer than the southern Peremitschka, which is flooded by Lower Lake Merzbacher for longer periods. After an outburst of the Lake, the Merzbach drains the deeply eroded and melting permafrost layers for several months until the lake fills again.

To sum up, mapping the micro-geomorphology of depressions on the Peremitschka plain clearly allows for distinguishing between sink holes initiated by melting permafrost below (glacier karst; Figure 11 A) and crater-like depressions, which occur due to the load of melting icebergs which, depending on the local micro-relief, can also cause local sliding structures on the surface (Figure 11 B).

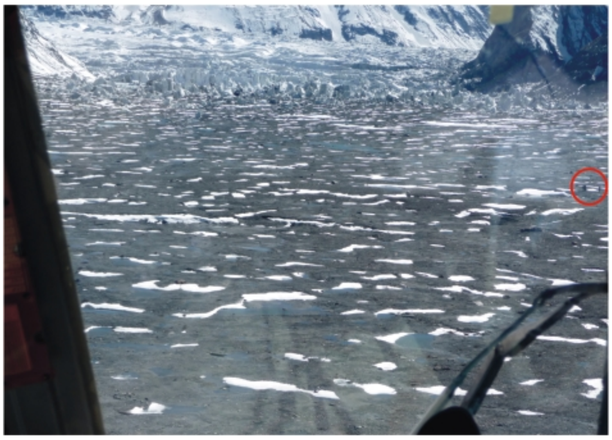

Figure 10: Oblique view of icebergs (in the background), which grounded on the Peremitschka plain after the 2008 outburst of Lower Lake Merzbacher. Note expedition camera team to the right for scale (photo by Häusler, 8 May 2009).

Figure 11: Comparison between a sink hole resulting from melting of subsurface ice lenses (glacier karst – see tents in background for scale; A) and depressions in the lake sediments as a result of melting of the grounded ice bergs (approximately 1 m in diameter; B; photos by Häusler, 24 August 2009).

4.4 Radio-Carbon dating of vegetation

The first description of the lake in front of the Northern Inylchek Glacier dates back to 1903 (Merzbacher, 1905), and therefore the glacier must have retreated prior to this point in time. In order to reconstruct the sequence of events, we took samples from profiles of lake sediments in the Peremitschka to date them by organic material. Due to the fact that several samples of the calcareous black silt were sterile, dating outcrops of the lake sediments by pollen was not successful. However, a dry root of a juniper tree, which was found by chance on the surface of the central Peremitschka, could be dated (Figure 12).

A calibrated ^{14}C-analysis of dry roots from ancient shrubs collected at the Peremitschka test site in 2009 (with 95.4% probability) dates back to 1630-1960 AD (anno domini; Figure 12).

Dating the juniper root to 1630-1960 supports the general idea of the glacier's retreat during the Little Ice Age but gives no reasonable information on the period since when the Northern Inylchek Valley was free of ice and grown over by juniper shrubs. Therefore, the timing of the Northern Inylchek Glacier's retreat is still under discussion.

5. Conclusion

From a time series analysis of remote sensing images we conclude that Northern Inylchek Glacier rapidly forwarded along a distance of about two kilometres due to reasons currently unknown. Due to the lack of characteristic features of a glacier surge combined with excluding a glacier lake outburst flood from Upper Lake Merzbacher, we rule out a typical glacier surge. From the processes described in the previous paragraphs we conclude that the drainage of the Northern Inylchek Valley in connection with the high melting rate of permafrost layers may have caused higher basal water pressure that might in turn have caused the movement of the Northern Inylchek Glacier in late 1996 (or early 1997). We believe that sliding processes of a wet-based glacier terminal, which was underlain by poorly consolidated lake sediments, accelerated an advance of the down wasted and thinned glacier. In other words, we think on a pasty flow due to reduced cohesion at

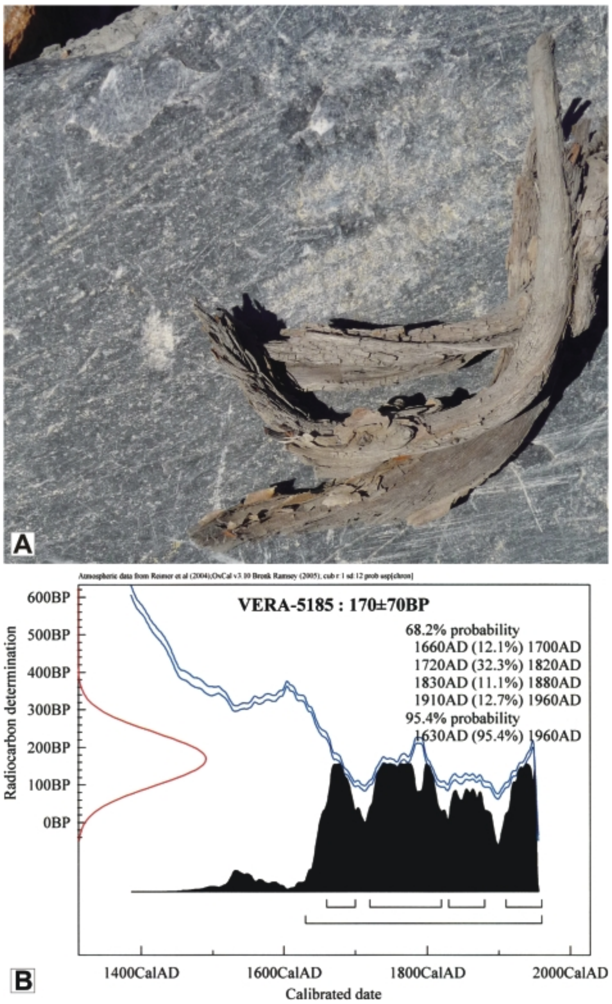

Figure 12: Striated boulder with dry old, 50 cm long juniper root deposited at the Peremitschka plain (A, photo by Häusler, 24 August 2009). The calibrated ^{14}C-analysis of this root dates back to 1630-1960 AD (B).

the base of the Northern Inylchek Glacier.

It is important to investigate and understand such processes, which can explain the unexpected change of the mass balance and behaviour of fluctuating glaciers in the Central Tien Shan. Perhaps the key to solving this phenomenon of a local positive mass balance lies in the regular interaction of the Northern Inylchek Glacier with the Upper Lake Merzbacher itself. In addition, further studies will also concentrate on the correlation of the previous regional glacier behaviour with regional climatologic trends.

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