

Historical glacier-dammed lakes and outburst floods in the Karambar valley (Hindukush–Karakoram)

Lasafam Iturrizaga

Geography/High Mountain Geomorphology, Institute of Geography, University of Göttingen, Goldschmidtstr. 5, 37077, Göttingen, Germany (Tel.: +49-551-39-12135; Fax: +49-551-397614; E-mail: liturri@gwdg.de)

Key words: backwater ponding, geomorphological flood impacts, glacial hazards, glacier-dammed lakes, Hindukush–Karakoram, outburst cascades, outburst floods

Abstract

At least six devastating glacial floods occurred in the Karambar valley in the 19th and 20th century. Previously mainly the Karambar glacier was considered as the origin of these outburst floods. However, in this project more detailed investigations revealed that up to eight more tributary glaciers could have dammed the Karambar valley in historical and prehistorical times. The ice-dammed lakes reached an approximate length of up to about 5 km and more. The dense concentration of the glacier dams along a horizontal distance of only 40 km results in a complex interfingering of lake basins and flooded valley sections. In the individual flood events were probably involved almost synchronously the drainage of at least two lakes resulting in a lake outburst cascade.

The Karambar case study highlights the characteristic geomorphological landforms of the glacier dams, their lake basins and the geomorphological impact of the outburst floods. The abundant occurrence of unconsolidated sediments mantling the valley flanks caused a high sediment load and enhanced the erosion potential of the flood. The erosion cliffs of sediment cones, up to 100 m high, wash limits along the slopes and longitudinal bars in the gravel floors are main characteristics of the flood landscape. Secondary temporary lake formations (back water ponding) during the flood events in consequence of blockages of the ice- and sediment-loaden flood masses occurred at many locations in the narrower valley sections and lasted for several days. Additionally, debris flows in-between the glacier dams have dammed temporarily the Karambar valley. On the basis of losses of settlement area and eyewitness reports, the extent, erosion rates and characteristics of the 1905 flood event could be reconstructed. In order to warn the villagers living downstream, the Karambar people established an early warning fire system (*Puberanch*) from Sokther Rabot to Gilgit which was operated until 1905. The reconstructed Karambar flood chronology represents one of the longest records for this region and provides also information on historical and recent glacier oscillations, especially on exceptional glacier advances. At present, the Chateboi glacier seals the Karambar valley over a distance of 4 km. An outburst flood would have disastrous impacts to the human infrastructure as the settlement areas expanded to the flood plains in the last decades.

Introduction

Glacier-dammed lakes and outburst floods have significantly shaped the sediment landscape in the Karakoram and Hindukush Mountains. Devastating glacier lake outbursts in the last two centuries are especially well known from the Karakoram Mountains. They are one of the most important types of current geomorphological processes below an altitude of 4500 m. In historical times, about 22 tributary glaciers formed ice-dammed lakes in the upper Indus catchment area, from which 12 dams were responsible for outburst floods (Hewitt, 1998a). Since 1826, 35 glacier lake outbursts have been monitored (Hewitt, 1982), although this number only includes a small selection of past flood events. Two localities were notorious for

glacier lake outbursts in the last two centuries: the tributary glaciers of the Shyok valley (East Karakoram) (Mason, 1929, 1930, 1935; Todd, 1930; Visser, 1938; Hewitt, 1982; Feng Qinghua, 1991) as well as of the side glaciers of the Shimshal valley (North West Karakoram) (Visser, 1938; Kreutzmann, 1994; Iturrizaga, 1996, 1997, 1998, 2005c). However, little is known to date about the glacier dams and glacier lake basins themselves as they are mostly located in difficult accessible mountain areas. Moreover, the upper catchment areas are mostly uninhabited, so that outburst events have been only monitored far away from the actual glacier dam failures.

A geomorphological reconstruction of the glacier dams and the downstream impacts of the floods was carried out in the Shimshal valley (Iturrizaga, 1994,

1997, 2005c). A new case study on glacier lake outbursts and glacier dams was conducted in the years 2002–2004 in the Karambar valley (Figure 1, Iturrizaga, 2004, 2005a). The principal aim of the Karambar research project was to identify the glacier dams which existed in the last 150 years in the Karambar valley as well as

which of the glaciers generated outburst floods. Moreover, the geomorphological impacts caused by the lake outbursts were investigated. Using geomorphological evidence, historical reports and photographs as well as eye-witness reports from the local people, the chronology of the glacier lakes and floods could be recon-

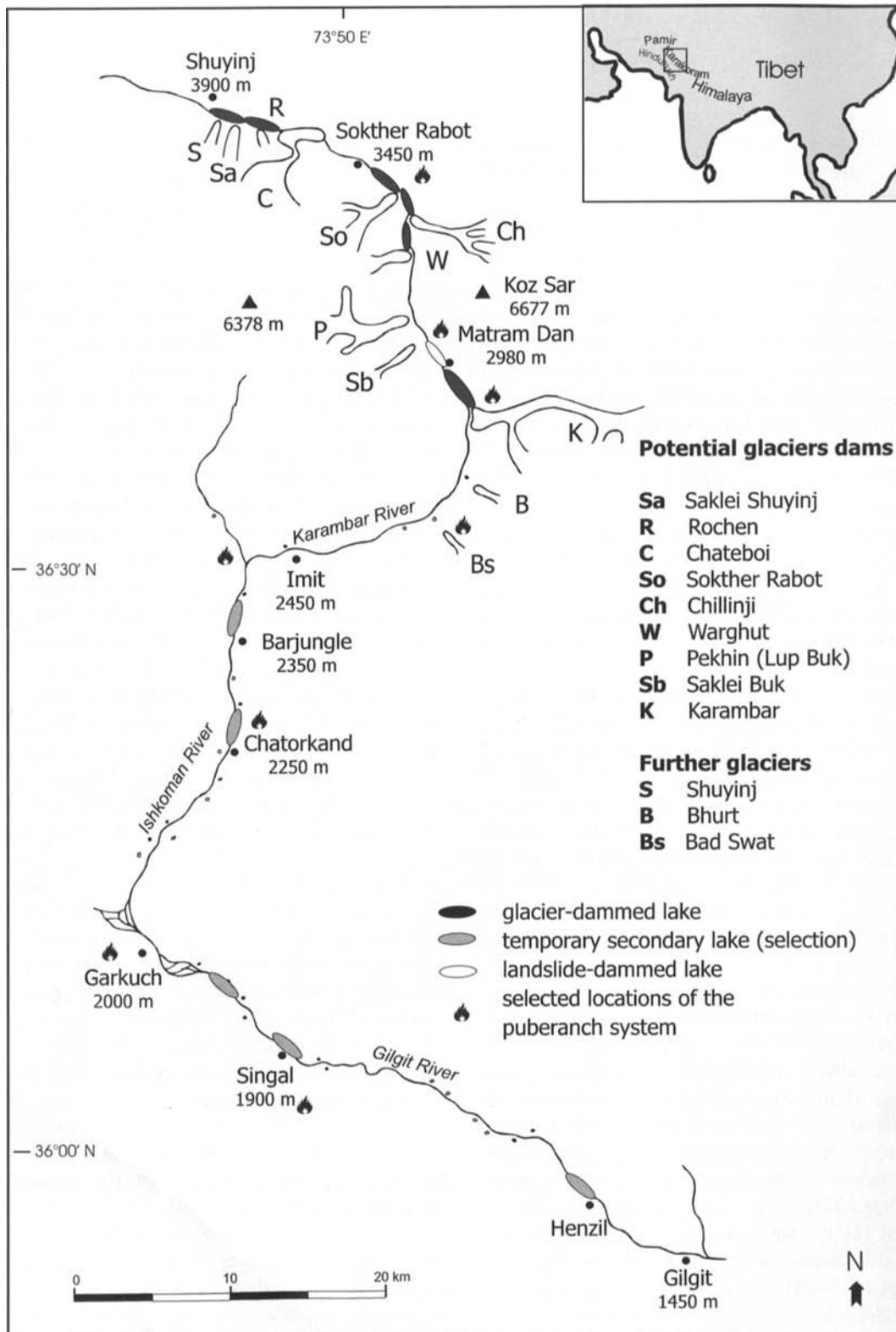


Figure 1. Historical natural dams in the Karambar–Ishkoman–Gilgit valleys.

structed in the Karambar valley. Geomorphological mapping was carried out from field surveys and later on also from aerial photographs. Interviews with the local people were carried out in selected villages in the Karambar, Ishkoman and Gilgit valleys in order to reconstruct the loss of settlement area by glacial floods. The photo archives of the Royal Geographical Society (London), the Royal Society of Asian Affairs (London), the Pitt Rivers Museums (Oxford) and the Bodleian Library (Oxford) provided photographs and descriptions of the glacier dams from early travellers to the Karambar area.

Only a few remarks on glacier lakes and dams are mentioned in form of travel descriptions by Hayward (1871), Biddulph (1880), Drew (1875), Stein (1928), Schomberg (1936), Longstaff (1951) and Tilman (1951). Kreutzmann (1994) investigated the settlement history of the Ishkoman valley with a notice on influences of the glacial floods on the settlement patterns. Hewitt (1998a, b) provides a first overview of the Karambar glacier barriers in the framework on a wider study on landslide interrupted fluvial systems and mentions already nine glacier dams, which have interfered with the Karambar river in the last 150 years. But overall, no detailed and systematic geomorphological studies on ice-dammed lakes have been carried out so far in the Hindukush area.

Topographical setting of the glacier dams in the Karambar valley

The Karambar valley is situated in the Eastern Hindukush (36°30′–36°45′ N/73°45′–74°10′ E, Figure 1). The highest catchment area is the peak Kampir Dior (7168 m) belonging to the western corner of the Batura-Yashkuk mountain group. The 90 km long Karambar valley originates in the Karambar Pass (4250 m) and drains near to Imit into the Ishkoman valley and at Garkuch into the Gilgit river. The topographical setting of the valley course changes again and again between expansive, basin-like valley sections and narrow gorge-like valley sections.

At least six major flood events occurred in the years 1844, 1860/1861, 1865, 1893, 1895 and 1905 in the Karambar valley (Todd, 1930), from which the 1905-flood supposed to be one of the most disastrous outburst events (Archer, 2001). Previously the lowermost and best accessible glacier dam, the Karambar glacier, was primarily made responsible for the outbursts, but the actual origin of the floods was unknown. In this study, the geomorphological field investigations and interviews with the local inhabitants revealed that nine tributary glaciers in the Karambar valley have blocked the main valley in former times (Figure 1). Among them, six glaciers impounded lakes since the mid of the 19th century, which drained catastrophically from time to time.

General characteristics of glacier dams and lakes in the Hindukush–Karakoram

The Karakoram and Hindukush glacier lakes are mainly the result of the blockage of the main river by advancing tributary glaciers. The principal characteristics of ice-dammed lakes outside the Asian regions are well researched (Haeberli, 1983; Costa and Schuster, 1988, Walder and Costa, 1996; Tweed and Russell, 1999). The topographic setting is at the current stage of glaciation in the Hindukush–Karakoram region favourable for the formation of this dam type: Tributary glaciers with catchment areas of over 7000 m in height descend down to low altitudes below 3000 m into the glacier-free trunk valleys and block temporarily the main river. A large number of glaciers terminates at confluence positions. The glacier dams consist of various glacier types, including short avalanche-cone glaciers as well as firn-stream glaciers of up to 60 km in length. Among them occur a lot of white, transversal glaciers in N-aspect.

The Karakoram rivers show discharge rates of up to 1000 m³/s (Ferguson, 1984; Hewitt, 1989). Therefore large-sized lakes, several kilometres in length, can be impounded in a very short time period. Lake volumes of up to 3.3×10⁹ m³ are reported from prehistorical ice-dams (Hewitt, 1982). In the Karakoram and Hindukush Mountains, a seasonal pattern dominates the outburst chronologies. The failures of ice-dammed lakes mostly occurred between July and August during the time of the highest discharge. Most of the dams fail periodically with irregular possible return intervals of about 1–2 years. The lakes often drain in successive years due to internal changes in the ice barrier itself.

Throughout the Karakoram, thick deposits of lacustrine sediments, up to 100 m in height, have been deposited at the valley flanks (Paffen et al., 1956; Owen, 1996; Iturrizaga, 2005c). They originate partly from glacier barriers, partly from landslide dams during the Postglacial and Late Glacial. However, the recent ice-dammed lakes discussed in this paper are much more short-lived lasting only several days to month. Nevertheless, the volume of the ice-dammed lakes is several times bigger than the volume of the moraine-dammed lakes in the Himalayas (cf. Yamada, 1998). But due to their short existence, lacustrine sediments are hardly deposited or they are removed by subsequent flood events. As a consequence, the geomorphological evidences of historical ice-dammed lakes are rather limited in the lake basins.

Chronology of flood events in the Karambar valley as stated in the literature

The following chapter summarizes the original statements referring to outburst floods in the Karambar valley and showing the fragmentary knowledge about the catchment areas. One of the first notes on ice-dammed lake outbursts in the Hindukush–Karakoram

is reported from the Karambar valley in 1844 by Drew (1875) referring to observations of Hayward (1871) director of the Geological Survey of India. He writes as follows: *“The next flood that I heard of occurred about the year 1844. It came from the Ishkoman valley, and was noticed in that of Gilgit; on the water going down, many fish were caught in the flats above Gilgit by the Sikh soldiers. Mr. Hayward recognizes the lake at the head of the Ishkoman Valley as the source of floods, past and to be expected; he has heard that it was formed by glaciers blocking up the valley, through which the water sometimes burst. There seems to be an impression on some that this blocking is due to the falling of glacier ice across the valley. This is not the case. It is only the gradual forward movement of the glacier which makes a dam, when its direction is such that it must in that movement abut against the opposite side of a connected valley...”*. However, the statement of Hayward, that falling glacier ice blocked the valley, could have been referred to undercutting processes of the glacier tongue by the main river leading to large-scaled ice failures. Moreover, ice avalanches could have also played a role in lake formation in the Karambar valley as described below.

According to observations of Hayward (1871), another flood occurred in 1860 or 1861. In 1870, a lake supposed to have been still impounded. As Hayward (1871) noted, *“It appears there is a large lake at the head of this valley, which has been formed by glaciers falling and blocking up the valley. An immense amount of water has accumulated, and the inhabitants fear that, should a very hot summer ensue, the lake may burst its bounds through the glacier melting, and cause much destruction in the Gilgit Valley. An inundation from a similar cause took place nine or ten years ago, the lake bursting its bounds, and the marks of the devastation then caused are still distinctly visible in the valley. I believe the destruction of the cantonment of Nowshera may be traced to this cause, the water brought down through the Gilgit Valley having flooded the Indus and driven the Sunda River back up its bed.”*

In the end of June/beginning of July 1865 a flood from the Ishkoman valley passed Gilgit around 9 or 10 a.m. (Drew, 1875). Todd (1930), political agent in Gilgit in the years 1929 and 1930, reports a flood on the 6th July 1893, which affected Gilgit between 11 a.m. and 8 p.m. It had a flood level of 7 m.

The last and maybe most devastating flood occurred at the 17th/18th June 1905. The flood reached Gilgit again in the morning at 8.30 a.m. and remained with a flood level of 6 m under that of 1893. All the mentioned floods were only registered in Gilgit (1450 m), which is located up to 150 km far away from the potential glacier dams. According to the interviews, prior to 1905, every year minor flood events occurred, but no flood was so devastating like the 1905-flood. The 1905-flood is remarkably well preserved by the local people by narrations of the older generation. These narrations of the 1905-flood were also the base of the interviews carried out in this study (Photo 48). In general, the individual

flood events are hardly distinguishable by geomorphological evidence. The great 1905-flood might have also wiped out the flood traces from previous flood events.

The geomorphological reconstruction of glacier dams in the Karambar valley

The glacier dams are located at altitudes between 2830 and 3850 m. The glacier lengths range between 4 and 23 km. The glaciers are mainly nourished by ice avalanches. The present climatic snow line runs between 4700 and 5000 m. Except for the Chateboi and Saklei Shuyinj glaciers, the Karambar dams are framed by lateral moraines up to 200 m high.

The Karambar glacier dam: A prototype of a temporary glacier barrier

In the past, the Karambar glacier supposed to have blocked from time to time the main river, the Karambar river, causing devastating outburst floods (Table 1, Figure 1). The 23-km-long, firn cascade glacier descends down from the Kampir Dior (7168 m) to an altitude of 2830 m and spreads with its debris-covered, partly disintegrating glacier tongue into the main valley (Photo 2). The glacier tongue is flanked by up to 150 m high lateral moraine ridges, crossing the Karambar valley. They are almost extending to the right Karambar valley flank (Photos 1 and 4). The Karambar glacier dam and its surroundings inherit a broad spectrum of geomorphological and glaciological features of a temporary glacier dam, which is also representative for the Saklei Buk (Photo 6), Warghut (Photo 9), Chillinji (Photo 12a and b) and Sokther Rabot (Photo 15). Figure 2 summarizes the geomorphological key forms for identifying former glacier advances, glacier dams and ice-dammed lake basins, which will be discussed in detail in the following case examples.

The actual dam is formed by the lateral moraine and the ice body of the Karambar glacier (Photos 1 and 4). The lateroglacial and proglacial areas show clear signs of a historical glacier advance which had blocked the main valley. The right Karambar valley flank shows at its foot part in the lower 50 m shallow undercutting lines at the parent rock. A marked change from light to dark rock colours indicates the former extent of the glacier surface. The pressure of the glacier tongue against the lower part of the mountain valley flank destabilised the foot slope generating rock failures after the glacier retreat. These valley flank sections located opposite of the glacier dams are highly stressed by repetitive oscillations of the glacier tongues. The “Bhurt rock slide” located opposite of the Bhurt valley exit (Figure 1) – mentioned by Hewitt (1998a) – could be such a glacial-induced rock slide during Lateglacial times.

A further indicator of a former glacier advance and therefore a glacier barrier of the main valley are moraine remnants along the opposite valley flanks. They are

Table 1. Records in the literature about glacier lakes and floods in the Karambar valley

Year	Date/Season	Supposed source area of the flood	Remarks	Sources
1844		Ishkoman	Glacier lake outburst	Drew (1875)
1860 or 1861		Karambar	Glacier lake outburst	Hayward (1871)
1865	June/July	Karambar	Lake at Karambar glacier 9–10 pm	Drew (1875)
		Sokther Rabot	Rope bridge at Gilgit Fort destroyed	Todd (1930)
			Lake at Sokther Rabot "Gilgit River Flood"	
1870		Karambar	Ice dam, no outburst	Hewitt (1982) (maybe identical with the 1861 flood)
1891–1892		Ishkoman	Ice dam, no outburst	Hewitt (1982)
1893	6/7th July	Karambar	Water rise at 11.20 p.m. on 6th July, reached 23 feet above high-flood level at Gilgit, subside at 3 a.m. on 7th July, two bridges at Gilgit destroyed	Todd (1930)
1895		Karambar	Glacial flood	Kreutzmann (1994)
1905	17/18th June	Karambar	Glacier dam broke at midnight 17/18th June, flood arrived at Gilgit at 8.30 am, 20 feet above high-flood level	Todd (1930)
1905		Sokther Rabot	Considerable damage to villages along the river banks above Gilgit	Kreutzmann (1994)
1905		Warghut		Tilman (1951) (maybe identical with 1909 flood)
1909		Warghut	Periodic and disastrous floods	Longstaff (1951)
1911–1913		Saklei Shuyinj (?)	Ice dam, subglacial drainage	Stein (1928)
1916		Karambar	Ice dam	Hewitt (1982) (maybe identical with the 1909 flood)
1929/1930		Karambar	Ice dam	Longstaff (1932)
1955		Karambar	Ice dam	Hewitt (1998)
1972		Chateboi	Small lake	Iturrizaga (2004) and local information
1990		Warghut	Lake	Iturrizaga (2004)
1993		Karambar	Ice dam	Hewitt (1998)
1993		Chateboi	Very small lake	Hewitt (1998)
2004		Chateboi	Very small lake	Iturrizaga (2004)

mostly deposited at the outer parts of the glacier tongues and preserved as moraine cones dovetailed with slope sediments. In the middle sections of the former ice margins, the moraines at the valley flanks are mostly removed by consecutive glacier advances. The Saklei Buk, Pekhin, Warghut, Chillinji and Sokther Rabot glaciers show all these kind of moraine cones at their opposite main valley flanks.

Moreover, the left Karambar lateral moraine was transformed by a spill-over tongue during the glacier advance which resulted finally in a break-through of the lateral moraine (Photo 1). The break-throughs are characteristic lateroglacial landforms of glacier advances. The glacier advance against the valley flank might generate an afflux effect (cf. Wiche, 1960; Röthlisberger, 1986). This causes in turn a local, hummocky upraise of the glacier surface. The glacier surface overflows the crest of the lateral moraine and can lead to the formation of a secondary glacier tongue. They are widespread landforms in the Hindukush–Karakoram region (Iturrizaga 2001), such as along the Malungutti, Hinarche and Yazghil glaciers. At the glacier dams of the Karambar valley, those moraine bulges are also present

at the Saklei Buk, Warghut and Chillinji glaciers (Photo 12b).

The right lateral moraine of the Karambar glacier is arranged in a series of accreted moraines. Moraine accretion preferably takes place when the valley floor widens, which is particular the case at valley confluence positions. Here the canalisation of the glacier stream ends abruptly and enough space is available for the deposition of adjoined moraines (dilatation moraines) (Photo 2).

The Karambar glacier was previously considered as the main source area for the lake outbursts in the Karambar valley (Table 1). Indeed, the Karambar glacier has blocked the Karambar river, but the field investigations and interviews suggest, that it might have played only a comparatively minor role among the other identified glacier dams. According to interviews with the local inhabitants, the ice-dammed Karambar lake extended up to Matram Dan (2980 m) implying a length of the lake of at least 4 km. The greatest width of the former lake basin measures 780 m. The average width was approximately 400 m. According to the height of the lateral moraines the glacier dam could have reached

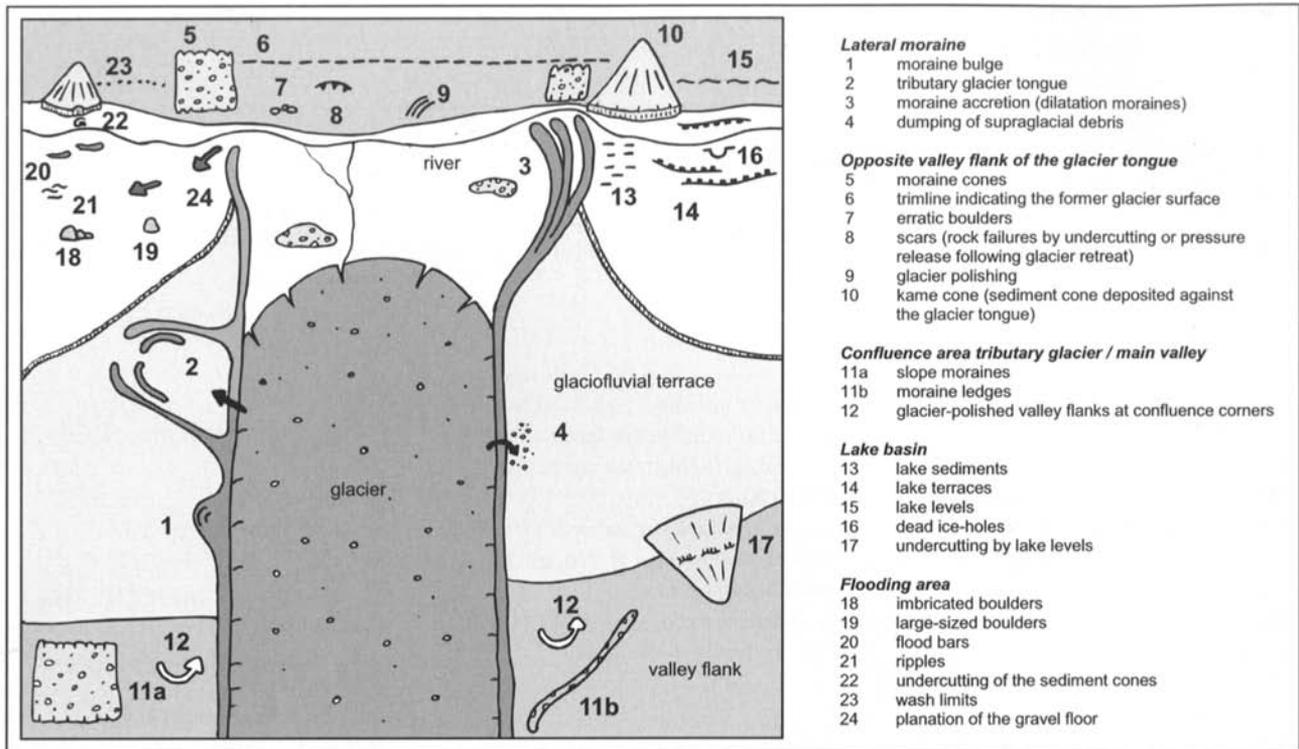


Figure 2. Geomorphological landforms for reconstructing former glacier advances with dam formations.

a maximum height of about 150 m, but the maximum lake height was presumably much lower and did not exceed 100 m. Fresh glacier polishings indicate a minimum height of about 50 m above the river level. An early British traveller, probably Schomberg, has built in the early 20th century a stone man at the right Karambar valley flank about 30–40 m above the Karambar river indicating the height of the glacier surface at the right Karambar valley flank. The lake volume reached an estimated size of about 100–150 mill. m³. The lake supposed to have lasted for 2 years in the beginning of the 20th century. Huge amounts of wood were piled up in front of the glacier dam. Those trees could originate from the forest in the lake basin itself described by Schomberg. However they also could evidence a lake outburst from a higher glacier dam (s. below). The lake basin is nowadays sparsely covered with trees younger than approximately 100 years (Photo 2). The trees grow partly on high active debris flow cones. Those nival-induced debris flows also could have triggered a lake outburst by generating a displacement wave.

In the whole, no observations of a glacier-dammed lake at the Karambar glacier are mentioned by travellers which passed the dam in the early 20th century. The most extensive description of the Karambar valley derives from Longstaff (1951), a British alpinist and political agent in Gupis. He visited the valley in 1916 and travelled as far as to the Sokther Rabot glacier. He has made the following notes from the Karambar glacier: “First we came to the great Karumbar glacier flowing down from the east at right angles to the river’s brink, its snout entering the water: even the Kirghiz, redoubtable horsemen, would not face the force of the

current. Dismounting, we led our horses over the moraine-covered ice. These horses can go almost anywhere if led, but the crossing of the glacier cost us two hours.” According to this description, the Karambar river did not block the valley in 1916.

Schomberg (1936) visited the Karambar valley in 1933 and did not mention any signs of a lake. He writes as follows: “We reached the Karambar Glacier, crossed it and found to our surprise and delight, a fine grazing ground, with cultivations, abundant willows, pencil cedar and grass, all high up on the right side of the valley.” However, all cultivations were located high upon the right side of the valley, which could indicate the unfavourable settlement conditions at the valley floor due to temporary lake formations (Schomberg, 1936, p. 86). The morphological evidence of a former Karambar lake is very limited. As a rule, ice-dammed lakes rarely deposited lake sediments because the sedimentation time is comparatively short and the sediment material very coarse. In the Karambar lake basin, large boulders, up to table size, are covering the valley floor.

The Karambar glacier is prone to sudden glacier advances. According to Hewitt (1998a), the glacier surged in 1955 and in 1993 when it supposed to move with 7–10 m per day in June over a horizontal distance of 3–4 km. The actual surge distance might have been shorter, because the morphology and the vegetation cover of the glacier forefield implies that in recent times not the entire glacier tongue moved forward, but only a southern ice lobe of the glacier tongue. The Skasastan glacier, flowing down from the Skasastan Peak (6258 m), could have also played a role in triggering a possible sudden advance of the Karambar glacier. This

short tributary glacier is overthrusting onto the Karambar glacier surface and influences the movement pattern of the Karambar glacier. Gardner and Hewitt (1990) showed for the Bualtar glacier (Hispar Muztagh) surge movements triggered by a landslide.

Nowadays, the proglacial area is occupied by a hummocky moraine landscape, in which proglacial lakes are embedded. During the field investigation periods in the years 2002–2004, the W-orientated glacier tongue was retreating. It terminated in a distance of 580 m from the opposite right Karambar valley flank.

The Saklei Buk glacier dam: Prehistorical glacier dam before 1850?

The Saklei Buk and Lup Buk glaciers have dammed the Karambar valley in prehistorical times, that means before 1850. The 5-km-long Saklei Buk glacier (Wakhi: *saklei buk* = small hill) projects into the Karambar valley, 7.5 km valley upstream from the Karambar glacier (Photos 5 and 6). It is a classical dam glacier with expansive lateral moraines rising up to 250 m above the valley floor. The Saklei Buk glacier tongue is located nowadays on a pedestal moraine located high above the river. The glacier terminates at 3300 m in a distance of about 1200 m from the Karambar river. Considering the maximum height of the catchment area of only 5846 m this is a remarkable low ice margin, even though it is oriented in NE-direction.

At present, the Saklei Buk glacier is overtopping its main lateral moraine in the lower glacier part and shedding surface moraine onto the lateral moraine. The left lateral moraine shows several former small tributary ice tongue basins and bulges at its distal slope, which were formed during former glacier advances. Small lakes are sometimes impounded in those moraine cirques (c.f. Wiche, 1960). The laterofrontal moraines were undercut by flood events of the Karambar river and disintegrated into morainal cones. The glacier forefield is occupied by a steep glaciofluvial fan which is covered already with *Juniperus*. Therefore, the moraine remnants on the opposite Karambar valley flank can be attributed to a prehistoric glacier advance.

Longstaff (1951) describes the passage of the Saklei Buk glacier as follows: “*Soon after this we were compelled by a cliff to ford the river to its right bank. There we met the Bukh glacier in our path, and just managed to skirt under the impending ice, praying that the rocks of the moraine, balanced on the melting surface, would not slope down on to our heads. Beyond that we forded again to a spot called Zak Ban, where there was a comfortable shelf, safe above the river, with a good growth of willow and sallow and grass for the horses*”. The description of Longstaff shows that the Saklei Buk glacier reached the Karambar river in 1916, but did not block it. Zachband (3200 m) is a small temporary settlement at the left Karambar valley flank on a glacial terrace. It is nowadays inhabited by Ghujer people. Nowadays the route

from Bhurt to the Karambar Pass leads usually on the left Karambar valley flank, even though no proper way exists. At many locations one has to climb on the precipitous rock walls or cross small tributary branches of the Karambar river. Only one wood bridge has been installed close to the Lup Buk glacier. The poor infrastructure resembles the situation in the Shimshal valley before the Shimshal Road has been completed (Iturrizaga, 1997).

The Lup Buk Glacier dam (Pekhin Glacier): Prehistorical glacier dam before 1850

The Lup Buk glacier (Wakhi: *lup buk* = big hill) or also called Pekhin glacier (10 km) joins the Karambar valley a little bit upstream of the Saklei Buk glacier at an height of 3250 m (Photo 7). The catchment area reaches a height of 6416 m. The Lup Buk glacier shows in its forefield about six recessional moraines, which indicate that the glacier did not block the Karambar valley in the 19th and 20th century. The glacier tongue lies in a horizontal distance of 1400 m from the Karambar river. Moraine remnants on the left Karambar valley flank prove an earlier glacier dam. At present, the hummocky and debris-covered surface of the Lup Buk glacier is downwasting and the glacier tongue is retreating.

The Warghut glacier dam: A combined glacier dam of ice and debris flow

The avalanche-fed Warghut glacier is only 4 km long, but almost half of the glacier stream spreads into the Karambar valley and terminates at an altitude of 3300 m. It is surrounded by up to 150 m high lateral moraines at both sides. The Warghut glacier barrier is – like the Karambar glacier – a temporary glacier dam (Photos 8 and 9). However, in the case of the Warghut glacier tongue, a special relief configuration occurs: not only the glacier, but also the combined arrangement of the glacier tongue and an active debris flow caused a lake. The Warghut barrier is formed by the lateral moraine of the Warghut glacier, the glacier ice itself and the debris flow cone. Opposite of the Warghut glacier tongue, a small tributary valley joins the Karambar valley. The debris flow cone is directly deposited against the glacier tongue (Photos 9 and 10). The river has incised into the debris flow cone and partly into the small glacial outwash fan of the Karambar glacier.

At the left Karambar valley flank, remnants of moraine deposits prove a former permanent glacier dam (Photo 9). As shown by the geomorphological evidence and interviews with the local inhabitants, the Warghut glacier played a pivotal role in the lake outburst history. In the Warghut lake basin, lacustrine sediments have been deposited directly upstream of the glacier dam. The lake sediments indicate a recent lake formation, otherwise they would have been already

eroded by the Karambar river. The sediments of the valley flanks have been strongly undercut by fluvial processes and show cliff heights of up to 10 m (Photo 34). The glaciofluvial terraces, belonging to former periods of glacier retreat, are distinctively carved out. The Warghut lake basin is characterized by flood deposits and erosional processes of lake outbursts from topographical higher glacier dams between the Chillinji glacier and Saklei Shuyinj glacier (Photo 11). The corresponding floods could also have removed potential lacustrine sediments. The close interfingering of lake basins and flood sediments is typical for the valleys with multiple ice dams in the Hindukusch–Karakoram (Figure 3). According to local information, the lake reached a depth of up to 30 m and reached as far as the Chillinji glacier.

Longstaff (1951) reports that a lake has formed in 1909 at the Warghut glacier dam. This lake supposed to have drained catastrophically at that time as well as in the previous years. Longstaff (1951) writes: “Next, on the right bank of the Karumbar, we came to the Wirgot glacier under which it was possible to creep along on foot

though the horses had to take the river. Seven years before this glacier had dammed the ravine and behind it a lake had formed; its bursting caused one of those periodic and disastrous floods.... The scenery of this part of the valley was now very wild: great cliffs rose to stark spires of rock on either hand; ...”. Depending on the glacial situation of the Warghut glacier, the foot path leads nowadays either over the Warghut glacier surface or otherwise one has to cross the Karambar river upstream of the Warghut glacier, which can be in summer time during high river levels almost impossible.

The valley section downwards of the Warghut glacier dam shows significant traces of a flood event (Photos 9 and 34). The sediment cones are bordered by distal cliff walls of up to over 50 m in height. The land was considerably cut back by flood events. In former times the barren gravel floor was taken up by wood land. In the valley floor sandy material is deposited in which are embedded boulders with diameters of 1.50 m. The flood has surged up the valley flank directly behind the dam.

The lateral moraines are connected with up to 30 m high terrace complexes (Photo 34), which are covered

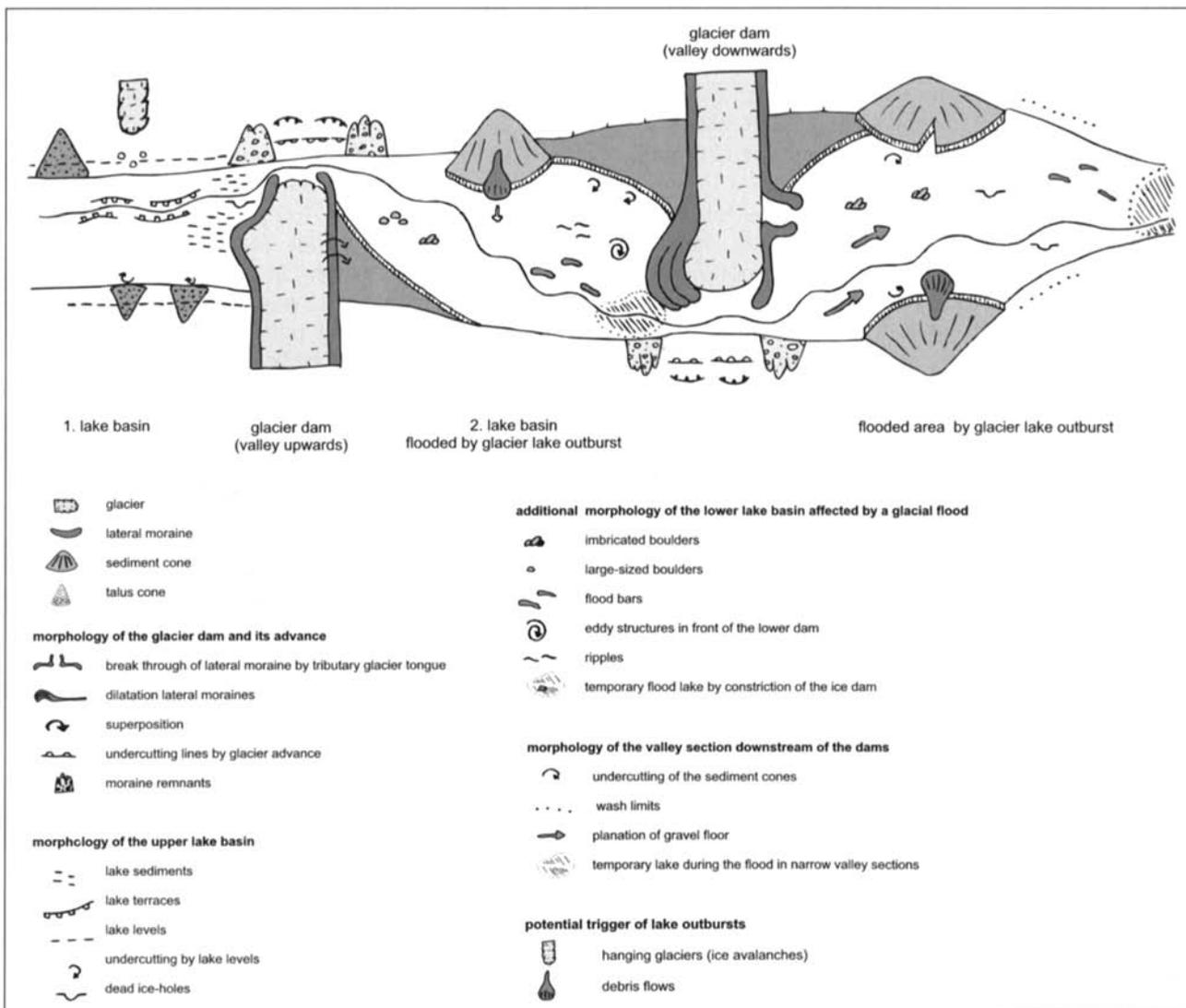


Figure 3. Generalized map of the landscape assemblage of two successive lake basins dammed by tributary glaciers.

with conifers older than presumably 100 years. Such terraces are also present along the other glacier dams in the Karambar valley. They consist partly of layered gravels and rounded boulders, mostly not larger than 20–30 cm in diameter. The question is whether their origin is linked to pre-Warghut glacier times, before this glacier entered the Karambar valley. So they would be glaciofluvial terraces from the Warghut valley which were dissected during a subsequent Warghut glacier advance. They also can be attributed to an individual genesis, so that the upper terrace complex was deposited due to damming effects of the Warghut glacier and the lower terrace complex at the lee side of the dam would be the deposits of successive flood events. A last alternative is that they represent relict glaciofluvial terrace complexes from the main valley.

At present the glacier tongue lies only in a distance of 51 m from the distal cone section of the debris flow at the left Karambar valley side and is undercut by the Karambar river. A new lake could be formed at any time. The Warghut glacier surface lies only several meters below the crest of the lateral moraine and at some parts the distal moraine has been supplied with fresh supraglacial debris.

The Chillinji glacier dam: Temporary glacier dam

Only about 3 km upstream from the Warghut glacier, the Chillinji glacier interferes with the Karambar valley (Photos 11 and 12). The 10 km-long avalanche-fed glacier flows from the Koz Sar (6677 m) down to 3370 m and occupies with its lateral moraines almost the entire Karambar valley floor. The Karambar river passes directly between the glacier tongue and the adjacent valley flank. The glacier tongue is flanked by massive lateral moraines. The glacier surface lies almost at the same level as crest of the lateral moraines. At some places, recent supraglacial dumping processes have taken place. The glacier tongue shows typical signs of a former glacier advance: It is slightly bifurcated into two lobes. A small outlet spill-over tongue has developed at its left side, which is embraced by a sander moraine. The formation of those tributary glacier tongues can buffer in parts the advance of the main glacier. These landforms are a very common phenomenon along confluence glaciers (Iturrizaga, 2003).

In the photographs from Longstaff (1951) taken in 1916 and from Stein (1928) in 1913, the Chillinji glacier tongue is much more convex shaped and the Karambar river drains apparently subglacially (Photos 13a and 13b). Longstaff (1951, p. 209) describes the Chillinji glacier in 1916 as advancing glacier: “...ahead the narrow left of the Karumbar appeared to be completely blocked by the great Chillinji glacier whose surface was raised several hundred feet above the level of the river. This glacier enters from the east, its upper snow basin quite invisible from below; it seemed as if the glacier sprang new-born from the living rock. But its ice is fed by the snows of Kampire Dior (23,424 feet) away to the north-

east. The Chillinji glacier was only half the breadth of the Karumbar, but it was much harder to get our horses across. The ice was steeper, more broken with crevasses and there was less surface moraine covering to give footing to the horses.” At present, the route does not lead over the glacier, but on the right, ice-free Karambar valley flank. Typical small and lofty wood beam-stone constructions were installed by the local people at the steep valley flanks (Photo 45). They require in some parts climbing and are difficult to pass by animals. Upstream of the Chillinji glacier, a rope bridge has been installed in order to cross the Karambar river for the way to the Chillinji Pass (5150 m).

The Sokther Rabot glacier dam: Temporary glacier dam

The Sokther Rabot glacier dam is located directly upstream of the Chillinji glacier tongue (Photo 14). When the Chillinji glacier impounded the Karambar river, the lower parts of the Sokther Rabot glacier tongue and its forefield might have been flooded by the Chillinji lake. Apart from the Karambar glacier, the Sokther Rabot glacier supposed to have played a role in the glacier lake outbursts of 1905 (Todd, 1930; Kreutzmann, 1994). In 1865, a lake was reported at Sokther Rabot, from which an outburst flood was released (*Gilgit River Flood*, Todd, 1930). Kreutzmann (1994) reports from a lake at this locality in 1905. From the descriptions, it is unclear whether the Sokther Rabot glacier or the Chillinji glacier has blocked the valley at that time.

The glacier tongue shows the most consolidated glacier forefield among the Karambar glacier dams indicating a stationary position over the last decades (Photos 15 and 16). It is surrounded by an outwash fan which is densely vegetated with juniper. However, a glacier block must not be generated by the entire glacier tongue, only a small outlet part is already sufficient to impound a lake.

At present, the Karambar river is sandwiched between the proglacial debris fringe and the opposite valley flank (Photo 16). The distance between the glacier tongue and the opposite valley flank measures 150 m. The valley flank shows signs of a former glacier advance in form of trimlines and moraine remnants.

The potential lake basin of the Sokther Rabot glacier and also of the Chillinji glacier is up to 2 km broad (Photos 17 and 46b). It is at the same time the flooding area of glacier lake outbursts released by the Chateboi- or Saklei Shuyinj glaciers. The Chateboi glacier tongue terminates in a distance of 7.5 km from the Sokther Rabot barrier.

The Chateboi glacier dam: Permanent glacier-dam with sub- and englacial drainage¹

At present, the Chateboi glacier seals the Karambar valley over a distance of 4 km and forms a permanent dam (Photos 18 and 19). In this section, the Karambar river drains completely subglacially. Nowadays, lakes

are impounded from time to time small lakes for a few days behind the ice dam (Photo 20). The formation of a large-scaled lake is possible at any time. Additionally, englacial water pockets can form inside of the glacier barrier (Haerberli, 1983). These water pockets are especially dangerous due to their unpredictability. In principal, a climatic deterioration, respectively, a glacier advance is not necessary for the formation of an ice-dammed lake in this case. A slight change of the

englacial drainage channels can already lead to a blockage. A lot of ice-dammed lakes drain gradually and no catastrophic outburst event occurs. After a catastrophic outburst or even a moderate drainage, the dam may reseal again. Repetitive outbursts are common for ice-dammed lakes (Costa and Schuster, 1988).

Surprisingly, no geomorphological descriptions of the Chateboi glacier dam or a glacier-dammed lake are mentioned in the literature. In this study, a historical lake

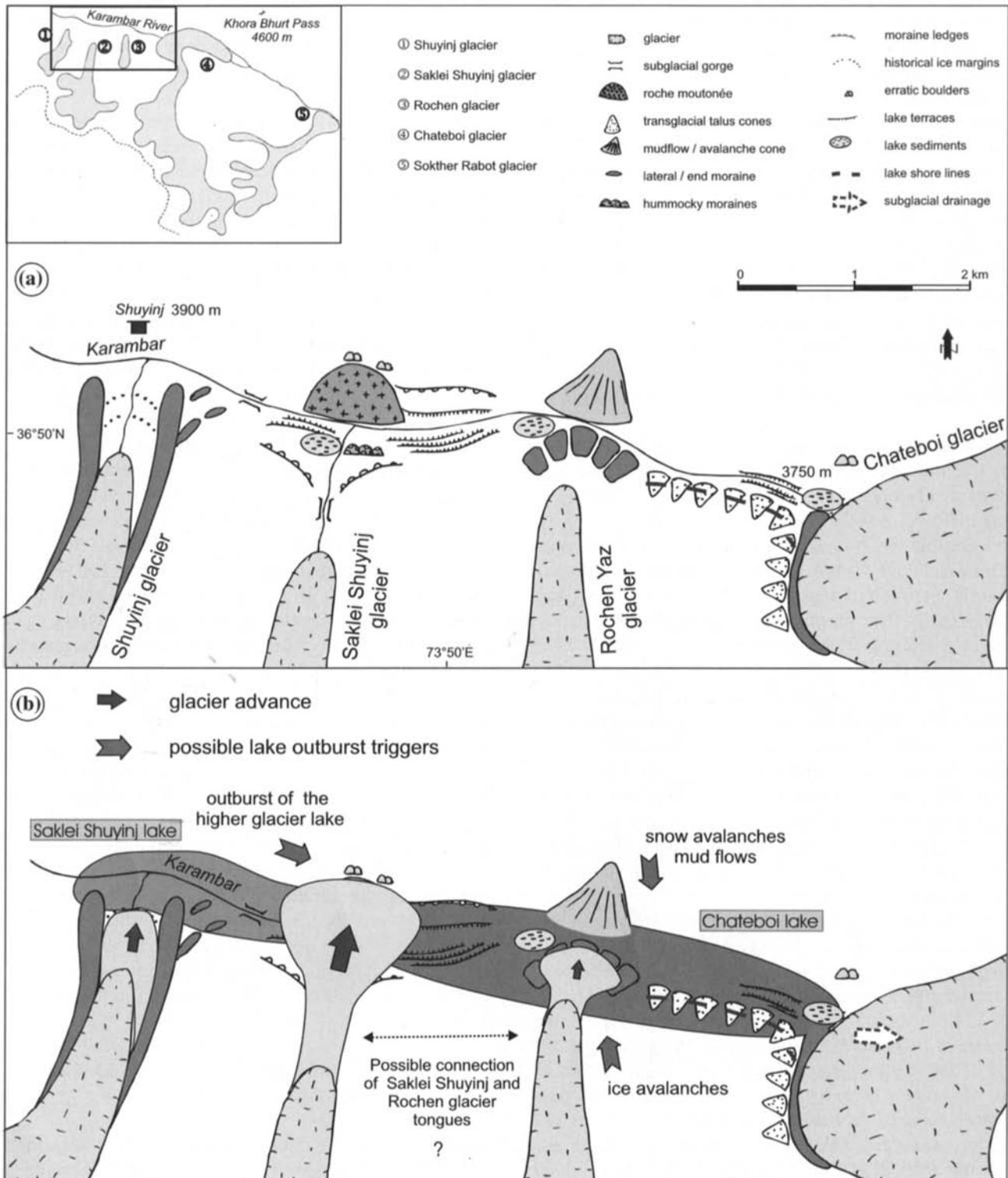


Figure 4. (a) Geomorphological map of the lake basins of the glacier dams Saklei Shuyinj and Chateboi (based on field observations in the years 2002 and 2004). (b) The glacial situation at about 1900 with the potential ice-dammed lakes.

of about 5 km in length could be reconstructed at the Chateboi glacier (Figure 4). Lake terraces and lake sediments extend at least up to Shuyinj (3900 m) (Photos 20, 21 and 23). Sandy-gravelly sediment terraces, 6–8 m high, are deposited in the lake basin. They are divided into at least six levels indicating the individual lake stages. A minimum average lake depth of 20 m could be reconstructed by undercutting lines along the slope sediments. Assuming a lake width of 150 m, a lake with a volume of about 15 mill. m³ could have been impounded by the Chateboi glacier. Grain size analysis was carried out for samples from the youngest lake sediments and the adjacent lake terrace (Figures 5 and 6).

The broad gravel floor, up to 2 km in width, downstream of the Chateboi glacier tongue (3550 m), has been clearly transformed by large-scaled flood events. Imbricated boulder clusters (Photo 33), with individual boulder sizes of up to 2 m in diameter, indicate high-

energy fluvial transport processes. The boulder size decreases gradually downstream towards the Sokther Rabot glacier. Moreover, the sediment cones are remarkably undercut by fluvial processes. Finally, upstream of the Sokther Rabot glacier dam, ripple structures and eddy bars are present indicating that back water processes have taken place during the Chateboi–Saklei Shuyinj-flood (Photo 17). Nowadays, the flood plain is taken up by seasonally alternating river beds.

The upper part of the glacier dam is located at 3750 m, the lowest part near the glacier tongue at 3550 m. The glacier dam itself is composed partly of the glacier, partly of the left lateral moraine (Photo 20). During the maximum historical glacier extent, probably at the turn of the last century, it was about 30–40 m high (Photo 21). The 15 m high left lateral moraine of the Chateboi glacier is incised by the Karambar river, which drains subglacially from there on.

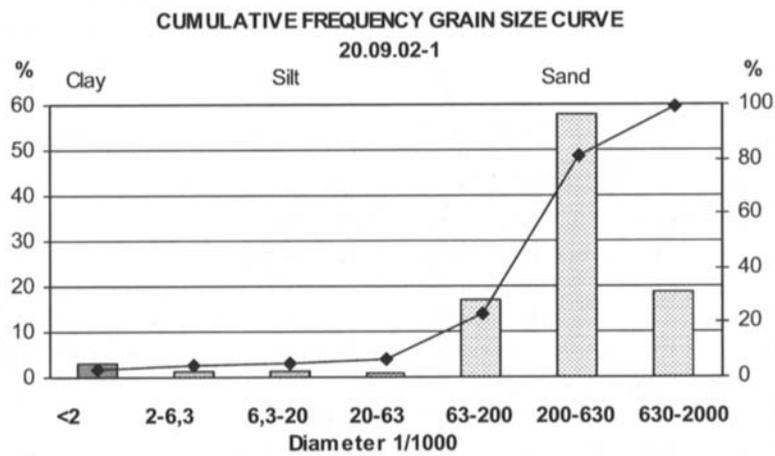


Figure 5. Sample 20.09.2002/1. Chateboi lake basin (3760 m). The sample was taken in the upper part of a terrace in the lake basin of the Chateboi glacier. The locality is located at the orographic left Karambar valley side directly upstream of the glacier dam. The terrace has a thickness of about 5–8 m and is superimposed by shallow lake sediments in its lower part. The sample shows with 58% a dominance in the medium sand fraction and therefore a moderate sorting, which is typical for river sand. The terrace consists mainly of fluvial transported pebbles and cobbles, which could have been deposited by drainages of the upper Saklei Shuyinj lake. The terrace cliffs were produced by the successive incision of the Karambar river. They can partly also be generated by different lake levels of the Chateboi lake.

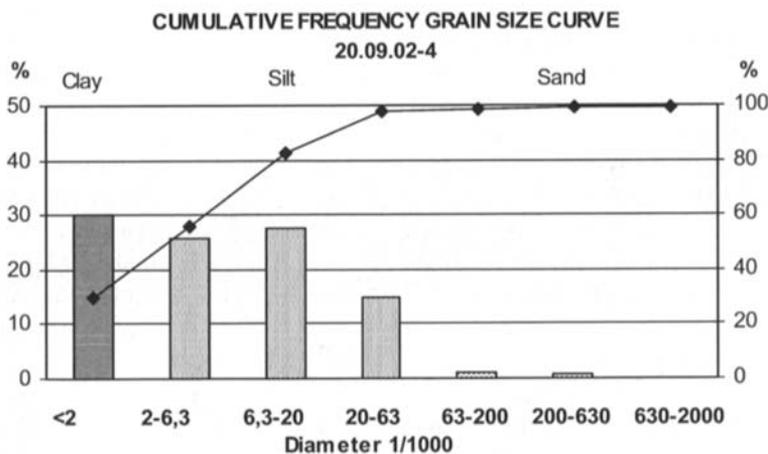


Figure 6. Sample 20.09.2002/4: Chateboi lake basin (3760 m). The sample originates from the lower part of the terrace in the lake basin of the Chateboi glacier. The fine-grained sample material lies on top of the sample 20.09.2002-4. The sample shows a primary peak in the clay fraction (30%). The silt fraction dominates the spectrum of grain sizes. The high content of fine material is typical for the glacial melt water streams, which transport fine-grained mud in suspension in high concentrations. The sample consists of the youngest lacustrine deposits of short-lived ice-dammed lakes of the Chateboi glacier.

A comparison of photographs from 1947 taken by Tilman (1951) and in 2002 by the author shows that the glacier surface has downwasted considerably during this time period (Photos 46a and b), but still forming a permanent glacier barrier. A similar permanent large-scaled glacier barrier without any bigger lake formations in the last decades is known from the Shimshal valley (Visser, 1938; Kuhle et al., 1998). The Khurdopin glacier seals the Shimshal valley over a length of 3 km and blocks therefore the tributary Virjerab river. In the last century about 20 glacial floods were monitored (Iturrizaga, 1997). The last lake formation occurred in the year 2000. A mitigation of those ice-dammed lakes is a difficult task. Tunnel constructions through the bedrock or siphons and pipes for lowering the water level or blasting actions for emptying the lake might not be effectively operated due the length of the ice dam and its spontaneous occurrence.

The Saklei Shuyinj glacier dam: A combined glacier dam of parent rock and ice

Within the former Chateboi lake basin, another remarkable dam was identified, the Saklei Shuyinj glacier dam (Wakhi: *saklei*=small, *shu*=black, *yinj*=gorge). It might have played a crucial role in the lake outburst history of the Karambar valley. Today this small hanging glacier is located far back in a distance of about 1.5–2 km from the left Karambar valley flank on a confluence step (Photos 24 and 25). It is almost not visible from the main valley. But geomorphological field evidence showed that the glacier dammed recently the Karambar valley and impounded a lake as well in historical times (Photo 23). In front of the valley exit, a rock bar, about 50 m in height, is situated at the Karambar valley floor. On top of this rock bar fresh granite erratics have been deposited. These granite boulders can theoretically derive from several source areas. Due to the freshness of the boulders, it can be excluded that they were deposited by an ice age-Karambar glacier flowing down from the Karambar pass. Another possibility would be that they originate from the Chateboi lake, in which the rock bar is located, but the size of the boulders seems to be too large to have been deposited by a lake. However, the combination of geomorphological field evidences shows that these boulders can be identified as erratics from the tributary Saklei Shuyinj glacier. That means that the Saklei Shuyinj glacier tongue formed a stable glacier dam in combination with the *roche moutonnée* (Figure 4). At the left Karambar valley flank, moraine ledges are deposited at the valley flank, which indicate that the Saklei glacier tongue spread out in a T-shaped form at the Karambar valley floor (Photo 24). At the confluence of the Saklei Shuyinj and Karambar valley, fresh and shallow moraine ledges are deposited along the right Karambar flank, up to about 50 m above the valley floor. The glacier thickness already indicates that the glacier tongue reached the opposite Karambar valley flank.

A little bit upstream of the Saklei Shuyinj valley exit, lake sediments, several meters in height, are deposited (Photo 24). That is one of the rare localities in the Karambar valley, where lacustrine sediments are present at the glacier dam. The lake basins of the downstream glacier barriers were transformed by flood events of upstream glacier outburst events. The interfingering of the lake sediments with the Saklei Shuyinj moraines proves that the lake sediments can be only attributed to the former Saklei Shuyinj lake and not to the Chateboi lake. It is unsolved whether both lakes existed at the same time and whether they were connected. It might be that the Saklei Shuyinj dam was partly flooded by the Chateboi lake. The Saklei Shuyinj hummocky moraines, which are situated on the Karambar floor, have a very subdued, rounded outer appearance, which could be a result of a water-related transformation. The mentioned gravelly lake terraces of the Chateboi lake basin also continue upstream of the Saklei Shuyinj valley exit. The terraces are up to 10 m high and composed of at least three levels (Photo 27). The lacustrine sediments of the Saklei Shuyinj lake are deposited on top of the Chateboi terraces (Photo 24).

Like the Warghut glacier, the Saklei Shuyinj glacier is a combined glacier dam. In this case, the barrier is formed by the glacier and a rock bar located in the main valley, the Karambar valley, in front of the exit of the Saklei Shuyinj valley. Therefore, the glacier moves forward against a stable abutment. Even though the dam type is quite similar to that of the Karambar glacier dam with an even valley flank, the stability of the dam and the possible drainage pattern of this dam will be slightly different.

As shown in a photo from Stein (1928), an unnamed tributary glacier blocked the valley in 1913 (Photo 26). Considering the topographic constellation and Stein's description, it is very likely that it is the Saklei Shuyinj glacier. Stein (1928) made the following statement about the glacier dam: "*About eight miles from the pass, the valley contracts below the last grazing grounds of Shuyinj. Beyond this the track led past the snout of a large glacier on the south, which has piled its ice against the rocky slopes opposite. The river thus blocked had cut its way in a big tunnel below it ...; this advance of the glacier beyond the river bed was said to have taken place only two years before. Less than two miles farther down, the river bed, broad as it was here, was completely blocked by a much larger glacier descending from the south, which had to be traversed for a distance of about a mile and a half.*" Interviews with the local inhabitants revealed that the Saklei Shuyinj glacier still reached the Karambar valley floor 20–30 years ago!

The Rothen glacier dam (Shu Yaz): A possible ice-avalanche dam

The Rothen glacier (Shu Yaz) (Wakhi: *rothen*=white) is a short hanging glacier with a steep glacier tongue end (Photo 22). It is located in the former Chateboi lake

basin between the Chateboi glacier and Saklei Shuyinj glacier. Hanging glaciers release during glacier advances – but in some cases also during glacier retreat – ice avalanches which can build a rather short-lived but nevertheless effective dam. That might have been the case at the Roehen glacier. In between, the Chateboi and Shuyinj glaciers such a type of temporary blockage might have occurred. Intensive ice-avalanche activity could have piled up beneath the glacier tongue and blocked the Karambar river. The ice avalanche-dam type occurs at discordant valley junctions where the tributary valley enters with a confluence step or a steep mountain valley flank into the main valley. Such dam types caused by ice avalanches are well-known from the European Alps. Ice avalanches of the advancing Giétro glacier formed in the years 1585 and 1817 a barrier which blocked in turn the Dranse river to a large-sized lake, the Lac du Mauvoison (Röthlisberger, 1981). Its repeatedly outbursts generated disastrous floods, which killed over 150 people (Tufnell, 1984).

To date, it is not solved whether the Roehen glacier formed an actual dam in the last century. The steep tongue of the Roehen glacier is nowadays surrounded by a pronounced end moraine arch, which is over-worked by melt water streams of the Roehen glacier (Photo 22). The 20–30 m high moraine arch actually implies that the glacier did not reach beyond it in the last century. Upstream of the moraine shallow lake sediments are present (Photo 28). Considering the fact that they lie in the Chateboi lake basin, they also can be attributed to the Chateboi glacier dam. However, the map *India and Pakistan (sheet Baltit NJ43-14, 1955)* shows the Saklei Shuyinj glacier and the downstream Roehen glacier as a combined glacier tongue. That means that the Saklei Shuyinj-Roehen glaciers would have blocked the Karambar valley as well over a horizontal distance of almost 1.5 km – only about 2 km upstream of the Chateboi glacier dam!

Hayward (1871) reports, that the 19th-century lakes in the Karambar valley were formed by falling ice boulders, which blocked the river. In this regard it would be possible that ice avalanches from the Roehen glacier have blocked temporarily the valley in former times.

The Shuyinj glacier, opposite of the pasture Sariküsha or Paskeja is one of the last tributary glaciers downvalley of the Karambar Pass. It has in former times interfered with the Karambar and terminates at about 3950 m (Photo 29). The glacier tongue is embedded with high rising lateral moraines which were affected by the Chateboi–Saklei Shuyinj lake. The bottom of the right lateral moraine is associated with lake terraces of the Chateboi–Saklei Shuyinj lake. The Shuyinj glacier itself did not dam the Karambar valley in recent times.

To sum up, the Saklei Shuyinj and Roehen Yaz glaciers could have played a role as trigger of lake outbursts of the Chateboi lake and also the lower ice-dammed lakes. During their retreat stage, ice avalanches

into the Chateboi lake could have also initiated displacement waves.

Other valley obstructions causing lake formations in the Karambar valley

Moraine-dammed lake

At present, the only permanent lake in the Karambar valley is the 2.5 km long Karambar Lake (Ak-kul, Turki = white stone, Stein, 1928), which is located at the Karambar Pass (4250 m). It is dammed by ground moraines of the former main valley glaciation (Photo 30). However, Hewitt (1998a) explains the origin of the Karambar lake as rockslide-dammed lake. Other examples for pass lakes are the lakes on the Shimshal Pass (4600 m) and the Shandur Pass (3650 m). Those pass lakes are permanent lakes without any lake outburst history.

Landslide-dammed lakes

Apart from the ice-dammed lakes, the Karambar valley has been blocked frequently by landslides. One of those blockages is located directly downstream of the Saklei Buk glacier dam, close to Matram Dan (Photo 31). Debris flows, coming from a left tributary valley of the Karambar river, repetitively impounded the Karambar river. They caused barriers in 1985/1986 (Hewitt, 1998a) and also in the 1990s according to the author's interviews to the villagers. Landslide dams are widespread in the Hindukush–Karakoram region and were investigated in detail by Hewitt (1998b). He identified in the Karambar valley several rockslides (i.e. at the Karambar Lake and in Bhurt), Nowadays, the main hazards for the settlements downstream of the glacier dams are cloud burst-triggered debris flows originating from the tributary valleys (Photo 32).

Temporary lake formations by secondary blockages during the flood

Interviews with the local inhabitants from various villages (i.a. in Chatorkand, Barjungle, Singal) revealed that during the flood secondary temporary lakes were formed at valley constrictions at several places (Photo 42, Figure 1). They might have been caused by fluvial undercutting of the slope sediments generating landslide-dammed lakes. Those temporary lakes can also drain abruptly causing small-sized floods.

Due to the high sediment concentrations, the flood waters themselves can build temporary blockages at nodal points in the valley course. The topographical setting in the Karambar valley provides favourable conditions for secondary lake formations for two reasons: the glacier tongues which project into the main valley cause obstructions to the flood waters. The

outburst of the uppermost lake at the Saklei glacier passed during its flood path six other dams. The smallest distance between the glacier tongue and the opposite sediment cone on the other river bank is at the Warghut glacier amounting at present only 51 m (Photo 10). Therefore, on the one hand, a high amount of sediment could be taken up by the flood waters leading to deposition of the sediment more downstream. On the other hand, temporary lake formations could be caused directly at the lower glacier dams. Upstream of the Sokther Rabot glacier dam, in the actual Sokther Rabot lake basin, ripple marks and eddy bars were found (Photo 17). They can be interpreted as the remnants of secondary lake formations, when the flood waters of the higher dam were abruptly backed up behind the lower glacier dam.

The high sediment and boulder content of the flood is evident by the fact that the inhabitants described the flood as an extremely powerful and noisy event, during which the earth was shaking. The approaching flood was first recognized by animals which became nervous and escaped to higher slope areas. The high sediment concentrations lead also to a widespread fish killing. In almost all villages were reported dead fishes at high levels above the valley floor.

From the outburst flood from Luggye Tsho (Bhutan) in 1994, it is reported that it generated a blockage by lodged tree trunks, which diverted the flood waters and directed it partly through a village section of Punakha killing 27 people (Richardson and Reynolds, 2000). During the Karambar floods a lot of wood land was also destroyed. Those wood lands mainly consisted of bush-like, thin-stemmed buck thorns. However, in large quantities they also could enhance a blockage in valley constrictions.

Geomorphological impacts of the glacial floods in the Karambar, Ishkoman and Gilgit valleys

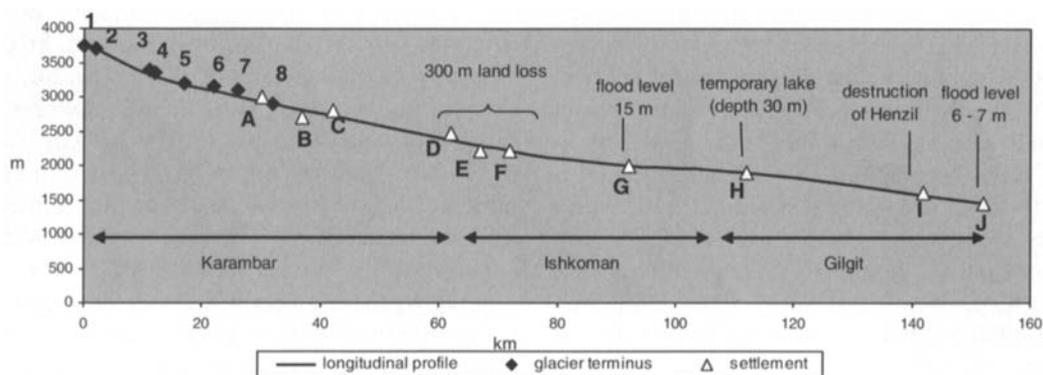
In this study, the extent of erosion by the floods has been mainly reconstructed by the amount of land loss

along the village areas downstream of the glacier dams and by eye witness reports (Figure 7). The Karambar valley is densely populated downstream of the Karambar glacier dams and a lot of field and housing area is located at the river side. Therefore, the settlement pattern and history in the Karambar region will be outlined briefly here.

The settlement history

Kreutzmann (1994) has investigated the settlement history in the Ishkoman valley and pointed out the correlation between the depopulation of the valley and historical glacier floods as well as war activities between the local rulers (Biddulph, 1880). The most important settlements during the flood events in the 19th century were Imit (2445 m) and Chatorkand/Dain (2250 m), which are already located in the Ishkoman valley, as well as Ishkoman itself, which is situated in a tributary valley of a Karambar valley. After an outward-migration trend due to local conflicts with the Yasin rulers in this region, Ali Mardan Shah, a local ruler, decreed a law for the resettlement of the Ishkoman valley in 1883. The first canals were constructed in the mid of the 19th century in Chatorkand and in Pakora (Saunders, 1983, cit. from Kreutzmann, 1994). When Biddulph (1880) visited the valley, he still found a lot of villages deserted. *"The Karoomber Valley, which contains the ruins of several large villages, now supports only 300 souls. The former inhabitants are said to have been exposed to constant forays from the Wakhis and Sirkolis, but the wars of the Yassin rulers since the beginning of the century have been the most powerful agent depopulating the country...More than once the glacier has temporarily dammed up the stream until sufficient water has accumulated to burst the barrier and carry destruction to the valley below."*

The Karambar valley was – like the Shimshal valley – difficult accessible up to the mid of the 20th century. This might explain the very poor knowledge about the glacier dams. Stein (1928) describes the Karambar valley as follows: *"To the south, along the Karambar or*



1 Saklei Shuyinj 2 Chateboi 3 Sokther Rabot 4 Chillinji 5 Warghut 6 Pekhin 7 Saklei Buk 8 Karambar
A Matram Dan B Bhurt C Bad Swat D BarJungle E Imit F Chatorkand G Garkuch H Singal I Henzil J Gilgit

Figure 7. Longitudinal profile Karambar–Ishkoman–Gilgit valley showing selected impacts of the 1905 flood on the settlement areas.

Ashkuman valley, there is no practicable route during the spring and summer. The extremely narrow gorges below the Chillinji glacier are then for several marches completely filled by the river, and the rock walls on either side are sheer precipices impassable for any but cragsmen unencumbered by loads. Even in winter the trek leading down the valley to the Gilgit river at Garkuch is extremely difficult, and at that season communication with Wakhan across the passes northward is blocked by snow. It is only for a few weeks in the early spring and autumn that it is possible to follow the route leading up the Karambar valley to the north end and across the Khora-bohrht pass (about 15,000 feet) to the Afghan Pamir.” Along the Karambar valley, an old trade route leads over the Khora Bhurt Pass (4630 m) into the Wakhan (Afghan Pamir), but it is only accessible from a tributary valley below the Chateboi glacier tongue. Therefore, the actual hazardous glacier dams, Chateboi and Saklei Shuyinj, were mostly not visited by the early travellers. Another trade route, which was much more frequented, lead over the Ishkoman Pass (Asumbar Haghost, 4560 m) to Yassin, offside of the Karambar valley. Like in Shimshal, it is stated that the Karambar valley had served as exile for criminals (Schomberg 1935, cf. Iturrizaga, 1996, 1997 for Shimshal). Nowadays, in the upper Karambar valley, upstream of Matram Dan, a proper way is still absent (Photo 44).

The settlements in-between the glacier dams

The highest temporary settlement locations are located in the Karambar pass area in 4250 m. The Pass provides extensive grazing grounds and is used by Kirgiz, Wakhi and Gujur people. Further pastures are situated in Shuyinj, Paskeja, Sokther Rabot and in the near of the glacier dams Chillinji and Warghut (i.e. Zachband). They are all located at places high above the river level. Matram Dan (2980 m), located at a debris cone, is the highest permanent settlement, which counts nowadays nine households, whereas in 1905 only one family supposed to have lived there (Photo 35).

The settlements downstream of the glacier dams

Downstream of the glacier dams, the Karambar valley shows a comparatively dense settlement distribution. In contrast, the settlement area in the Shimshal valley – excluding the settlement Shimshal itself – starts only 75 km downstream from the glacier dams. Settlements are mostly oasis settlements and therefore dependent on the irrigation of glacial melt water. They are mainly located on sediment cones, such as debris flow cones, moraines and glaciofluvial terraces, all of which are generally placed high above the flood water level. A decentralised settlement pattern is widespread. The valley floors are used for the cultivation of woodland.

Bhurt (2730 m) is the first settlement downstream of the Karambar glacier dam and consists nowadays of

about 14 households (Photo 36). Six houses are located on the opposite valley side. Only one house supposed to have been in Bhurt during the flood event of 1905. The flood-prone areas were mainly covered by forest. Bad Swat (2785 m) is located on a glacial sediment cone, up to 100 m high above the Karambar valley floor (Photo 37). On the right flank, wash limits from the flood are clearly visible. The sediment cones are heavily eroded by fluvial processes. About seven houses were located here in 1905. Flood bars are deposited in the valley floor. In Immit (2445 m), severe losses of settlement land were reported. According to the interviews, as much as 500–600 m of land supposed to be eroded by the flood. However, the fort in Immit stayed undamaged. A moraine covered rock downstream of Immit projects into the valley floor and flood sediments are deposited in its lee side. The Immit villagers report that the flood happened at day time. House sized boulders were transported. They mention a lake at Shuyinj in 1905. Immit was composed of 11 houses in 1905. Downstream of Immit, at the confluence Karambar/Ishkoman valley, the valley floor widens up to 1200 m (Photo 39). The valley floor is over its entire width freshly flooded by temporarily flood channels. Close to Barjungle (2215 m) the valley floor narrows again to a width of only 300 m (Photo 40). At present, here are located six houses. It is reported that huge ice boulders have flooded the land and rested there for several days. Visser (1938) shows impressive examples of 30-m high ice boulders in the Shaksgam valley. Some of them lasted for about 11 month (v. Klebelsberg, 1948/49). At least 300 m of land were taken away by the flood, but the land was unsettled. At Barjungle, a secondary lake has formed during the flood.

Most affected by the flood was the settlement of Chatorkand, but again mainly woodland was destroyed and animals were killed (Photo 41). The main settlement was located on higher locations. Hayward (1870) has mapped Chatorkand only on the right valley flank, where nowadays the settlement Dain is located. Kreuzmann (1994) concluded therefore that parts of Chatorkand were completely destroyed. However, interviews with the local residents showed that at least Dain supposed to have still existed after the flood. The main settlement areas are in both parts of the villages located high above the river level. Apparently up to 300 m of land were taken away on both valley sides. The minimum distance between Dain and Chatorkand measures currently 250 m. Here the two settlements are connected with a bridge. During the flood of 1905 the bridge was destroyed. It is reported that the flood lasted for two days in Chatorkand. In 1976, new settlements were founded in the flood prone valley floor.

Despite the fact that the flood passed valley sections of up to 2 km in width on its way – such as in Garkuch – its erosion potential was still enormous further downstream. Due to the high availability of debris in form of unconsolidated scree, debris flow cones and other sediment cones along the flood path, the floods incorporate

a lot of debris during their way downstream. These hyperconcentrated flood water possess a high erosion power. Especially when the main river, which is upstream of the glacier obstructions mostly composed of several meandering river branches, is near the glacier dams sandwiched to a single, more erosive river stream. The same is true for other valley constrictions in form of sediment cones projecting into the main valley.

Near to the Chinese bridge the valley profile narrows abruptly to a few decametres and could have produced a bottle-neck effect for the flood masses. Downstream of the Chinese Bridge a memorial stone reminds the 15 m flood level of the 1905 flood (Photo 43). The settlement of Henzil, 10 km valley upwards from Gilgit, was split into two half by the flood. Further temporary lakes were formed at Hattun and in Garkuch. Surprisingly, hardly any humans were killed by the floods.

The reported runout distances indicate a minimum value for the distance of the flood impacts. The lowest destructions are reported from Gilgit in a distance of 120–150 km, even though the destructive impact might have reached much further downvalley. The 1905-Karambar flood caused a 7 m high flood level above the normal level and several bridges were destroyed (Todd, 1930).

In comparison, Mason (1929) and Todd (1930) report from runout-distances of about 1200 km in the Shyok valley and flood levels of 21 m over normal flood level in the gorge section between Unmaru and Biagdangdo, 300 km far away from the origin. To sum up, the populated sediment cones are all heavily undercut by fluvial processes and show cliff edges of up to 100 m at their distal sections. This study shows that the sediment cones were considerably eroded by flood waters and were cut back by about 300 m and more. These distances correspond with previous reconstructions in Shimshal and Passu (Iturrizaga, 1997).

Wash limits are located along the Karambar valley flanks up to several decametres above the valley floor, such as in Bad Swat. Flood bars are deposited in the valley floor. Outsized boulders in the valley floor are quite rare and derive mostly from the tributary valleys rather from the glacier outbursts from the main valley. The settlement area of Chatorkand has been mostly affected by the floods, especially in 1905 (Kreutzmann, 1994). However, since the 1970s a settlement expansion has taken place to the more flood prone areas. Nowadays the main hazards for the settlements are debris flows originating from the tributary valleys. In Imit, Chatorkand and Barjungle severe land loss occurred in the last years by debris flows due to cloudbursts.

The geomorphological landform assemblage of consecutive ice-dammed lake basins

No other valley in High Asia shows such a high number of glacier dams on a comparatively short horizontal distance like the Karambar valley, even though con-

secutive glacier dams are quite common in the Karakoram mountain range (Shaksgam valley: five glacier dams in 50 km, Shyok valley, three glacier dams in 10 km, Shimshal valley: four glacier dams in 30 km, Upper Yarkhun Valley five glacier dams in 16 km, Hunza valley: three glacier dams in 15 km). The dense concentration of eight glacier dams at altitudes between 2830 and 3850 m and along a horizontal distance of only 40 km results in a complex interfingering of lake basins and flooded valley sections. The lower lake basins show conspicuous flood landforms instead of lacustrine sediments due to the fact that the lake basins were transformed by outburst floods from higher glacier dams. In the lake basins, flood traces are recognizable by immense fluvial undercuttings, flood bars, traces of secondary lake formations and large boulders up to 3 m in diameter. The specific landscape assemblage of consecutive lake basins is demonstrated in Figure 3.

The flood scenario in the Karambar valley: Possible lake outburst cascades

There are evidences that two or more ice-dammed lakes existed simultaneously in the Karambar valley (Iturrizaga, 2004). Assuming the coexistence of those lakes, the drainage of the Chateboi (Saklei Shuyinj) lake could have triggered the outburst of the lower located Warghut and Karambar lakes and initiated an outburst cascade of lakes (Figure 1). This multiple lake outburst would explain the enormous impact of the 1905-flood event on the settlement areas, which exceeded those of other Karakoram glacial floods.

In general, a catastrophic drainage of the Saklei Shuyinj or Chateboi lake would have had severe morphological impacts. The Karambar valley floor shows in its upper part a relatively steep valley gradient. It declines from the Chateboi lake basin (3750 m) by 400 m over a horizontal distance of only 9 km. Flood waves originating from the Chateboi–Saklei Shuyinj lakes passed four further glacier dams (Sokther Rabot in a distance of 9 km, Chillinji in 10 km, Warghut in 15 km and Karambar in about 30 km), which also dammed the valley at that time. Therefore huge masses of glacier ice and sediment from the laterofrontal moraines were taken up by the flood and caused a high erosional power.

In the Karambar valley a relative vertical difference in height of 1500 m is passed from the glacier lake to the former largest settlement Chatorkand (2215 m) over a distance of 70 km. For comparison, in Shimshal the vertical difference amounts only 800 m from the Virjerab lake (3300 m) to Passu (2500 m). The Karambar valley shows an average gradient from the highest lake basin to Gilgit of 0.86°. At the first 30 km the gradient amounts 1.5°. In the Shimshal valley, the valley gradient between Virjerab and Gilgit amounts only 0.57°.

As a rule, ice dam failures by subglacial drainage cause smaller-sized floods than the sudden rupture of a moraine-dammed lake (Costa and Schuster, 1988;

Clague and Evans, 1994). If the glacier dam collapses in form of a mechanical rupture, the hydrograph shape and runout-distance can be similar to breaches of moraine-dammed lakes. However, according to the descriptions of early travellers, glacier lake outbursts in the Karakoram (Shyok valley) seem to have produced even bigger and far-reaching floods than in the Himalayas due to the large volume of the lakes (Todd, 1930; Hewitt, 1982). Also mechanical failures of the dam had occurred in the Karakoram Mountains (Visser, 1935).

Up to now, for all glacier lake outbursts mentioned above the outbreak mechanisms are unknown. Several drainage trigger mechanisms can be taken into consideration (cf. Tweed and Russell, 1999; Walder and Costa, 1996):

1. Enlargement of sub- and englacial cavities: some glacier barriers show a permanent subglacial drainage, such as the Chateboi or the Khurdopin glacier in the Shimshal valley. Most of the glacier lake outbursts in the Karakoram take place during the time of highest discharge rates in July and August (Charles 1984, Iturrizaga, 1997). The Hindukush–Karakoram rivers show a distinctive seasonal drainage pattern. Up to 60% of the drainage occurs in the summer months (Ferguson, 1984) and can then preferably lead to an outburst of an ice-dammed lake.

2. Overspill processes of the ice-dam: The Chateboi glacier dam is the lowest glacier dam in height and spillover drainage is likely to happen. This could have been also the reason that the lake outbursts in the Karambar valley occurred already very early in the year in June. Moreover, high active sediment cones drains in almost all glacier lake basins, which could have produced displacement waves and therefore an overspill of the dam. Hanging glaciers are also draining into the Chateboi glacier lake basin.

3. Mechanical break of the dam (subaerial breach widening): With potential lake heights of up to 150 m, a mechanical collapse of the ice dams can easily occur. The mechanism of ice dam flotation (Thorarinsson, 1939) is unlikely to happen in the Karambar valley, because the debris content of the glacier tongues – and therefore their density – is too high to lift up the glacier ice.

4. Seismic activity: The Karambar glacier dams are situated in a tectonic active mountain area. The Reshun Fault passes right through the Chillinji–Sokther Rabot–Chateboi glacier tongues. However, up to now a link between glacier lake outbursts and earthquake activities in this region has not been observed.

Puberanch system (Pumberanch, Pumberech): Early warning systems for glacier lake outbursts

In order to warn the villagers in the Ishkoman and Gilgit valley against the glacier lake outbursts, a fire warning system was established by the villagers (Wakhi: *puberanj*, *pu* = Feuer). On good visible, high located hill sides in up to 4000 m a.s.l. local posts of two or three

people were set up, the so called lybbies (Photo 47). The highest post was located above the Sokther Rabot glacier. From here, fire signals were sent to the lower posts, which were located in Bhurt, Bilhanz, Imit, Gichgich, Barjungle, Shonas, Pakora, Chatorkand, Hammani, Hattun, Dammas, Singal and probably down to Gilgit. The observation started only at the 25th June and therefore already after the lake outbursts in the Karambar valley. The fire warning system has been operated the last time in 1905.

This early warning-system could also be reconstructed in the Shimshal valley, where it was successfully operated until the 1960s (Iturrizaga 2005c). Over a horizontal distance of 90 km, over 30 post were active over a time period of three weeks on passes of up to 4000 m (pers. comment Mr. Shambi Khan (Shimshal); cf. Bridges 1908; Todd, 1930). Fire-warning systems are wide-spread in the Karakoram and were originally used for the alert against war attacks from hostile neighbour communities.

The current situation of the glacier dams in the Karambar valley

Whereas the general glacier retreat considerably enhanced the development of moraine-dammed lakes in the Himalayas in the last 50 years (Yamada, 1998), in the Karakoram the number of glacier lakes has decreased. At present, there are only a few glacier-dammed lakes recorded (i.e. Kyagar glacier lake). However, a lot of glaciers are interfering with the main river and form potential glacier dams. Even though the Chateboi glacier has downwasted considerably in the last 50 years, it still blocks temporarily the Karambar river (Photos 46a and 46b).

The same is true for the glacier lakes in the Hindukush area. Apart from the moraine-dammed Karambar lake in the Karambar Pass area (4250 m), there is presently no permanent naturally dammed lake in the Karambar valley. However, the glacier tongues of the potential barriers discussed here terminate at present in a distance of only 150–1400 m from the opposite valley flank (Table 2, Photos 1, 6, 9, 12, 13b and 15). To generate a dam, a small glacier lobe is sufficient to block the river. Even though the glaciers have been rather stationary in the last century, some glacier surfaces are currently at the same level like the lateral moraine crest or even dumping debris on the outer slopes of the lateral moraines. Surging glacier advances are quite common in this mountain region (Kick, 1958; Gardner and Hewitt, 1990; Iturrizaga, 2002), so that even today the risk of a new lake formation has to be taken into consideration. In particular, a lake could be formed at the Warghut glacier, either by a glacier advance or a debris flow against the glacier tongue from the left Karambar valley flank (Photo 10). Further more, the Karambar river drains beneath the Chateboi glacier over a distance of 4 km and is sometimes impounded to a small lake for a short time. Considering the recent settlement expansions

Table 2. The glacier dams in the Karambar valley

Glacier dam	Glacier length in km	Current glacier tongue end Height in m	Aspect of glacier tongue	Distance between valley flank and glacier dam in m (year 2004)	Type of glacier dam (GD)
Karambar	23	2830	W	580	Temporary GD
Saklei Buk	5	3300	NE	1200	Prehistoric GD ?
Pekhin (Lup Buk)	10	3250	E	1400	Prehistoric GD
Warghut	4	3300	E	51 (debris flow cone) 200 (valley flank)	Temp. combined GD glacier/debris flow cone
Chillinji	10	3370	WNW	340	Temporary GD
Sokther Rabot	8	3450	NE	150	Temporary GD
Chateboi	~11	3550 dam: 3750	E dam: N	0	Permanent GD
Rochen (?)	?	3800	N	~100	Ice avalanche dam (?)
Saklei Shuyinj	~7	~3850	N	>1500	Temp. combined GD glacier/rock bar

In principal, all historical glacier dams could have caused the lake outbursts mentioned in this table except the Saklei Buk and Pekhin glaciers, which have dammed the valley probably before 1850.

towards the flood prone valley floor areas in the Ishkoman–Gilgit River area, a potential flood would have devastating effects on the infrastructure. Nevertheless, operational warning mechanisms to mitigate the flood impacts are absent. Especially, in the case of a permanent glacier dam, such as the Chateboi, an installation of an early warning system would be advisable.

Wider implications

Including five flood events before 1900, the Karambar flood chronology provides one of the longest compilations of glacier lake outbursts in the Hindukush–Karakoram region. Assuming that a glacier advance corresponds with the formation of ice-dammed lakes, the dates of glacier outburst floods can provide information on the timing of the glacier oscillations, in this case especially on the decline of the Little Ice Age. In 1905, when the great Karambar flood happened, glacier lake outbursts also occurred in the Shimshal valley (Khurdopin glacier) (Iturrizaga, 2005c) and in the East-Karakoram at the Kichik Khumdan dam (Hewitt, 1982). In this time period, further examples of glacier advances of short tributary glaciers were monitored (Visser, 1938; Iturrizaga, 2002). Overall the glacier lake period, extending from at least 1840 to 1930 (Hewitt, 1982; Kreutzmann, 1994), suggests that glacier advances have occurred during this time period. Its end indicates the turn down of the Little Ice Age. T. Longstaff (Himalayan Journal, 1932; Mercer, 1975) suggests a 12–13 year cycle of glacier advances of the Karambar glacier considering the dates of maximal advance in 1891–1892, 1904–1905, 1916–1917 and 1929–1930.

During Postglacial and Late Glacial times, the number of glacier dams in the Karakoram has been even higher than today. This is shown by expansive lake sediment sequences throughout the Karakoram valleys. They developed probably during the deglaciation of the former High glacial to Late Glacial ice stream network

(cf. Kuhle, 2001). Lacustrine sediments originating from ice-dammed lakes were already mentioned by Thomson (1852). Megafloods could have played a prominent role in the Karakoram Mountains in the past with runout distances as far as to the Punjab (Cornwell, 1998). Such superfloods are known from the Altai Mountains (Rudoy and Baker, 1993) and the Tibet–Himalaya region (Kuhle, 2002; Montgomery et al., 2004).

However, in contrast to other Karakoram valleys (Shimshal, Hunza valleys), in the Karambar valley lacustrine sediments are scarcely deposited from older ice-dammed lakes. During the Late Glacial and Last Glacial Maximum, the glacier dams were combined to a single trunk glacier. At the confluence Ishkoman–Gilgit valley, they were connected with the Gilgit-ice-stream coming down from the Shandur Pass (Derbyshire et al., 1984; Kuhle, 2001).

Conclusions

At least six major glacial outburst floods were reported from the Karambar valley between 1844 and 1909. In this study, nine glacier dams have been reconstructed by geomorphological evidence, interviews of the local inhabitants and archive material. The Saklei Shuyinj, Chateboi, Sokther Rabot, Warghut and maybe also the Chillinji glaciers have played – apart from the apparently notorious Karambar glacier – a vital role in the devastating outburst history of the Karambar valley. The Chateboi and Saklei Shuyinj lake basins have partly overlapped leading to an interfingering of their lacustrine landform assemblages. The outburst of the higher Chateboi–Saklei Shuyinj glacier lake could have initiated a domino-like succession of lake drainages of lower glacier-dammed lakes, such as the Warghut or Karambar lake. The topographic constellation of successive glacier dams is also present in other Karakoram valleys, so that the interlocked landform assemblages from the Karambar dams are of greater regional importance.

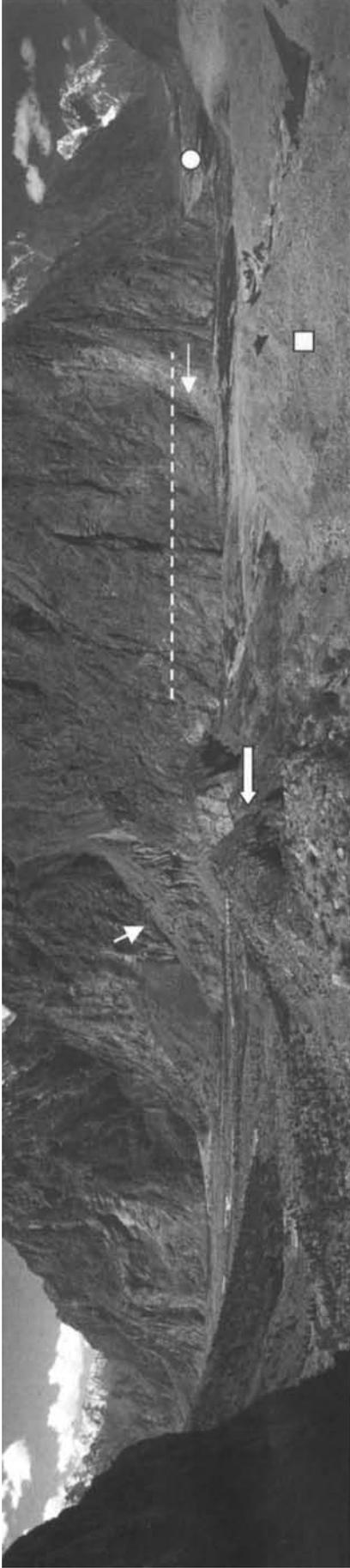


Photo 1. Temporary glacier dam: The morphology of the proglacial environment of the Karambar glacier tongue (□) evidences former glacier advances. Moraine remnants (↖), glacial trimlines (- - -) and rock failures (—) after the glacier retreat can be found at the right Karambar valley flank. During the glacier advances the glacier broke through its Little Ice Age moraine (⇐). The Karambar lake (○) reached up to Matram Dan. Photo: L. Iturrizaga 09.09.2002.

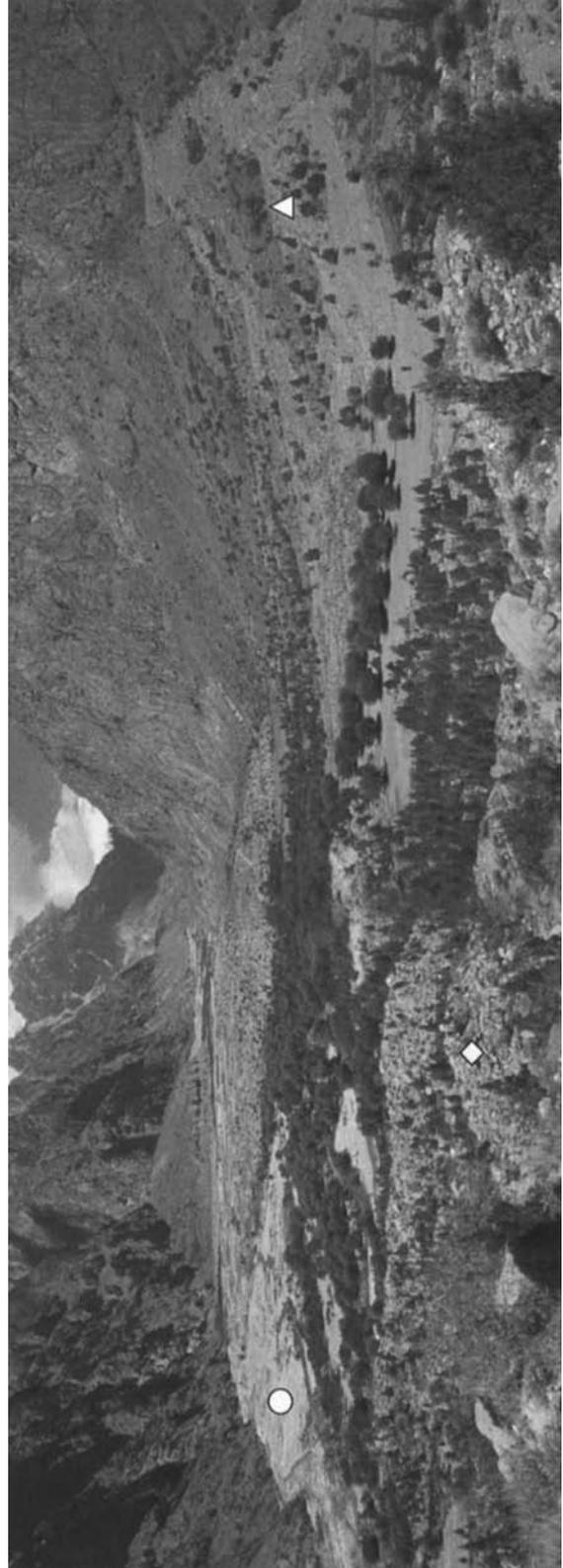


Photo 2. View from the right Karambar lateral moraine upstream into the former Karambar lake basin (○). Only a few geomorphologic traces can be found from the lake which reached up to Matram Dan. Lake sediments are hardly preserved indicating the short life span of the ice-dammed lake. High active debris flow cones (△) enter into the lake basin. Mass movements may have triggered a lake outburst. In the foreground, an older lateral moraine (◇), attached to the main lateral moraine, is visible. Photo: L. Iturrizaga 13.09.2002/1, 13.09.2002/4.



Photo 3. View from the left side of the Karambar glacier close to Sikritjashek (3400 m) onto the upper Karambar glacier. The Karambar glacier is a firn cascade glacier with catchment areas of over 7000 m in height. It is partly fed by ice avalanches. In the past, the Karambar glacier has been subject to sudden exceptional glacier advances. Photo: L. Iturrizaga 12.09.2002/7.



Photo 4. View from 3100 m towards the lower Karambar glacier tongue. When the Karambar glacier (□) dammed during historical times the Karambar valley (↓), its glacier surface reached up to the crest of the right lateral moraine (→). At present, the downwasting glacier surface runs up to 50 m below the former ice level. Photo: L. Iturrizaga 12.09.2002/2/21.

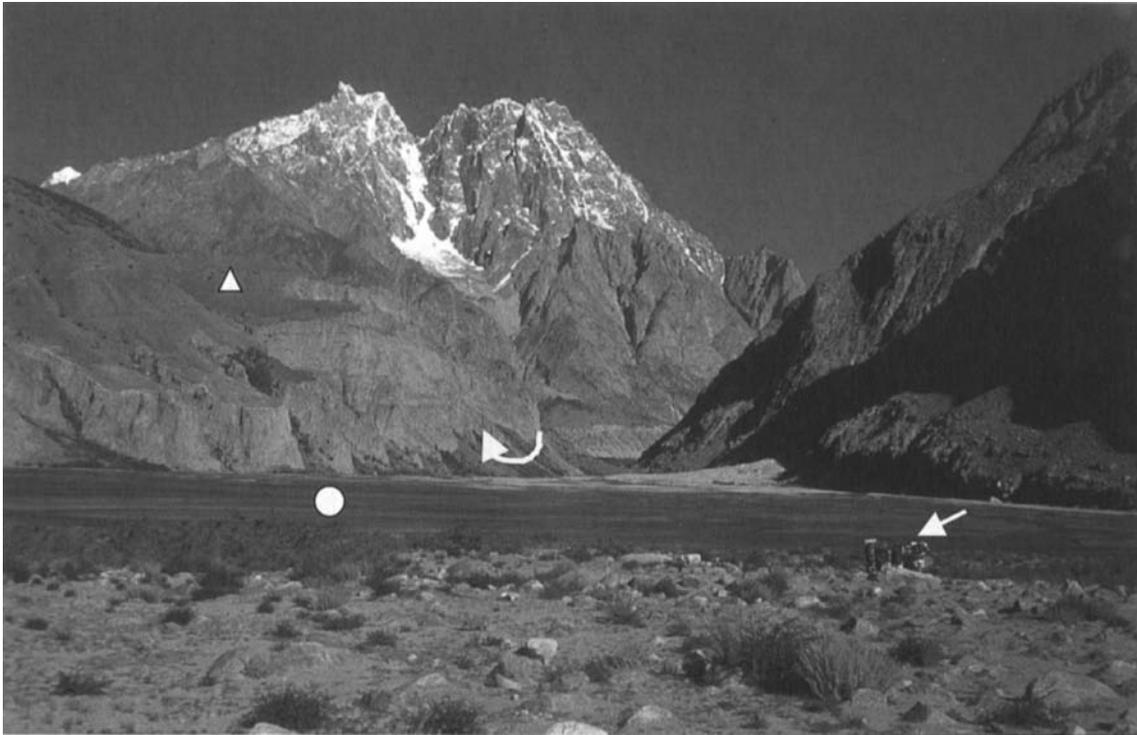


Photo 5. View from a debris flow cone upstream of Matram Dan to the right lateral moraine (△) of the Saklei Buk glacier. At its distal part, it is undercut (↪) by the Karambar river, for which only a narrow passage remains to drain between the moraine and the left Karambar valley flank. The Saklei Buk glacier has not blocked the Karambar valley in recent time. But in the center, downstream of the glacier dam, a part of a former lake basin (○) can be seen which originates from a landslide dam close to Matram Dan. In this valley section there is again no proper way. One has to wade – if possible – through the river or climb along the valley flanks. Note the people in the foreground for scale. Photo: L. Iturrizaga 13.09.2002/30.



Photo 6. The Saklei Buk glacier tongue (□) is embedded in a moraine pedestal. The lateral moraines (△) are up to 250 m high. In the laterofrontal section, a small tributary tongue basin and moraine bulges (↘) evidence former glacier overlappings and break throughs. On the opposite valley flank moraine cones (↗) prove the former extent of the glacier tongue which blocked the Karambar river. Photo: L. Iturrizaga 14.09.2002/06.



Photo 7. Glacier dam assemblage: View from 3900 m above Buk towards N to the Chillinji (✓), Warghut (↘) and the Lup Buk glacier (□) in the front. The left Karambar valley flank shows geomorphological signs of a former prehistorical glacier advance: moraine remnants (1), trimlines generated by the glacier surface on the parent rock (---) and rock scars (→). Historical end moraines are deposited in the glacier forefield (↘). The Karambar valley profile narrows considerably in this valley section. The sediment cones (△) show decameters high cliff walls, which are partly generated by glacier outburst floods. Photo: L. Iturrizaga 14.09.2002/04.



Photo 8. View from the right Warghut lateral moraine into the upper catchment area of the avalanche-fed glacier. The lateral moraine was overridden by the glacier in recent times (↪). A sudden enhanced input of ice avalanches could lead to an advance of this short glacier and cause a new dam. Photo: L. Iturrizaga 15.09.2002/21.



Photo 9. Combined dam of lateral moraine, glacier ice and debris flow cone: An active debris flow cone (◇) is deposited against the Warghut glacier tongue and blocked in combination with the glacier tongue from time to time the Karambar river. Previously, the Warghut glacier (□) reached the left Karambar valley flank, which is covered with moraine pillars (△) and also dammed the river. In the foreground the former lake basin (○) is visible. The sediment cones downstream of the Warghut glacier were strongly undercut by the glacier floods (↔). In former times the sediment cones reached far more into the gravel floor. As typical for the glacier dams in the Karambar valley, the Warghut glacier is surrounded by up to 150 m high lateral moraine ramps (▷). During a former glacier advance, a small tributary glacier tongue was formed (⋈). Photo: L. Iturrizaga 16.09.2002.



Photo 10. View from the right Warghut lateral moraine onto the combined Warghut glacier dam. The high active debris flow cone consists partly of dislocated moraine material covering the valley flanks (△) and projects towards the Warghut glacier tongue (□). The Karambar river has incised (↓) between the two landforms. Debris flow deposits (✓) are also found at the side of the glacier tongue evidencing that a debris flow had previously dammed the river and not only a former glacier advance. Photo: L. Iturrizaga 15.09.2002/23.

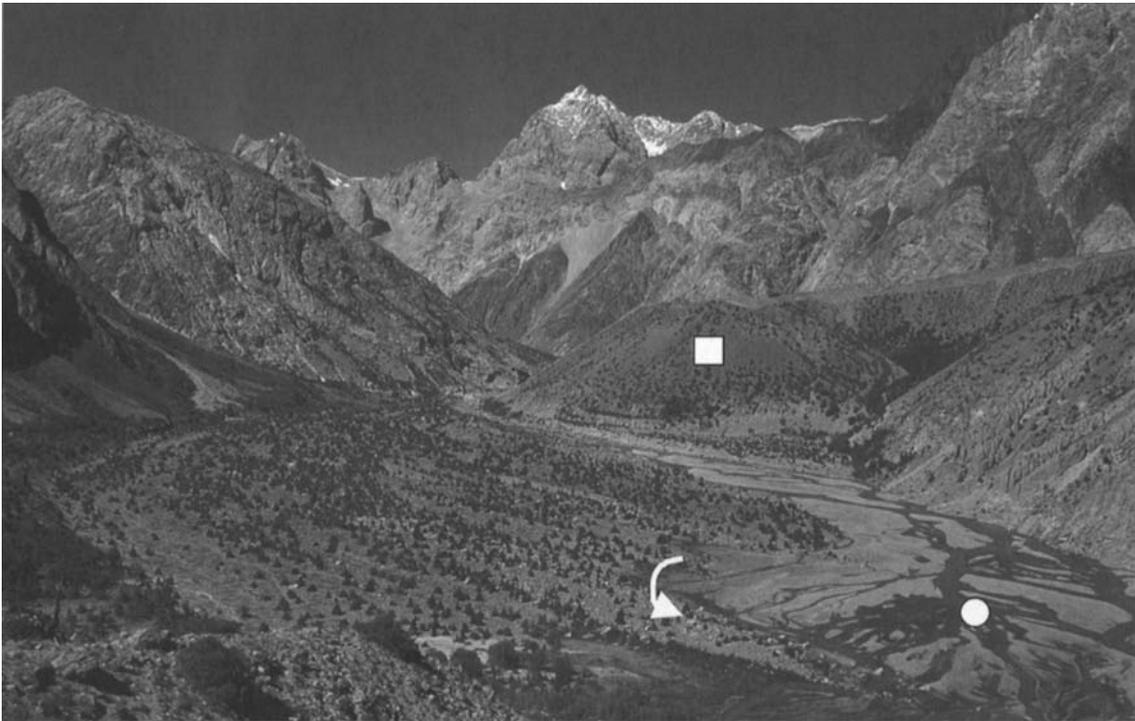
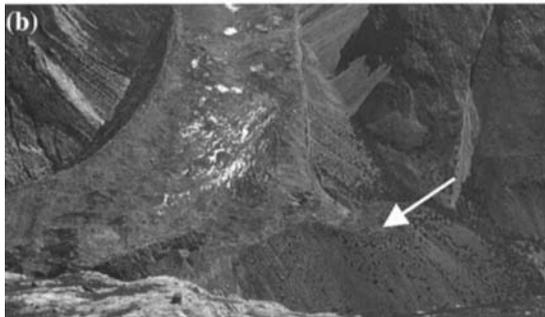
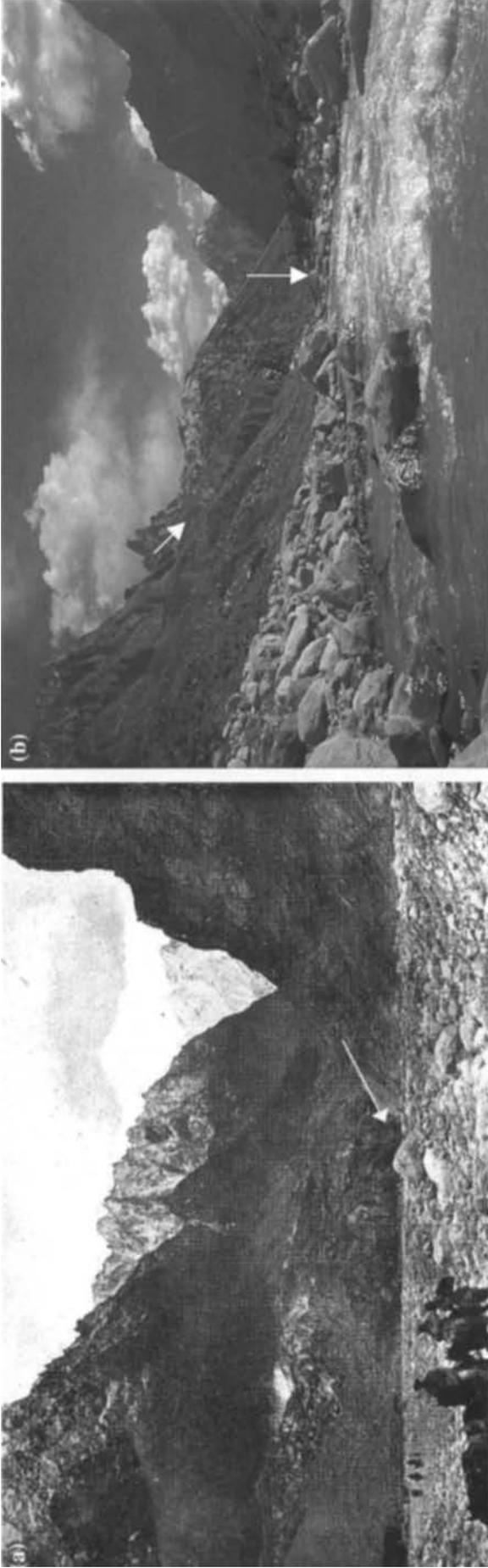


Photo 11. Interfingering of lake basin and flood landscape: View from the left lateral moraine of the Warghut glacier upstream into the Warghut lake basin (○). In 1909, the ice-dammed lake stretched at least up to the Chillinji glacier (□). To that time, also the Chillinji glacier blocked the valley further upstream. The Warghut lake basin has been transformed by flood events from higher glacier dams (↪). Photo: L. Iturrizaga 15.09.2002.



Photos 12 a and 12 b. Temporary glacier dam: The Chillinji glacier flows down from the Koz Sar (6677 m) to the Karambar valley and expands in a mushroom-shape at the valley floor at 3370 m. The glacier tongue is located only about 1 km downstream of the Sokther Rabot glacier. A small tributary glacier tongue is visible at its southern part (↙) (small photo). The lateral moraines are at some places shedded by supraglacial debris of the Chillinji glacier. Photo: L. Iturrizaga 16.09.2002/20.



Photos 13a and 13b. The Chillinji glacier tongue in 1916 and in 2002. The left photograph was taken by Longstaff (1951, Plate 16a) in 1916 from upstream of the Chillinji glacier. The Chillinji glacier tongue blocks the Karambar valley and the river seems to drain subglacially (✓). In 2002 (Photo: L. Iturrizaga 21.09.2002/29), the Chillinji glacier tongue (↘) terminated at a distance of 350 m from the right Karambar valley flank and the Karambar river could pass without hindrance. Nowadays the glacier tongue is rather stationary, but unpredictable surge movements can take place at any time at this avalanche fed glacier.

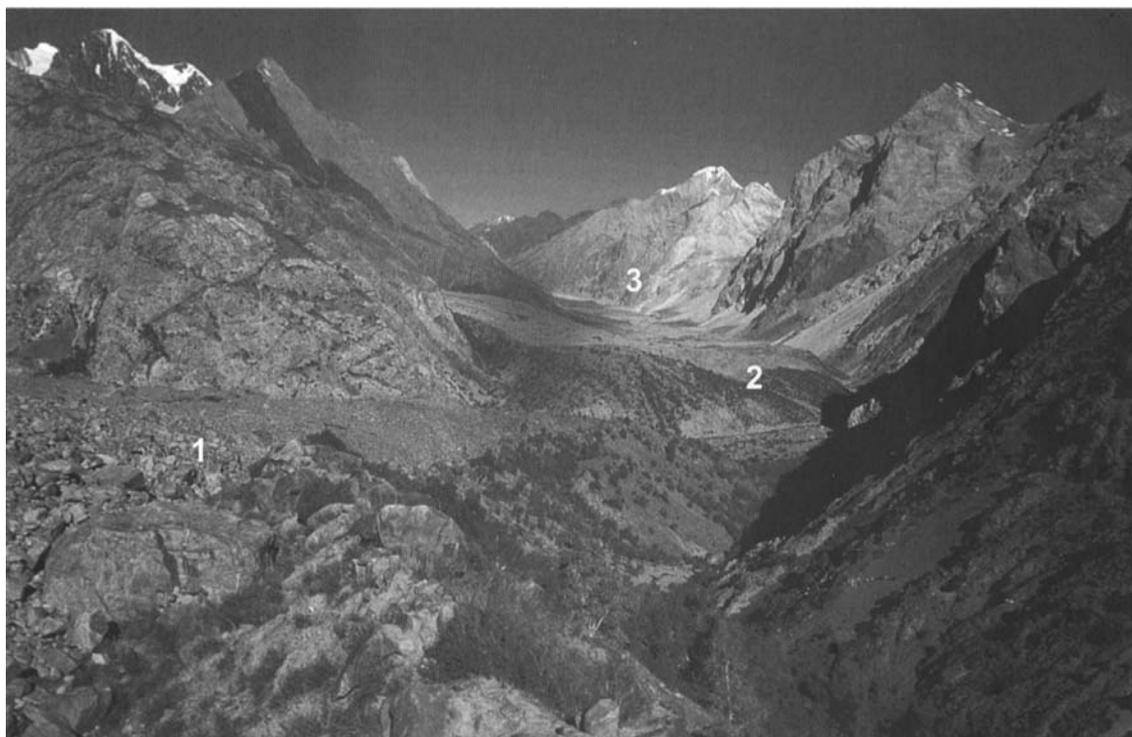


Photo 14. Successive glacier dam: View from the right side of the Chillinji glacier (3550 m) towards the upper Karambar valley with the three successive glacier dams, Chillinji (1), Sokther Rabot (2) and Chateboi (3). Except for the Chateboi glacier, the glacier ends are heavily debris-covered. Photo: L. Iturrizaga 21.09.2002/2/1.



Photo 15. Temporary glacier dam: The debris covered Sokther Rabot glacier tongue (□) spreads almost over the entire Karambar valley floor (3450 m) and leaves only a narrow passage of about 150 m for the drainage of the Karambar river. The end moraine sanders are mostly densely covered with juniper (↘), except for the glacier outlet, where the glacier (△) could have blocked the Karambar river in recent times. Moraine pillars from previous glacier advances cover the valley flank (△). Photo: L. Iturrizaga 16.09.2002.



Photo 16. The Sokther Rabot glacier tongue (↘) reaches close to the Karambar river. However, most of the glacier tongue is skirted by a morainic ramp which is covered by trees. Therefore, only part of the glacier tongue could have dammed the Karambar river. In the background the Chillinji glacier tongue is visible (↓). Photo: L. Iturrizaga 21.09.2002/17.

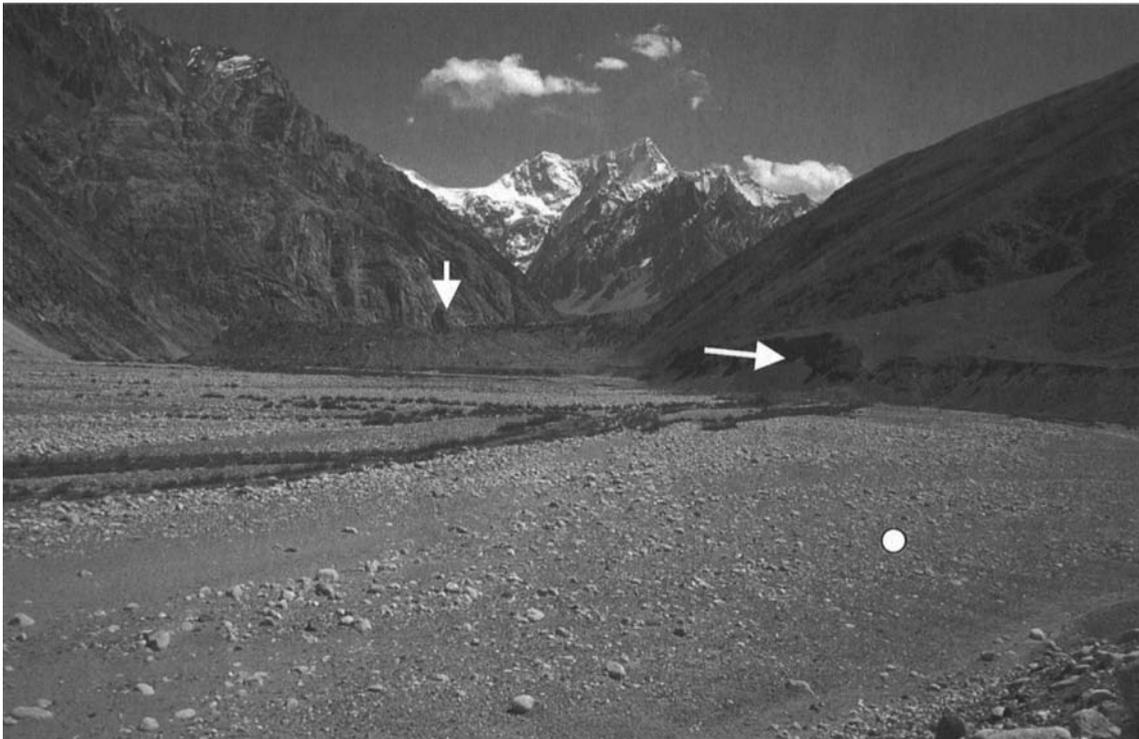


Photo 17. View towards on the Sokther Rabot glacier dam (↓) from upstream. The sediment cones adjacent to the broad valley floor are strongly undercut by fluvial processes (→). Upstream of the glacier dam, the sediments are sickle-shaped eroded by the past high-energy floods. In the foreground some ripple marks (○) can be seen on one of the higher terrace levels. Photo: L. Iturrizaga 17.09.2002/6.



Photo 18. Permanent glacier dam: View from 4100 m towards the lower part of the Chateboi glacier tongue, which presently blocks the Karambar valley, which presently blocks the Karambar valley. The Karambar river drains subglacially in this section. The valley floor (○) downstream of the glacier terminus has been significantly transformed by glacial lake outbursts. At the same time this flooding section of the Karambar valley was in former times the lake basins of the Sokther Rabot (△) and Chillinji glacier dams (◇). The Koz Sar (6677 m), one of the highest catchment areas of the Karambar valley, can be seen in the background. In the foreground, granite erratics (◊) from prehistorical glacier advances have been deposited at the valley flank. At present the glacier surface lies several decametres beneath the historical crest of the lateral moraine (◇). Photo: L. Iturrizaga 18.09.2002/19.

Photo 19. Continuation of Photo 18 with a view towards the highest catchment area of the Chateboi glacier. The glacier descends in forms of a narrow ice fall into the Karambar valley and expands in mushroom-shape a little bit upvalley to the right. The Karambar river drains from here on en- and subglacially (⇌). Nowadays the Chateboi glacier is strongly crevassed and provides many drainage passages for the Karambar river. At the turn of the last century, the Chateboi glacier reached the crest of the lateral moraine (△) and impounded the Karambar river to a lake several kilometres in length. Photo: L. Iturrizaga 18.09.2002/12.

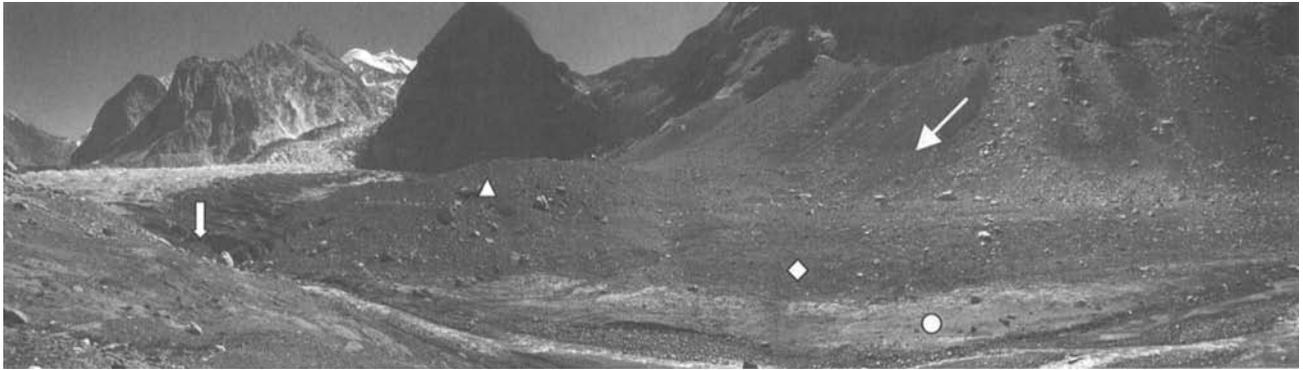


Photo 20. In the Chateboi lake basin shallow lake sediments (○) were deposited, which originate partly from very recent lake formations. From time to time, a small lake was impounded during the summer 2004. During the 19th century and at the beginning of the last century, a lake was formed by the Chateboi glacier barrier, which extended up to Shuyinj. Lake levels (↙), about 20 m above the valley floor, indicate the former ice-dammed lake. The barrier consisted of the left lateral moraine (△) and the Chateboi glacier. The lateral moraine is incised by the Karambar river. Several lake terraces (◇) consisting out of gravelly sediments prove the corresponding lake levels. Photo: L. Iturrizaga 18.09.2002/28–29.

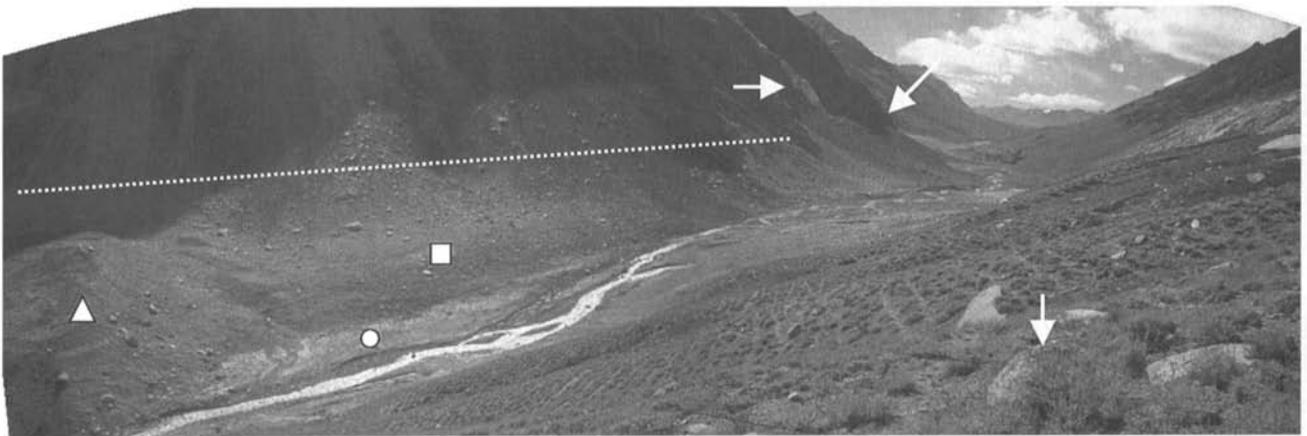


Photo 21. View into the Chateboi lake basin from the glacier dam towards Shuyinj. To the left, the Chateboi lateral moraine (△) is visible, which is linked with the lake terraces (□) and lake sediments (○). The Roehen Yaz (Shu Yaz) (→) and the Saklei Shuyinj glacier (↙) drains into the former Chateboi lake basin. In former times they dammed the Karambar river as well. The dotted line (- - -) marks the former lake level, probably at the beginning of the last century. In the foreground granite erratics (↓) are deposited, originating from the ice-age main valley glaciation. Photo: L. Iturrizaga 18.09.2002/11,14.



Photo 22. Possible ice-avalanche dam: Did the Roehen glacier block the Karambar valley in the last century? Previously, the Roehen glacier tongue supposed to be connected with the upstream Saklei Shuyinj glacier tongue. The Roehen glacier tongue is surrounded by an end moraine wall (□), which is several decametres in height and dissected by the melt water streams. This huge moraine wall actually implies that the glacier did not reach beyond this moraine in the last century. However, intensive ice avalanches or a surge like event must be taken into consideration for a possible dam. The Karambar river (↙) drains at the foot of the moraine. Note people in the foreground for scale. Photo: L. Iturrizaga 18.09.2002/36.

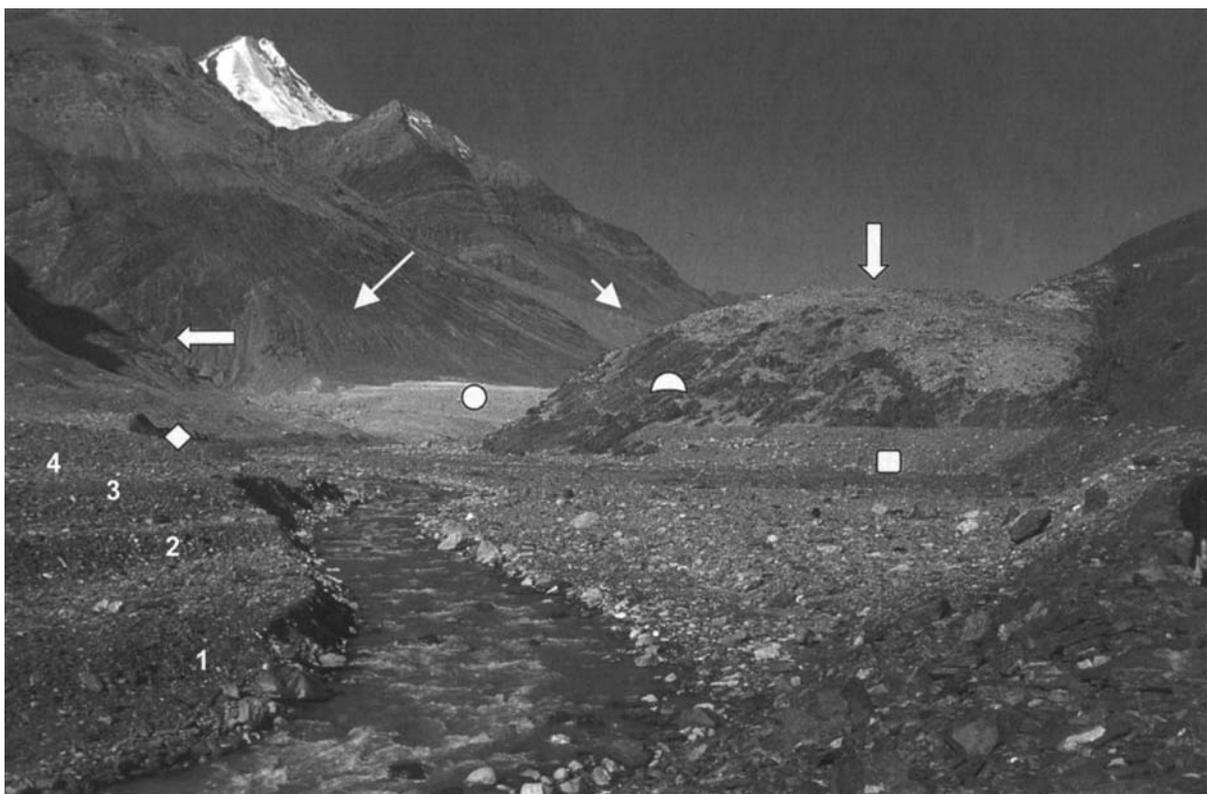


Photo 23. Combined dam consisting of glacier ice and rock bar: View from the Chateboi Lake basin upstream towards the former Saklei Shuyinj glacier dam, the highest historical glacier dam in this valley. The exit of the Saklei Shuyinj valley is visible to the left. From here originated the Saklei Shuyinj glacier, which formed in combination with the roche moutonnée (◐) a glacier barrier and blocked the Karambar river. Granite boulders, deposited on top of the rock bar, prove that it was flooded by the glacier. Shallow moraine ledges (✓) from previous glacier advances are preserved at the valley flanks. Moreover, a hummocky moraine landscape (◇), which is upstream interfingering with lacustrine sediments (○), indicates the former ice barrier. The terrace levels (1,2,3,4,□) of the Chateboi lake basin are visible in the foreground. Note the cow at the right photo margin as scale. In the background, the Shuyinj glacier projects into the Karambar valley (\). Photo: L. Iturrizaga 18.09.2002/2/1.



Photo 24. Panorama view from the Saklei Shuyinj valley (↓) exit to the Shuyinj glacier (✓). The valley floor is taken up by terrace sequences which are interfingered with the remnants of the former Saklei Shuyinj ice margin (○) and the left lateral moraine (↓) of the Shuyinj glacier. On top of the gravel terraces are deposited lake sediments (←) which are left behind from a younger lake. Photo: L. Iturrizaga 18.09.2002/15–18.



Photo 25. Detail from the previous panorama. View from the left Karambar valley side towards the confluence area of the Saklei Shuyinj and Karambar valleys. At present, the Saklei Shuyinj glacier terminates at the confluence step (↓), whereas 100 years ago, the glacier spread over the whole valley Karambar valley floor. At the right Karambar valley flank, the moraine ledges (✓) show the former glacier extent. In the foreground a sediment complex consisting of lake terraces (□), lake sediments (○) and the fluted hummocky moraine landscape (◇). Photo: L. Iturrizaga 18.09.2002/2/10.



Photo 26. The photograph was taken by Stein (1928, Photo 53) in 1913 when he passed the upper Karambar valley. It shows a glacier between the Chateboi glacier and Shuyinj. According to the descriptions by Stein it can only be the Saklei Shuyinj glacier tongue, which obstructs the Karambar river. The river (↓) drains beneath the ice. See photos 25 and 27 for location.



Photo 27. View from Shuyinj (3900 m) into the Chateboi–Saklei Shuyinj lake basin. At the right side the Saklei Shuyinj valley (⇒) joins the Karambar valley. Here are deposited the lake sediments (○). In the foreground the lake terraces (1,2,3,4) are visible. The maximum extent of the lake towards the Karambar Pass area is difficult to determine. The Karambar river has formed subglacial gorges (↙) during the ice-age glaciation of the Karambar valley. Photo: L. Iturrizaga 18.09.2002/2/22.

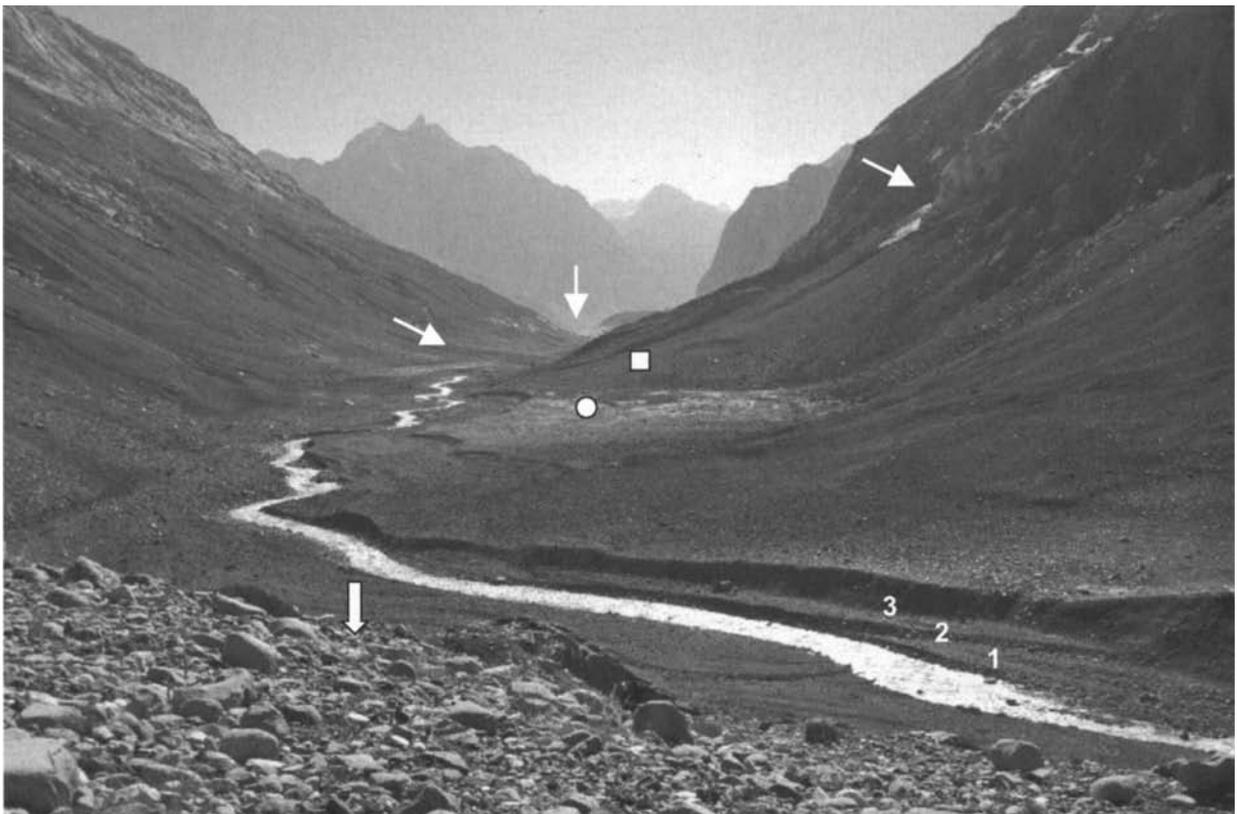


Photo 28. View from the highest glacier dam, the roche moutonnée, into the Chateboi Lake basin. In the foreground the granite erratics (↓) can be seen on top of the roche moutonnée. Lake terraces stretch along the lake basin (1,2,3). The Rochen Yaz glacier tongue is surrounded by an end moraine (□) and hangs above the lake basin. Upstream of this glacier dam, lake sediments (○) were deposited from a former ice-dammed lake. Ice avalanches from this glacier could have triggered a lake outburst, but at the same time they also could have form a temporary dam. Snow avalanches (↘) from the left Karambar valley flank are also very frequent. In the background the Chateboi glacier dam (|) is visible. Photo: L. Iturrizaga 18.09.2002/2/4.



Photo 29. The Shuyinj glacier is surrounded by a sander-like lateral moraine, which has been transformed by supraglacial melt water streams (↷). A historical end moraine (→), probably from the beginning of the last century, is accreted to the inner slopes of the lateral moraine. At the foot of the lateral moraine, lake terraces of the Chateboi or Saklei Shuyinj lake are deposited (□). In the foreground, the historical to neoglacial end moraines are visible (◇). The Shuyinj glacier fore field shows no evidences for a former glacier barrier. The polished mountain flanks (↷) indicate the former ice expansion, during which the Shuyinj glacier merged with the Saklei Shuyinj glacier. Photo: L. Iturrizaga 18.09.2002/2/17.



Photo 30. The Panorama was taken from 4600 m onto the Karambar lake located at the Karambar Pass (4250 m). It is the only large-sized permanent lake in the Karambar valley. It is dammed by ground moraine. Photographs taken from Stein (1928) in 1913 show that the moraine girlands of the Ambar glacier were filled up by the glacier tongue at that time (←). Photo: L. Iturrizaga 19.09.2002.



Photo 31. Many debris flow cones project into the Karambar valley and can cause temporary blockages in-between the glacier barriers such as here upstream of Matram Dan. The debris flow cone (Δ) has repeatedly dammed the Karambar river in the last decades. Photo: L. Iturrizaga 13.09.2002/33.



Photo 32. At present, debris flows are the most frequent and severe hazard for the permanent settlements in the Karambar and Ishkoman valleys. They are mostly triggered by cloudbursts. The steep and high rising catchment areas of the tributary valleys provide favourable conditions for the release of high-energy mass movements. High deposited slope moraines can also be the supply areas for the debris flows. In this case a secondary debris flow cone (Δ) is deposited at the base of the parent sediment cone. Photo: L. Iturrizaga 07.09.2002/9.

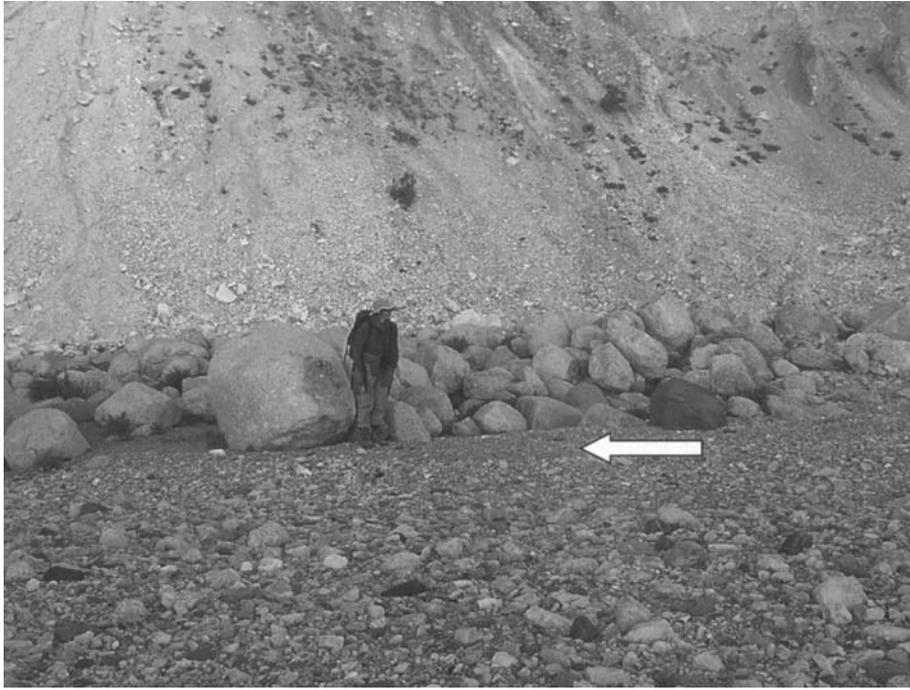


Photo 33. The flood landscape in-between the glacier dams: Boulder cluster downstream of the Chateboi glacier tongue at the Karambar valley floor in 3450 m. The arrow indicates the transport direction of the Karambar river. The boulders, up to 1.60 m in diameter, are imbricated and were deposited by high energy flood events. Photo: L. Iturrizaga / E. Ali Khan 15.09.2004.

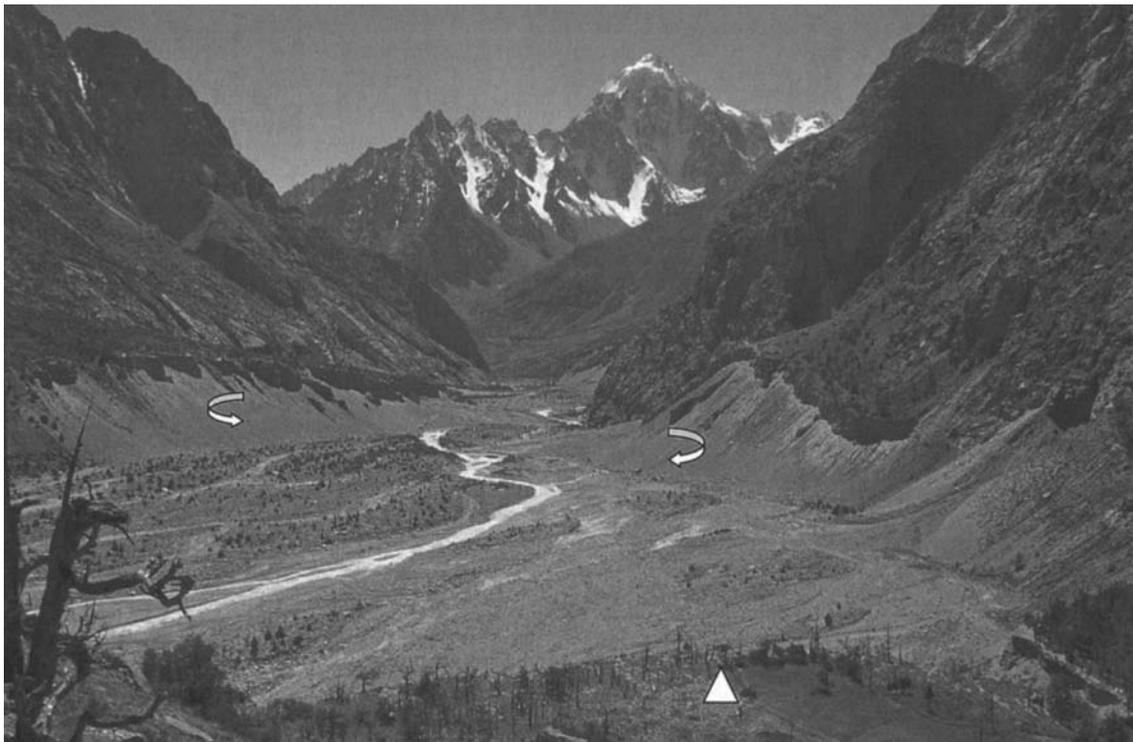


Photo 34. Downstream of the Warghut glacier dam the sediment cones have been severely eroded by glacial outburst floods (↺). The cliff edges are up to 70 m in height. Before the flood, the valley floor was settled with extensive woodland. The settlement areas are located high above the river on glaciofluvial terraces (△), even though temporary settlements can be also found at the lower terraces of the flood prone valley floor. Photo: L. Iturrizaga 14.09.2002/32.



Photo 35. Matram Dan (2980 m) is located between the Saklei Buk and the Karambar glacier dams and is one of the highest permanent settlements in the valley consisting nowadays of about 11 households. The settlement area has been considerably cut back (↶) by flood events originating from glacier outbursts, but probably also from landslide-induced floods. However, the housing area is located at safe places high above the river level. In 1905 the *puberanch* early fire warning system was operated here. Photo: L. Iturrizaga 13.09.2002/23.

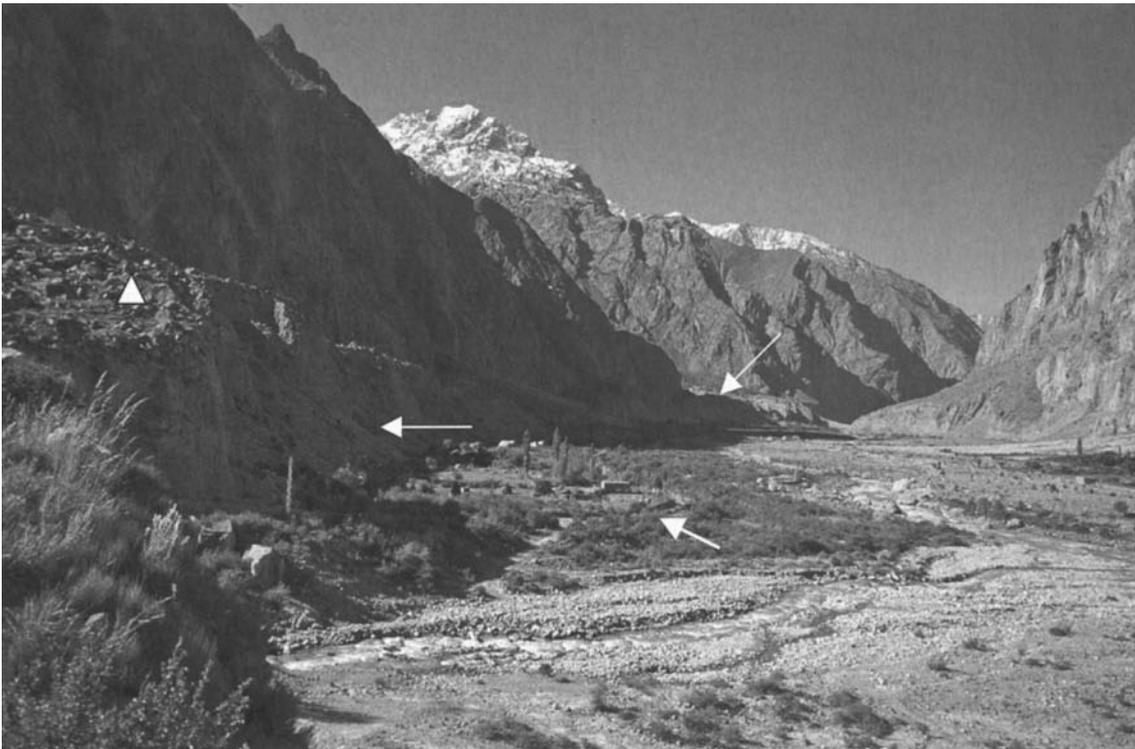


Photo 36. Bhurt (2780 m) is the first permanent settlement below the glacier dams. It is located on a glacial sediment cone (Δ) high above the river (not visible in the picture). Only some houses are situated at the valley floor (∞). The up to 50-m-high cliff edges (←) of the sediment cone indicate how strongly they were affected by the floods. However, during the time of the 1905-flood Bhurt was only scarcely settled. The flood destroyed mainly wood land along the valley floor. In the background Bad Swat (↙) is visible, which shows pronounced cliff edges. Photo: L. Iturrizaga 08.09.2002/30.

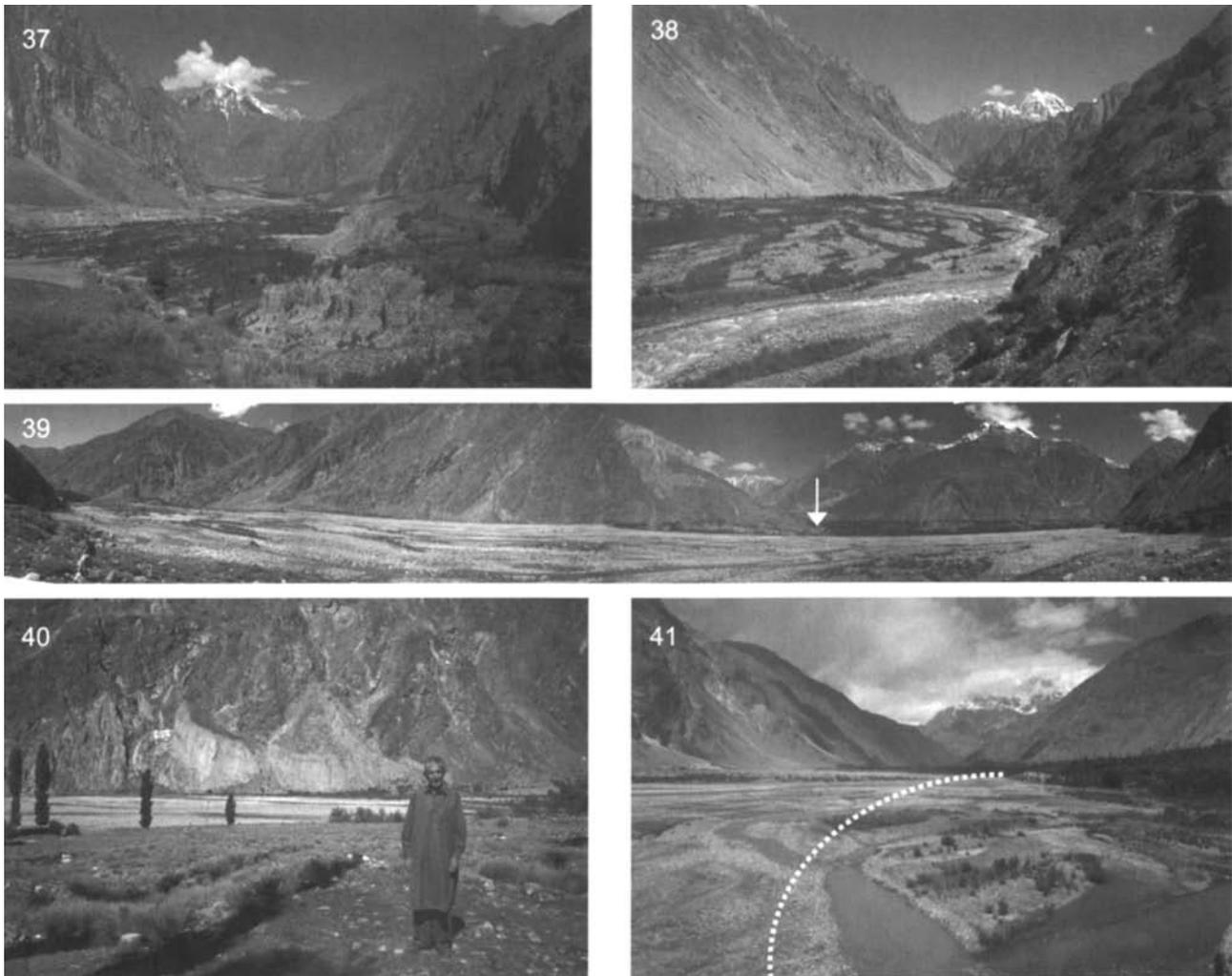


Plate 1. Changing valley topography and settlement loss in the Karambar–Ishkoman valley: The valley physiognomy changes several times from narrow gorge-like sections (Photos 37 and 38, 12.09.2003/1) to up-to-1200 m broad valley sections (Photo 39). The valley constrictions are partly caused by expansive sediment cones such as close to Bad Swat (37). Downstream of Imit, close to the confluence of the Ishkoman–Karambar valleys (↓) the Karambar valley widens significantly (Photo 39, 11.09.2003/28–31). In Barjungle, a land loss of 300 m was reported (Photo 40, 11.09.2003/27). The story of the devastating 1905-flood is well remembered by the older generation who were told about the flood impacts by their fathers. Chatorkand in a distance of about 70 km from the outburst localities was heavily affected by the floods. The dotted line (- - -) indicates the approximate former extent of the settlement area (Photo 41, 06.09.2002). All photos: L. Iturrizaga.



Photo 42. Secondary lake formations were formed at several valley constrictions far below the glacier dams such as upstream of Singal (1980 m). The flood level was 15 m above normal in this valley section (Photo 43). Photo: L. Iturrizaga 12.09.2003/2/1.



Photo 43. The 1905-flood is well remembered among the local population throughout the Karambar, Ishkoman and Gilgit valleys. A stone pillar commemorates the past flood level in the valley section shown in the previous picture. Photo: L. Iturrizaga 12.09.2003/2/2.

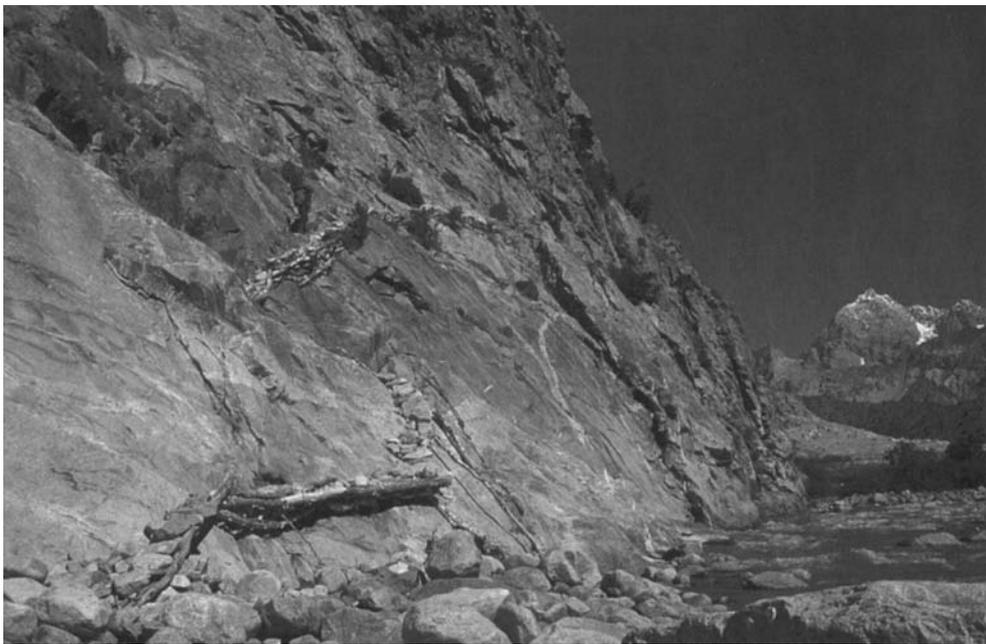


Photo 44. Many glacier and river crossings are necessary to reach the upper Karambar valley. The route leads often along steep valley flanks. Constructions of trees and stone plates are common to pass these valley sections like here downstream of the Warghut glacier. For pack animal these ways are sometimes not accessible. Photo: L. Iturrizaga 14.09.2002/18.

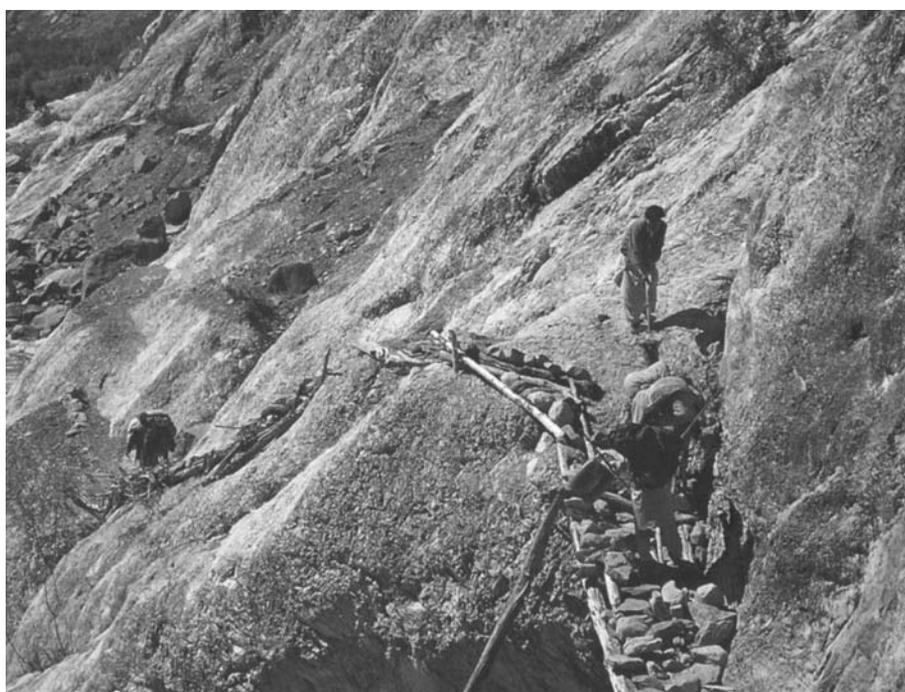
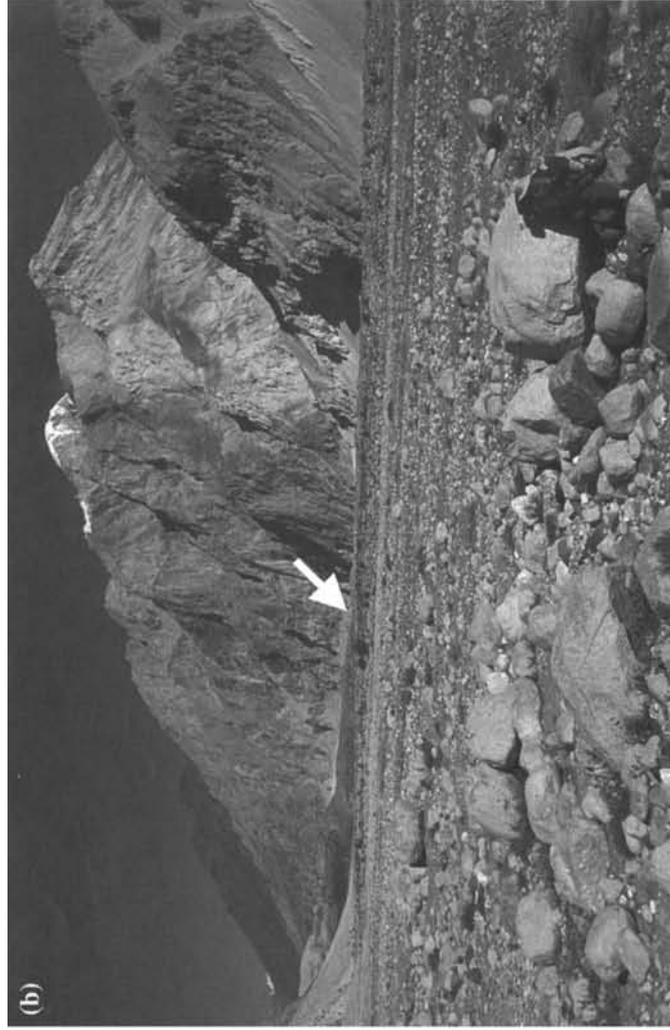
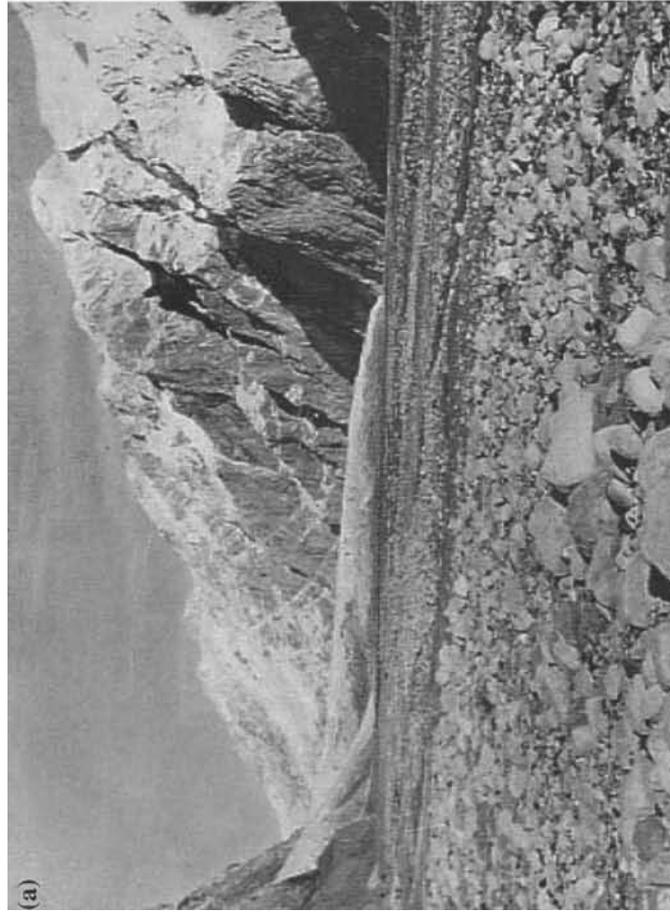


Photo 45. Opposite of the Chillinji glacier a similar wood-stone construction is installed high above the Karambar river. Local people are pulling a packed donkey along the precipitous valley flank. The Chillinji glacier tongue touched the valley flank in the beginning of the last century. Photo: L. Iturrizaga 13.09.2004.



Photos 46a and 46b. The Chateboi glacier tongue photographed by Tilman (1951) in 1947 and in 2002 by Iturrizaga. The Chateboi glacier tongue (✓) has downwasted considerably in the last century. Nevertheless the Chateboi glacier still seals the Karambar valley. Photo: L. Iturrizaga 17.09.2002/15.

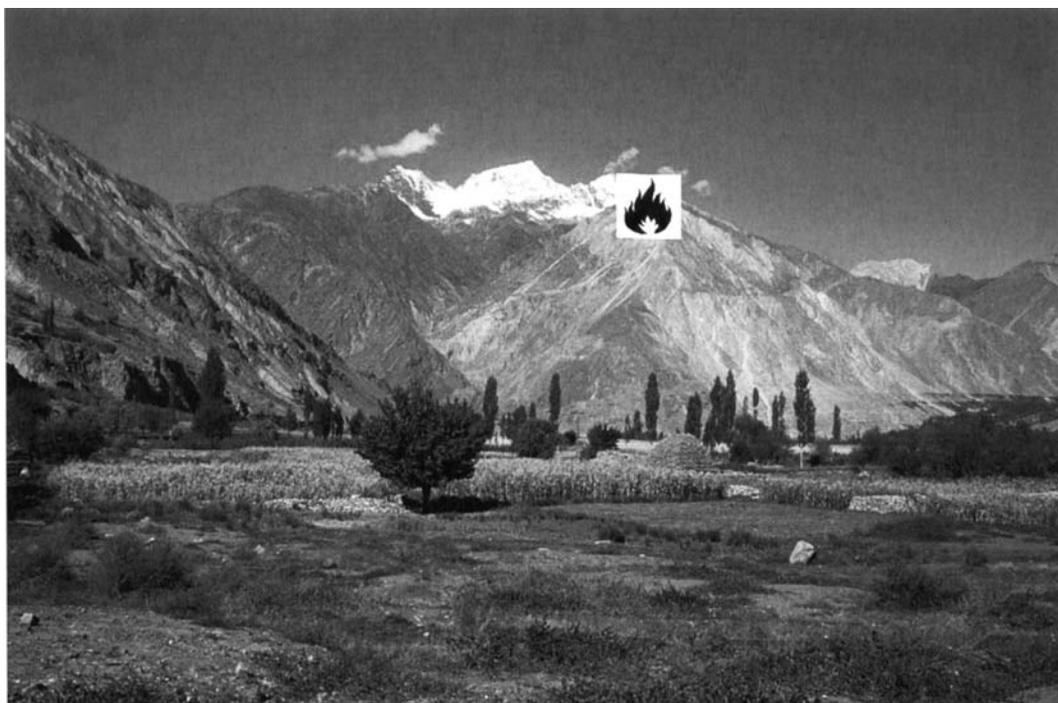


Photo 47. In the Karambar–Ishkoman–Gilgit valleys a fire early warning system was active until 1905. Posts were setup at good visible look-out points at the valley flanks, high above the valley floor such as here close to Imit. Photo: L. Iturrizaga 12.09.2003/9.

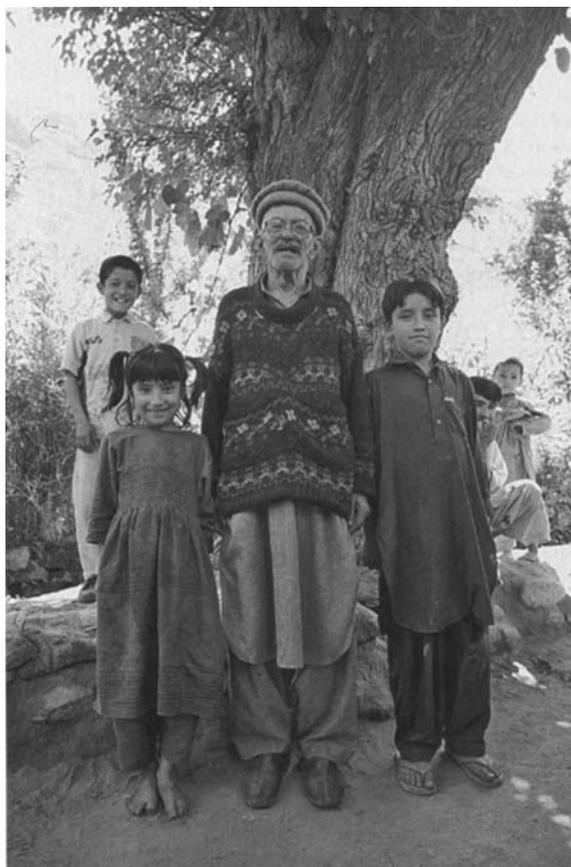


Photo 48. A lot of information about the historical floods was provided by the local elder people, who were told about the 1905-flood by their fathers. The photo was taken in Singal after an interview. Photo: L. Iturrizaga 12.09.2003.

Moreover, the glacier floods have triggered temporary lake formations by secondary blockages during the flood downstream of the glacier dams. The minimum runout-distance of the floods is in the range of 150 km. Loss of settlement areas occurred over a width of 300 m along the bank areas.

The Karambar valley shows a variety of natural ice and sediment barriers. Most of the Karambar dams are temporary glacier barriers which occur in different topographical settings such as in the combination with active debris flow cones or rock bars. The Chateboi glacier forms a permanent glacier barrier and seals the Karambar valley even today with sporadic small-sized lake formations. In-between the glacier barriers landslide-dammed lakes have also blocked recently the Karambar valley. This multi-dam situation contributes to the formation of a complex sedimentary river system.

The flood history of the Karambar valley provides further evidence for a general glacier advance or at least for the advanced positions of the glacier tongues in the beginning of the 20th century in the Hindukush–Karakoram area. The reconstruction of the former glacier dams revealed especially in the case of the Saklei Shuyinj glacier a remarkable glacier advance. In terms of the present risk of glacier lake outbursts in the Karambar valley, the potential formation of ice-dammed lakes must be taken into account at anytime regarding the close positions of the glacier tongues near to the Karambar river and the surging behaviour of some of the avalanche-fed glaciers in the Karambar valley. The Chateboi glacier presently seals the Karambar valley over a distance of 4 km. Slight changes in the glacier interior and its subglacial environment could therefore again produce a large-sized lake. A future flood event would have disastrous impacts to the human infrastructure as the settlement areas expanded to the flood plains in the last decades.

Acknowledgements

The article summarizes partial results of the research project “Recent and prehistorical glacier lakes in the Karakoram Mountains (Karambar and Chapursan valleys)”, which was financed by the Deutsche Forschungsgemeinschaft (DFG IT 14/11–1, 14/11–2). Thanks are due to Björn Weber for carrying out the grain size-analysis (sediment laboratory of the University of Göttingen) and for preparations of the diagrams. I like to thank Mr. Asif Khan (Gilgit) for the translation of the interviews with the local inhabitants and my interview partners, especially Syed Qasim (Muki of Matram Dan), Gulakbar Shah (Chatorkand), Mahmmat Isah Khan (Chatorkand), Jarkut Shah (Barjungle), Raja Muzafar (Imit), Shirin Khan (Singal) and the Pir-family from Chatorkand. My sincere thanks go to the local guides Mr. Ejaz Ali Khan (Passu), Mr. Ali Madad (Bhurt) and Mr. Gulbarah Khan (Imit), who managed the glacier and river crossings in the Karambar valley. They provided as

well useful information on the history of the glacier dams and assisted me during the field work.

Note

1. Apart from the mentioned Chateboi glacier between Shuyinj and Sokther Rabot, in the Hindukush exist two other glaciers, which bear the same name as additional name. (1) The Pechus-Gletscher in the upper Yarkhun valley close to Chikor, which dammed in former times the Yarkhun and Darkot valley, (2) The Chillinji glacier in the Karambar valley between Sokther Rabot and Warghut., “Chateboi” means in the local language Wakhi, flood and all three glaciers were involved in glacier lake outbursts.

References

- Archer D.R., 2001: The climate and hydrology of northern Pakistan with respect to the assessment of flood risk to hydropower schemes. Unpublished report, GTZ/WAPDA/VSO, Lahore.
- Biddulph J., 1880: Tribes of the Hindoo Koosh. Calcutta. Reprint: Karachi 1977. 164 pp.
- Bridges F.H., 1908: An unpublished Report on Hunza glaciers. *The Geographical Journal* 75: 166–172.
- Charles, C., 1985: La Vallée de Hunza Karakoram. Thèse de Doctorat de 3^e Cycle. Université de Grenoble I. Institut de Géographie Alpine.
- Clague J.J. and Evans S.G., 1994: Formation and failure of natural dams in the Canadian Cordillera. *Geological survey of Canada, Bulletin* 464: 4–12.
- Cornwell K., 1998: Quaternary break-out flood sediments in the Peshawar basin of northern Pakistan. *Geomorphology* 25(3–4): 225–248.
- Costa J.T. and Schuster R.L., 1988: The formation and failure of natural dams. *Geological Society of American Bulletin* 100: 1054–1068.
- Derbyshire E., Li Jijun, Perrott F.A., Xu Suying and Waters R.S., 1984: Quaternary glacial History of the Hunza Valley, Karakoram Mountains, Pakistan. In: Miller K.J. (ed.), *The International Karakoram Project*. Vol. 2. pp. 456–495. Cambridge University Press.
- Drew F., 1875: *The Jumoo and Kashmir Territories. A Geographical Account*. Akademische Druck- und Verlagsanstalt, Graz 568.
- Feng Qinghua, 1991: Characteristics of glacier outburst flood in the Yarkant River, Karakorum Mountains. In: Kuhle M. and Xu Daoming (ed.), Tibet and High-Asia. Results of the Sino-German Joint Expeditions (II), *GeoJournal* 25(2/3): 255–263.
- Ferguson R.I., 1984: Sediment load of the Hunza River. In: Miller K.J. (ed.), *The International Karakoram Project*, Vol. 2. pp. 581–598. Cambridge University Press.
- Gardner J.S. and Hewitt K., 1990: A surge of Bualtar Glacier, Karakoram Range, Pakistan. A possible landslide trigger. *Journal of Glaciology* 36(123): 190.
- Haerberli W., 1983: Frequency and characteristics of glacier floods in the Swiss Alps. *Annals of Glaciology* 4: 85–91.
- Hayward G.W., 1871: Letters from Mr. G. W. Hayward on his Explorations in Gilgit and Yassin. *Journal of the Royal Geographical Society* 41: 1–46.
- Hewitt K., 1982: Natural dams and outburst floods of the Karakoram Himalaya. In: Glen J.W. (ed.), *Hydrological Aspects of Alpine and High-Mountain Areas. International Commission on Snow and Ice (ICSI) Symposium, Exeter, UK, 19–30 July 1982. Proceedings. International Association of Hydrological Sciences. IAHS/AISH Publication*, no. 138: 259–269.

- Hewitt K., 1989: Hydrological investigations at Biafo glacier, Karakoram range, Himalaya. An important source of water for Indus River. *Annals of Glaciology* **13**: 103–108.
- Hewitt K., 1998a: Himalayan Indus Streams in the Holocene: Glacier-, and Landslide-“Interrupted” Fluvial Systems. In: Stellrecht I. (ed.): *Karakorum – Hindukush–Himalaya: Dynamics of Change*. Part I, Culture Area Karakorum, Scientific Studies 4(1): 3–28.
- Hewitt K., 1998b: Catastrophic landslides and their effects on the Upper Indus streams, Karakoram Himalaya, northern Pakistan. *Geomorphology* **26**(1–3): 47–80.
- Himalayan Journal, 1932: Notes: The Karambar glacier (from T. Longstaff). pp. 182–183.
- Iturrizaga L., 1994: *Das Naturgefahrenpotential in der Talschaft Shimshal, NW-Karakorum*. Unveröffentlichte Diplomarbeit, Universität Göttingen 210.
- Iturrizaga L., 1996: Über das Naturgefahrenpotential für die Hochgebirgssiedlung Shimshal (3080 m), Nord-West-Karakorum. *Die Erde*, **127**, 3: 205–220.
- Iturrizaga L., 1997: The Valley of Shimshal – a geographical portrait of a remote high mountain settlement and its pastures with reference to environmental habitat conditions in the North West Karakorum. In: Kuhle M.(ed.) Tibet and High Asia IV, *GeoJournal* **42**(2/3): 305–328.
- Iturrizaga L., 1998: Gletscher als Existenzgrundlage und Gefährdungspotential für die Hochgebirgssiedlung Shimshal im Nordwestkarakorum. In: Petermanns Geographische Mitteilungen, Bd. 3/4, vol. **142**, 233–239, Justus Perthes Verlag Gotha.
- Iturrizaga, L., 2001: Lateroglacial valleys and landforms in the Karakoram mountains (Pakistan). In: *GeoJournal* (M. Kuhle ed.), Tibet and High Asia (VI). Glaciogeomorphology and prehistoric glaciation in the Karakoram and Himalaya. Vol. 54(2–4), 397–428.
- Iturrizaga L., 2002: Der Pumari Chhish-Gletscherausbruch (Karakoram, Pakistan): Geomorphologische Überprägungen des paraglazialen Sedimentationsumfeldes durch kurzzeitige Gletscherveränderungen. In: Terra Nostra, Schriften der Alfred-Wegener-Stiftung, pp. 128–133.
- Iturrizaga L., 2003: The distribution and genesis of lateroglacial valleys in the Karakoram Mountains (Pakistan). In: *Zeitschrift für Geomorphologie* N.F., Suppl.– Bd. **130**: 51–74.
- Iturrizaga L., 2004: Ice-dammed lakes in the Karakoram–Hindukush Mountains (Pakistan): Geomorphological impacts of glacier lake outburst floods in the Karambar valley. *Himalayan Journal of Sciences* **2**(4): 160–161 Special Issue.
- Iturrizaga L., 2005a: Rekonstruktion von historischen Eisstauseen und Gletscherseeausbrüchen im Karambar-Tal (Hindukusch-Karakorum). In: Berliner Geographische Abhandlungen, pp. 9–18.
- Iturrizaga L., 2005b: Paraglacial (transglacial) landscapes in the Karakoram (Pakistan). In: Samuel Etienne (ed.): *Shifting lands. New insights into periglacial geomorphology*. Collection “Géoenvironnement”, Editions Mélanie Sèteun, 22–23.
- Iturrizaga L., 2005c: New observations on glacier lake outbursts in the Shimshal valley. *Journal of Asian Earth Sciences* **11**: 545–555.
- Kick W., 1958: Exceptional glacier advances in the Karakorum. *Journal of Glaciology* **3**: 22, 229.
- Klebsberg R.v., 1948/49: *Handbuch der Gletscherkunde und Glazialgeologie*. Wien, 2 vols.
- Kreutzmann H., 1994. Habitat conditions and settlement processes in the Hindukush-Karakoram. *Petermanns Geographische Mitteilungen* **138**(6): 337–356.
- Kuhle M., 2001: The maximum Ice Age (LGM) glaciation of the Central- and South Karakorum: an investigation of the heights of its glacier levels and ice thicknesses as well as lowest prehistoric ice margin positions in the Hindukush, Himalaya and in East-Tibet on the Minya Konka-massif. In: *GeoJournal* (M. Kuhle ed.), Tibet and High Asia (VI), Glacio-geomorphology and prehistoric Glaciation in the Karakorum and Himalaya. **54**(2–4): 109–396.
- Kuhle M., 2002: Outlet glaciers of the Pleistocene (LGM) south Tibetan ice sheet between Cho Oyu and Shisha Pangma as potential sources of former megafloods. In: Martini I.P., Baker V.R. and Garzón, G. (eds.), *Flood and megaflood processes and deposits: recent and ancient examples*, Special Publication of the International Association of Sedimentologists, **32**, 291–302.
- Kuhle M., Meiners, S. and Iturrizaga, L. 1998: Glacier induced hazards as a consequence of glacial Mountain landscapes, ice-dammed lake outbursts and Holocene debris production. In: Kalvoda, J. and Rosenfeld, C. (eds.), *Geomorphological Hazards in High Mountain Areas*. pp. 63–96. The GeoJournal Library.
- Longstaff T., 1951: This my voyage. London. 324 pp.
- Mason K., 1929: Indus Floods and Shyok glaciers. *The Himalayan Journal* I: 10–29.
- Mason K., 1930: The Shyok flood – a commentary. *The Himalayan Journal* II: 40–47.
- Mason K., 1935: The study of the threatening glaciers. *Geographical Journal* **85**: 24–41.
- Mercer, J.H. 1975: Glaciers of the Karakoram. In: Field O.W. (ed.), *Mountain Glaciers of the Northern Hemisphere* Vol. 1, pp. 371–409.
- Montgomery D.R., Hallet B., Yuping L., Finnegan N., Anders A., Gillespie A. and Greenberg H.M., 2004: Evidence for Holocene megafloods down the Tsangpo River gorge, southeastern Tibet. *Quaternary Research* **62**: 201–207.
- Paffen K.J., Pillewizer W. and Schneider H.J., 1956: Forschungen im Hunza-Karakorum. *Erkunde* **10**: 1–33.
- Owen L.A., 1996: Quaternary lacustrine deposits in a high energy semi-arid mountain environment, Karakoram Mountains, northern Pakistan. *Journal of Quaternary Science* **11**(6): 461–483.
- Richardson S.D. and Reynolds J.M., 2000: An overview of glacial hazards in the Himalayas. *Quaternary International* **65/66**: 31–47.
- Röthlisberger H., 1981. Eislawinen und Ausbrüche von Gletscherseen. In: Kasser P. (ed.), *Gletscher und Klima – glaciers et climat, Jahrbuch der Schweizerischen Naturforschenden Gesellschaft, wissenschaftlicher Teil 1978*, 170–212.
- Röthlisberger H., 1986: *10.000 Jahre Gletscher geschichte der Erde*. Verlag Sauerländer.
- Rudoy A.N. and Baker V.R. 1993: Sedimentary effects of cataclysmic late Pleistocene glacial outburst flooding, Altay Mountains, Siberia. *Sedimentary Geology* **85**(1–4) May 1993: 53–62.
- Schomburg R.C.F., 1936: *Unknown Karakoram*. Martin Hopkins, London.
- Stein A., 1928: *Innermost Asia. Detailed Report of Explorations in Central Asia, Kan-Su and Eastern Iran*. Oxford at the Clarendon Press.
- Thomson T., 1852. *Western Himalaya and Tibet; a narrative of a journey through the mountains of Northern India during the years 1847–48*. London. 501 pp.
- Tilman H.W., 1951: *From China to Chitral*. Cambridge at the University Press, 124 pp.
- Todd H.J., 1930: Gilgit and Hunza River Floods (Correspondence). *The Himalayan Journal* **2**: 173–175.
- Thorarinnsson S., 1939: The ice-dammed lakes of Iceland with particular reference to their values as indicators of glacier oscillations. *Geografiska Annaler* **21**: 216–242.
- Tufnell L., 1984: *Glacier hazards*. Longman, London and New York.
- Tweed F.S. and Russell A.J., 1999: Controls on the formation and sudden drainage of glacier-impounded lakes: implications for jökulhlaup characteristics. *Progress in Physical Geography* **23**: 79–110.
- Yamada T., 1998: *Glacier Lake and its Outburst Flood in the Nepal Himalaya*. Monograph No. 1, March 1998, Data Center for Glacier Research, Japanese Society of Snow and Ice, Tokyo.
- Visser Ph.C., 1935: *Durch Asiens Hochgebirge: Himalaya, Karakorum, Aghil und Kun-lun*, 256 pp.
- Visser Ph.C., 1938: Glaziologie. In: Visser Ph.C. and Visser Hooft J. (eds.), *Wissenschaftliche Ergebnisse der Niederländischen Expeditionen in den Karakorum und die angrenzenden Gebiete in den Jahren 1922, 1925 und 1929/30*. Band II, 215 pp.
- Walder J.S. and Costa J.E., 1996: Outburst floods from glacier-dammed lakes: the Effect of mode of lake drainage on Flood magnitude. In: *Earth Surface Processes and Landforms* Vol. 21, pp. 701–723.
- Wiche K., 1960: Klimamorphologische Untersuchungen im westlichen Karakorum. In: *Tagungsber. u. Wiss. Abh., Dt. Geographentag 1959* (Berlin), Vol. 32, pp. 192–203, Wiesbaden.

The glacial history of landscape in the Batura Muztagh, NW Karakoram

S. Meiners

Department of Geography and High Mountain Geomorphology, University of Goettingen, Goldschmidtstr. 5, 37077, Goettingen, Germany (Tel.: +0551-3912515; Fax: +0551-397614; E-mail: smeiner@gwdg.de)

Key words: Batura, Bar Valley, glacial history, Karakorum, late glacial, lateral moraine, neoglacial period

Abstract

The most recent glacial history of the Bar Valley on the Batura south side of the great Karakorum main ridge shows a marked retreat of the Kukuvar and Baltar glaciers since 1915 by 8 km. This tendency is continuing. A great lateral moraine (GLM), which shows the latest, historical maximum postglacial stage, is accompanied by a higher level, which reflects a neoglacial glacier level whose ice margins no longer exist. An earth-pyramid moraine rising high above the glacier, as also occurs on the northern declivities of the Batura, does not mark a specific level, but bears witness to a valley-filling glacier, for which further indicators can be found along the valley flank. In the gorge-like narrow trough valley, the flanks of which are covered by steep debris cones originating from the postglacial, numerous former glacial characteristics contrast with the current glaciation of the far retreated Kukuvar and Baltar glaciers. Moraine material found at the valley outlet at Chalt and also on the Talmutz pass demonstrates complete ice filling of the Bar valley, also supported by the Daintar glacier. From a glacial geomorphological perspective, this confirms a late to high glacial connection of the Bar glacier to a Hunza glacier, as postulated by Kuhle (2005).

Introduction

In the present paper, the glacial geomorphological indicators of the extent of late to postglacial glaciation are attributed to individual glaciation stages according to the principle of their positional relationship. The differentiation and chronological classification of the stages is done strictly according to geomorphological aspects, which results in a relative chronology of the glaciation. The calculation of the snowlines (mathematical index after Kuhle (1998a), based on von Höfer, (1879)) as an expression of temperature change from the average peak heights and the respective glacier terminus yields evidence of climatic change.

The differentiation of late to postglacial moraine stages shows a shift to more recent stages and thus indirectly provides confirmation of a more important, high glacial ice filling, as postulated by Kuhle (most recently in 2005). In numerous investigations, ice margins and lateral moraines of the neoglacial and historical stages have been determined, so that ice margins rated as 'older' means Last Glacial Maximum in literature according to the relative chronology could now be classified as 'more recent'.

Detailed glacial geomorphological analysis is an integral part of landscape reconstruction and is therefore the basis for all subsequent investigations, for example, on current geomorphological processes, on

fresh water availability in arid regions, or on archaeological questions.

The valleys in the Karakorum, characterised by Quaternary to Holocene glaciation, were reshaped postglacially by current geomorphological processes, such as the formation of mud and debris cones. The condition of moraines and glacial fluvial gravels is subject to large-scale repositioning as a result of the high-relief energies in the Karakorum main ridge and especially in the area of investigation on the south side of the high Batura Muztagh range (7792 m), additionally forced by the course of the Northern suture fault zone (Coward et al., 1984) through the Bar valley.

A current landscape interpretation is not available for the area of investigation. An initial investigation on the extent of the glaciers in the Bar valley was conducted by Schomberg (1933), who precisely described the positions of the glacier termini in 1933 and determined a strong retreat tendency of the Bar glaciers and the Daintar glacier. He pointed to an intensive period of glaciation in which the Bar valley was filled with ice. In the mid-1950s, the area was taken into consideration by the German–Austrian Himalayan–Karakorum Expedition of 1954.

Paffen et al. (1956) writes about the deepest of moraine walls at Chalt, which were deposited as late to postglacial terminal moraines from the side valleys into the large Hunza longitudinal valley. Paffen thus equated the terminal moraine positions of the Hunza valley with

Dainelli's (1922) 'fourth glaciation'. Schneider (1959) did not agree with this opinion. He wrote (*ibid.*, p. 208) that the side valley glaciers often exceeded the middle of the Hunza valley and forced the terminal moraine walls up to the opposite slopes, as for example from the Bhola Das valley up to Chalt at 1900 m, although there is 'no evidence of the existence of a continuous 'young' diluvial Hunza glacier'! He classified the moraine at Chalt as an 'young' diluvial (LGM-Würm) ice extension of the Bar glacier.

Most recently, Kuhle (2005) described glaciation indicators in the Bar valley (Tutu Uns) that point to a glacier contact with the Hunza glacier during the High Glacial (LGM, Würm). He reconstructs a glacier surface elevation of 3700–3600 m at the valley outlet, with contact to the Hunza glacier. The lower Bar valley was thus filled with ice to a depth of 1900 m.

Comparable papers on the more recent glaciation history are available by the author for the Haramosh region and from the Hunza valley (Meiners, 1996, 1998, 2001). Whereas the Batura Investigation Group (1979) still assumed in 1978 that a high glacial (LGM) Batura north glacier only extended up to Saret at 2300 m, Derbyshire et al. (1984) outlined a Hunza glacier during the LGM (late Pleistocene) up to the confluence with the Astor valley (1300 m) within the context of the International Karakorum Project (see Miller, 1984). A glaciation chronology on the Batura north side was drawn up. This chronological classification of these stages was confirmed by Owen (2002) by absolute ^{10}Be datings for the *Batura Stage* up to the *Borit Jheel Glacial Stage* (t3 – t6), but could not find any correlation for the older stages. In a review article, Haserodt (1989) also mapped a late Pleistocene Bar glacier, terminating before the confluence with the Hunza valley. Haserodt (1989, p.195) supports the view that 'a continuous late Pleistocene glacier did not exist in the Hunza main valley in the direction of Gilgit'.

As early as 1987 (Kuhle, 1988b,c) and up to his most recent publications in 2005 (an overview is given in Kuhle (2004) see Ehlers, 2004), Kuhle has demonstrated a maximum glaciation tracing back to 800–850 m in the Indus valley. Kuhle (2001, p. 172) outlined a high glacial ice-flow network from the Hunza valley with a connection of the Indus valley to the Deosai plateau to below Daret and Tangir. In view of the glacial geomorphologically mapped stages of the glacier extensions in the side valleys from the recent glacier terminus up to the valley outlets to the Hunza and Indus valley, Meiners (1998) calculated smaller snowline depressions that, in the case of the side valley outlet moraines, did not nearly correspond to the values of the High Glacial (LGM; Würm/ Weichsel) of at least 1200 m in High Asia.

Thus, an elevation of 100–250 m could be calculated for the well preserved great lateral moraines (GLM) closer to the glacier and often restricting it (Great Lateral Moraines after Kick, 1985). They are classified to

the Neoglacial. ^{14}C datings by Röthlisberger (1986) pointed in the same direction.

Area of investigation

The area of investigation with the currently still glaciated side valleys (Baltar/Toltar-Kukuar/Satmaro and Daintar valleys) is located on the south side of the NW–SE running Batura-Muztagh range up to the Kampe Dior south side and, with the Daintar valley, borders on the Naltar group in the south (see Figure 1). Morphologically, the catchment areas of the Baltar and the north-east side of the Kukuar glacier with their typical hanging valleys with high gradient steps (Shittlingbar, Bar east glacier) (Schneider, 1959, p. 205) belong to the Karakorum main ridge with peak elevations of over 7000 m, whereas the western part of the Kukuar glacier with its Satmaro component and the gipselflur of the orographic right Bar valley side belongs to the Daintar and Naltar groups, which have much lower elevations and no obvious gradient steps. Here, old residual areas at high elevations are strongly glaciated. This is reflected in the average relief energy, which is up to 600 m lower in the Kukuar and Daintar valleys. The transitional area between Karakorum and Hindukush is represented here.

From a geological point of view, the Batura Muztagh group belongs to the crystalline Karakoram batholith with granodiorite, while it is separated from the southern Chalt group of the Kohistan sequence by the Northern suture zone. In the area around Chalt at the Bar valley outlet, vulcanites are found, overlaid with lime and sandstone. Up to the confluence of the Daintar valley, Ganchen pelites (silt and siltstones, clays and claystones, slate clays) and metamorphites (biotite, plagioclases, quartz) occur at Torbuto Das (Searle, 1991). In the area of the settlement Bar, the Karakoram batholith is found, while the Ganchen pelites occur again as metamorphites up to the valley confluence of the Baltar with the Kukuar (Tahirkheli and Jan, 1984, p. 58; Searle, 1991). Westward of Chalt big lenses of Quartzite and limestone, mixed with other sediments occur (Coward et al., 1984, p. 75).

The water draining from the Kukuar and Baltar side valleys, which are still glaciated today, flow into the Bar valley at 2740 m, which at its outlet at Chalt at 1860 m leads into the Hunza valley after a course of 23 km. The orographic right, 24 km long Daintar valley of the Naltar group, which is also still glaciated today, leads into the Bar valley from the west at 2100 m at the Torbuto Das settlement.

Since the mathematical snowline computed predominantly in the S, SW and SE position (average peak elevation plus glacier terminus: 2) runs at around 4400 m in the lower area of the steep flanks, the Baltar and Eastern-Kukuar glaciers are the avalanche-fed type without firn hollows, while the transition to the firn basin glacier type is indicated in the western component

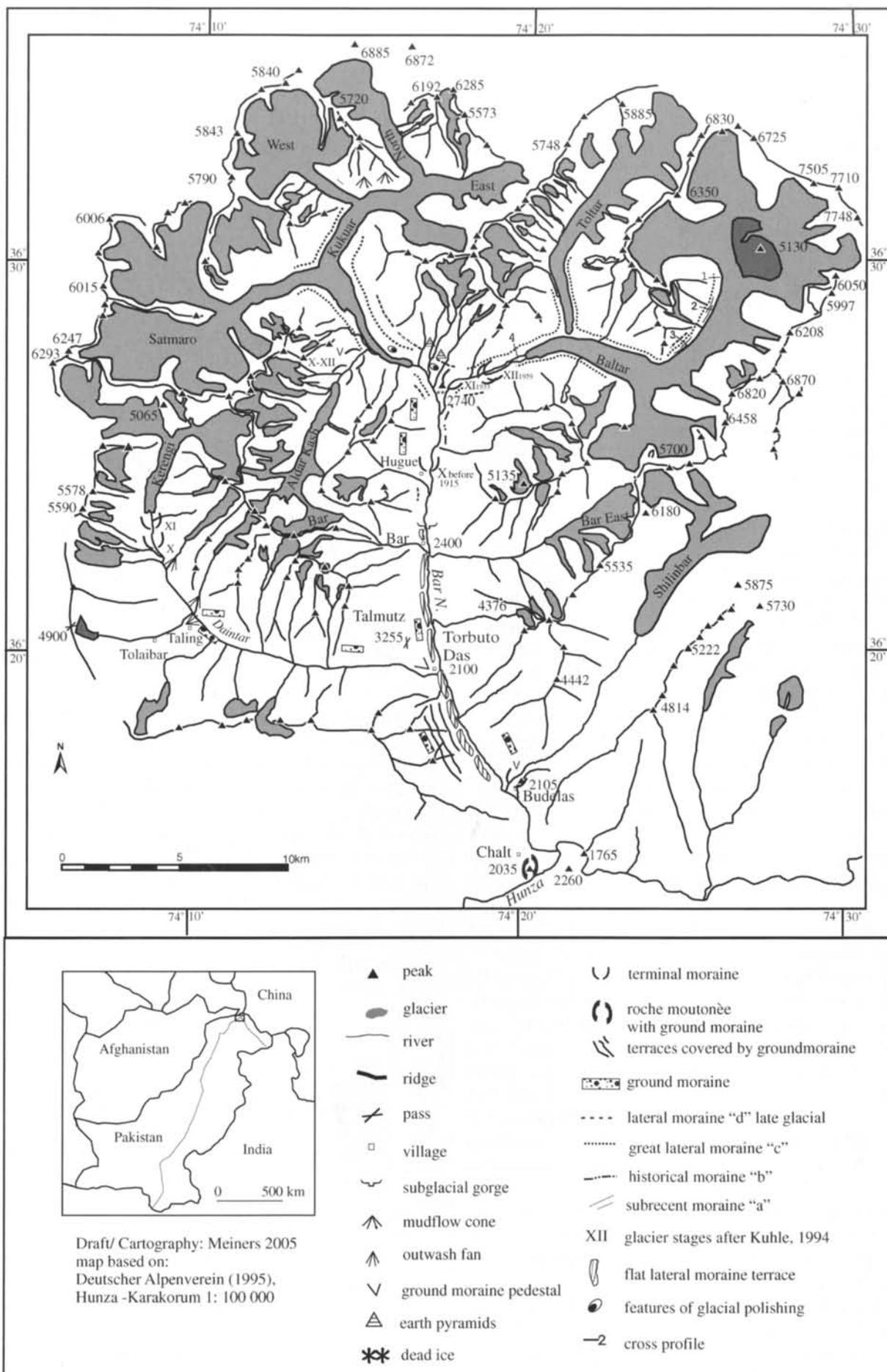


Figure 1. Glaciogeomorphological indicators of the Post- and Late Glacial valley construction of the Batura south side (Bar valley).

Table 1. Glaciation data and topography of the areas of investigation

	Baltar/ Toltar	Kukuar/Satmaro	Daintar	Bar
Position	36°25'–34' N 74°17'–30' E	36°26'–35' N 74°06'–20' E	36°20'–26' N 74°06'–17' E	36°15'–27' N 74°17' E
Catchment area	Batura Muztagh	Batura Muztagh	Naltar Mts.	Batura Muztagh/Naltar Mts.
Main valley direction	W	SSE	S/E	S
Valley length in km	23.5	18.3	24	23
Glacier length in km	20	16.5	7.5	
Tongue end	3065	2975	3600	–
Maximum elevation of catchment area	7785	6885	6293	7785
Average elevation of catchment area	6141	5527	5320	5902
Average relief energy*	3401	2785	3220	4042
Rec. snowline	4621	4251	4460	–
Valley outlet in m	2740	2740	2100	Chalt 1860
Glacier type	Avalanche basin	Firn basin	Firn basin	
Total valley length in km				46.5

* The average relief energy is calculated from the difference between the average peak elevation and the elevation of the valley outlet.

of the Kukuar glacier (Satmaro) and in the Daintar valley (Kerengi glacier).

Baltar glacier

At a total valley length of 23.5 km, 20 km are filled with the Baltar glacier, which terminates at 3065 m. In the valley section downstream of the glacier tongue up to the Bar and Kukuar valley confluence, moraines from the retreating glacier are to be found over a distance of 1.6–2 km and a gradient of 365 m (5.2% = 18°) at 2900 and 2850 m.

In its cross-sectional profile, this is a glacially eroded, U-shaped valley, the flanks of which are covered by lateral moraine weals (Photo 1, see Figure 1).

About 1.5 km upstream of the glacier terminus (Photo 1), the 13 km long Toltar partial stream flows from orographic right with a south exposure into the Baltar, with an ice-cliff surface elevation of 3420 m. The only remaining contact is in the basal part of the tributary glacier. With a difference in elevation of 90 m, the ice cliff of the Toltar towers above main glacier tongue of the Baltar.

The main catchment area of the Baltar is limited by the south side of the Batura wall and thus has southern and western exposure. The average catchment area elevation is at 6177 m, while the maximum peak elevation is determined by the Batura I (7785 m). The Toltar glacier component has a maximum catchment area elevation of 6885 m with a predominant south-east exposure. For both glaciers, the recent computed snowline runs at c. 4600 m in the steep wall, which means that this is an avalanche-fed glacier type.

A particularly broad lateral moraine valley (approx. 700 m) has developed on the orographic right side of the Baltar glacier in south exposure in the intersection with the Toltar glacier.

In the following, the moraine sequences from the catchment area of the Baltar glacier up to the valley outlet will be described on the basis of four conclusive cross-sectional profiles.

Cross-sectional profile 1

At the outlet of the Baltar avalanche basin, a vegetation-covered lateral moraine wall starts at 4050 m orographic right (Figure 1). The unstructured, steep inner slope is undercut by the recent glacier.

Cross-sectional profile 2

Around 1 km down the lateral moraine valley, evidence is already found of several moraine levels (Figure 1 and Photo 2).

- Glacier with current lateral moraine at 3930 m glacier surface elevation.
- Subrecent lateral moraine with initial vegetation at 3975 m, which was classified as being historical stage.
- GLM 'c', partially developing a wall and, with its crest height of 4025 m, is classified as Neoglacial.
- Upper, highest moraine terrace 'd' at 4050 m, the age of which is classified as latest Late Glacial.

The (late glacial) highest lateral moraine 'd' rises around 120 m above the subrecent lateral moraine.

At some points, the glacier deposits debris over the current lateral moraine 'a', which has no vegetation as yet. Just a few metres higher, there is a subrecent moraine 'b' with pioneer vegetation, in which the wall form is maintained continuously. A hanging glacier flowing in from orographic right with a catchment area elevation of 5940 m and a steep ice front at 4055 m deposits its pedestal moraine over the highest moraine terrace and destroys the GLM. A snowline of 4900 m is calculated for this south-east exposed hanging glacier.

Cross-sectional profile 3

Downstream of the hanging glacier, there is a spacious south-exposed lateral moraine valley (Figure 1 and Photo 2), which is limited by the sharp moraine ridge of the GLM 'c' and drops steeply to the glacier. At around half the distance between the GLM 'c' and the current

lateral moraine 'a' on the glacier, there is a further moraine wall 'b', which is located much closer to the edge of the glacier further upstream (Photo 2). Between the valley flank and the GLM level 'c', there is a higher moraine terrace 'd'.

Further downstream, the course of the lateral moraine valley and the GLM moraine is abruptly interrupted by a rocky outcrop which projects with a steep edge directly over the glacier surface. At the break-off edge of the outcrop the crest of the lateral moraine at 3765 m rises 125 m above the recent glacier surface at 3685 m. Downstream of the rocky outcrop, the lateral moraine continues close to the edge of the glacier, while the increasingly broader lateral moraine valley is used as a grazing and temporary settlement area (Toltar Alm). It reaches a maximum width of around 700 m.

In turn, this lateral moraine is limited by the inflow of the Toltar partial glacier component from orographic right. A lateroglacial valley build in the intersection between the Toltar and the Baltar glacier is covered by a bank sander and sediment, transported from the Toltar lateral moraine valley, and is limited by the GLM. After Visser (1938) this is a classic ablation valley at a south faced valley side, where the GLM was deposited during a later advance. Iturrizaga (2003, p. 61) found out that the topography and not the exposure is the limiting factor of building a glacial ablation valley.

Here, the moraine sequence is arranged as follows.

Cross-sectional profile 4

Between the 3500 m high GLM lateral moraine ridge and the recent glacier surface at 3330 m, a further lateral moraine 'b' is located at 3400–3420 m. This subdivision can be seen on Photo 1 orographic right after the Toltar confluence.

While the GLM rises up 200 m over the Baltar glacier in the confluence area, in the central Toltar glacier section it is surmounted and partially overflowed by the glacier ice in the area of an elongated right curve. The lateral moraine valley is also filled in with thick debris cones from the orographic left valley flank. Because the glacier ice is pressed upwards and pushed together along the inner side of the curve, one cannot identify a thrusting movement here, but it cannot be ruled out. The Toltar glacier component has a minimal contact to the Baltar glacier. However, a steep ice cliff has formed in the confluence area, which points to a break-off in the near future (Photo 1).

Both the Baltar and the Toltar tongues are completely covered by debris. 2.5 km after the confluence of the Toltar glacier, the Baltar glacier terminates at 3065 m (Photo 3). After a horizontal distance of 3 km, the valley confluence with the Kukuar glacier is reached at 2740 m. On this partial section, all that remains of the GLM moraine is a high lateral moraine margin on both sides, the steep inner slopes of which are incised by

channels resulting from fluvial erosion. On the orographic left valley flank, the upper edge of the GLM is blurred ahead of the valley confluence, as loose material slips from the underlying rock and is washed away. Instead, a more recent, deeper lateral moraine (b) becomes more prominent and continues uninterrupted downstream up to the ice margin in the Bar valley at around 2560 m (glacial maximum of the last century) (Photo 4). Without differing in shape, the overlying moraine material differs in colour (light yellow) from the deeper lying, more recent level of a darker colour.

On the right valley flank, a low lateral moraine margin is preserved, marking a glacier stagnation at 2800–2950 m. This involves 2–3 low terminal moraine walls from a glacier retreat stage, which has been joined by a mudflow from the orographic right side (Photo 4). This level marks a most recent glacial stage, which according to Schomberg (1933: 136) formed the glacier terminus around 1933 – 1.6 km distant from the Kukuar glacier – while the Kukuar glacier still filled the valley up to 2560 m. However, at least from the valley confluence, the Baltar glacier tongue was inactive and retreating rapidly.

The meltwater of the currently stagnant glacier cuts into the still unsorted, glacial fluvial gravel field on the orographic left side.

There is an interesting report obtained by Schomberg (1933, p. 138) from the local population that both the Baltar and the Kukuar glaciers had retreated far back into their side valleys 100 years previously, that is, around 1833. In other words, within 82 years (1833–1915), the glaciers have advanced by around 10 km and 690 m in altitude.

Kukuar glacier

The Kukuar glacier is a dendritic valley glacier with two different catchment areas. One is the Kampire Dior group in the extension of the Batura wall, the other is the Satmaro glacier component with low catchment area elevations in the Naltar region. The Kukuar glacier, consisting of three large partial glaciers (west, east and north), ends at 2800 m covered in debris (Photo 9), while the Satmaro component already comes to an end at 3150 m (Photos 8, 9, see Figure 1). These glacier tongues, like the Baltar glacier, are also completely covered by surface moraine. The Satmaro/Kukuar glacier confluence is located at an altitude of 3350 m, from which the Satmaro glacier terminus is 1 km distant, and the Kukuar glacier terminus 6 km distant.

The average snowline of the Kukuar and Satmaro component can be calculated at 4250 m.

The valley flanks of the two glaciers are dominated by a GLM (Photos 8, 9, 10), which emerges particularly markedly in the confluence areas of the partial components to the main stream, for example, at the confluence of the West-Kukuar glacier component and the Kukuar Main stream. The deepest point in the wide intersection

of these lateral moraine valleys at 3580 m is filled with a lake. There is a remarkable mudflow activity on the right main valley flank, which is increasingly filling the lateral moraine valley (Photo 8). Iturrizaga (2003, p. 68) described adjacent valley flanks as the source area of mudflow processes filling the lateroglacial valley, which was now destroyed by fluvial processes.

Here, the GLM moraine rises up around 150 m over the recent glacier surface.

The postglacial glaciation history is markedly reflected in the valley section ahead of the confluence of the Satmarao with the Kukuar down to the inflow of the Baltar glacier valley.

Sunk around 300 m deep, the glacier tongue is framed by its GLM. Wherever small side valleys on the orographic left valley flank converge, the moraine is deeply incised. Initially, there is only a monotonous subdivision on the orographic left valley flank, with the GLM (c) rising up around 250–280 m above the sunken glacier tongue (Photo 8). Strong tree growth characterises the spacious lateral moraine valley. Above this, the valley slopes are covered by ground moraines, which do not reveal any uniform level.

Slightly further downstream, at the altitude of the opposite Aldar Kush glacier valley (Photo 9), the moraine stratigraphy changes: around 30–40 m higher than the GLM level, downstream of a side valley channel, a margin starts that can be traced continuously downstream to the Baltar confluence (Photo 10).

The GLM moraine and the level above it can no longer be differentiated at the Baltar outlet. In the middle run of the Baltar glacier valley, the GLM level 'c' could be used to identify a higher moraine terrace 'd', which may be involved here.

Above this GLM level and the 30–40 m higher level, ground moraine covers the valley flank in a thickness of several tens of metres up to the flat valley shoulders on the edge of the cols of the Toltar Alm (Photos 7 and 10).

Just before the confluence with the Baltar glacier, four meltwater channels from a glaciated col with the highest peak (5500 m) cut up an exposed ground moraine on the Toltar east flank (Photos 6 and 10). The snowline of these cols is calculated to be 4750 m. The loose material has been strongly eroded to form large pillars (max. 10–20 m) and deep gorges (Photo 7). Here, the moraine levels described above have been destroyed, but continue again immediately thereafter, before the Baltar confluence. An upper limit of the channelling can be determined at 3200 m, although this does not mean that an upper limit of the moraine accumulation has been reached (Photo 6).

Schneider (1959, p. 210) calls this pillar-like weathered moraine (Photo 7) a 'young diluvial earth-pyramid series'. Standing on its terrace and looking out over the lateral moraine on the opposite side of the valley, he refers to the light debris margin as an ice maximum around the turn of the century.

On the orographic right valley flank, after the confluence of the Satmarao and Kukuar glaciers, ground moraine material is scattered undifferentiated over the slope above the up to 280–350 m high GLM level (Photo 8). Around 100 m below the GLM, a more recent level can be seen, which is maintained up to the confluence of the Aldar Kash side valley (see Figure 1). This level appears again further downstream (Photo 7) and corresponds to the orographic left Baltar moraine, which has only been preserved from about 1.5 km before the valley outlet (b, Photos 4 and 11). These two levels lead over to an ice margin at 2560 m. This moraine level is not mentioned by Schneider (1959).

The strongly collapsed and debris-covered glacier terminus of the Satmarao (Photo 8) comes to an end at 3150 m, roughly where a deep channel incises the orographic right GLM moraine and a large block has become wedged in the drainage channel.

In the intersection of the Aldar Kash, the GLM lateral moraine does not turn into the side valley, so that a connection at the time of the GLM cannot be assumed (Photo 9). The more recent Aldar Kash lateral moraine is covered by debris cones on the orographic left valley flank. Remains of a terminal moraine are found in the curve before the valley outlet, whose inner slope is covered by lake sediments (Photo 10). Everything points to the fact that a lake dammed by a moraine must have existed here. The 7-km long Aldar Kash glacier recently terminates at 3500 m and thus hangs 600 m above the main valley bottom (2900 m). For this glacier, at a maximum catchment area elevation of 5680 m, a snowline in NE exposure of 4590 m can be calculated.

The glacial history on the valley flank section orographic right of the Aldar Kash inflow along the Baltar confluence up to the Hugue, the first permanent settlement terrace at 2550 m, appears as follows.

Downstream of the Aldar Kash side valley, the GLM (c) continues orographic right up to the height of the valley confluence with the Baltar valley with a visible level. At a distance of around 100 m above this, a moraine margin can be seen, which corresponds in its height position to the 30–40 m higher moraine margin on the opposite valley slope (Photos 10 'd' and 11). In the horizontal, this is limited here to a few 100 m. The GLM moraine 'c' is also no longer recognizable as a level further downstream. The upper slope up to the high cols is completely covered with light-coloured loose material, sprinkled with large blocks. As a result of the relief energy and the great steepness, the erosion of the morainic loose material is so great that such accumulations have only been preserved in fragments.

Schneider (1959, p. 210) classifies the lateral moraine terrace on both sides of the Kukuar glacier, that is, the moraine 'c' referred to as a GLM by the present author, as a 'light debris margin' of an ice maximum around the turn of the century and refers to the earth pyramid series as 'young' diluvial.

Glacial geomorphological indicators in the upper to middle Bar valley

The gravel bottom of the upper Bar valley is covered by fluvio-glacial gravels downstream of 2740 m. The confluence area in the middle of the valley between the tributaries of the Baltar and Kukuvar contains fine material. In this fine matrix of the fluvio-glacial gravel field, which lies flat on the valley bottom, small hollow forms can fill with water. Glacier milk in a water-filled hollow form points to a dead ice content.

Accordingly, this involves very recent deposits in the vicinity of the ice margin. Only on the orographic left valley slope is a marked moraine level 'b' recognizable. On the flat valley bottom downstream, the proportion of fine material decreases, so that just before the Hugue settlement at 2560 m a towering fluvio-glacial gravel pile reveals an ice margin, which lies across the valley (Photos 5 and 7). The meltwater stream has deviated to the right side of the valley and has cut its way through completely. This is the only ice margin in the Bar valley (see Figure 1). At this point, reference is made to Schomberg (1933), who published a glaciomorphological description of the Bar valley. According to his publication, the active Kukuvar glacier terminus was around 800 m downstream of the Aldar Kush valley confluence, while he reports on a no longer active glacier tongue, that is, dead ice, in the further course up to just before Hugue at 2560 m (*ibid.*, p. 138). At the same time, the Baltar glacier has separated from the Kukuvar glacier and retreated into the Baltar side valley (see Baltar section). For the years before 1915, a contact of the two valley glaciers has been demonstrated by a cartographic study based on a field investigation of 1915 (Paffen et al., 1956, p. 16).

From the catchment area up to a valley floor height of 2500 m, the Bar valley shows a classical trough profile, the valley flanks of which become increasingly steep downstream and narrow the valley like a gorge (Photo 6). The flat areas are the remains of an old ground moraine terrace, beginning at the Hugue settlement up to the valley outlet in the Hunza valley (Nagar area) at Chalt (Photo 14).

The water required to irrigate the fields at Hugue from the orographic right 'Bar' hanging valley incises the moraine terrace down to the valley bottom (Photo 12). At this orographic right hanging valley outlet, already on the main valley flank, there are the remnants of a lateral moraine with a marked reversal of slope downstream (Photo 12). It must be a lateral moraine, which was deposited during inflow into the main valley as it shows a high gradient in its longitudinal profile and therefore does not come into question as a main valley lateral moraine.

Large dimensioned debris cones cover the moraine remnants in the Bar valley on the valley flanks, just like the alluvial fans of the side valley outlets, which inter-finger with the ground moraine terrace. The settlement area of Bar at 2400 m (Photo 6) is also limited by a rock-

fall cone. The orographic left Bar East glacier valley is connected to the main valley via a high step.

Starting at the Bar settlement about 1.5 km upstream, the river flows in a roughly 15 m deep ravine, the initial genesis of which is understood to be subglacial, caused by hydrostatic pressure of the meltwater of a valley-filling glacier.

According to Kuhle (2005, p. 16), ground moraine covers the slopes up to an elevation of 4150 m, while the highest ice level on the slope of the upper orographic right Bar valley shows the highest abrasion limits at 4500–4600 m in the confluence area (SW opposite Toltar). On the basis of the moraines, a high glacial ice thickness of 1500–1600 m can be assumed. Kuhle (*ibid.*) pointed out that 'an ice thickness of 1500–1600 m is proved just by moraines'.

Daintar valley

In the lower Bar valley, the Daintar valley flows in from orographic right at the settlement Torbuto Das at 2100 m (see Figure 1). Geologically, the Daintar valley, like the western part of the Kukuvar glacier, belongs to the Naltar group. In other words, the average catchment area elevations of 5300 m are much lower than those of the Karakorum main ridge at 6100 m. Schneider (1959, p. 205) stresses that the orographic border between Hunza and Ishkoman is not only underlined by the structure, but also by the morphology, in which the cirque glaciers dominate. The upper Daintar valley is divided into two arms, the western Tolaibar valley and the northern Kerengi glacier valley. Smaller hanging glaciers also occur on the orographic right side valley flank of the Daintar valley (Photo 19). Given a recent glacier terminus at 3600 m, the current snowline for the Kerengi glacier (Photo 17) can be calculated to be 4460 m. The Daintar valley has a length of 24 km, whereby the Kerengi glacier is 7.5 km long.

According to information from the local population, the Kerengi glacier ending at 3600 m today terminated 2 km further downstream at around 3270 m 80–90 years ago, where a roughly 150 m high terminal moraine is located in a valley-blocking position (Photo 18).

From a valley flowing in from the orographic right with a hanging valley, which is breaking off with a straight front over a 700 m high steep step, a mud fan is depositing against the terminal moraine.

According to reports from the local population, the hanging glacier reached the valley bottom 20 years ago. Schomberg (1933, p. 140) reports of a glacier terminus of the Kerengi glacier in the year 1915 at a distance of around 1 km from the stated terminal moraine, that is, at an altitude of around 3350 m. The distance from the then ice margin to the terminal moraine was filled with dead ice.

The latest glacial maximum of the Kerengi is characterised by a hummocky moraine at 3350–3400 m, which leads into the recent and completely debris covered glacier terminus (Photo 17).

The glacier retreat from 3270 to 3400 m up to today's ice margin at 3600 m over a horizontal distance of 2.5 km and 330 m in altitude took place within 67 years. A terrain step below the recent glacier terminus up to the terminal moraine at 3400 m is responsible for the large distance in altitude and accelerated the retreat. This relativises the calculated snowline depression. For the stated glacier terminus positions, we can calculate a snowline depression of 165 and 100 m, which cannot be correlated with a historical or neoglacial stage, because local inhabitants give a very young age for these stages.

The western end of the valley (Tolaibar) is filled by a small firn basin glacier (Photo 19). The hanging glaciers of the orographic right valley flank mark the current snowline. According to information from the local population, the largest glacier 'Tolaibar' reached the valley bottom up to the orographic right moraine terrace (Photo 19) 40–50 years ago. As a result of the steepness of the flank, numerous avalanches have descended into the valley in the more recent past. The small birch woods have been flattened by winter snow or run over by frequent avalanches.

It is remarkable that, particularly on the Daintar main valley flank and also already on the orographic left side of the Kerengi glacier valley, ground moraine has been channelled several tens of metres deep (Photos 15). Even the side valley ridges have been rounded off, so that it can be assumed that the valley was not only filled with ice, but that the ice extended beyond the valley flanks during the Last Glacial Maximum (Würm).

On the Talmutz Pass (3255 m) (Photo 13) on the orographic left Daintar valley outlet around 1000 m above the Bar valley bottom, a few rounded, light-coloured quartzite blocks could be found between fine slate debris. This light-coloured quartzite stands out on the outcrop at a step below the pass. The fact that these blocks are rounded leads to the conclusion that they were being transported through ice.

The orographic left flank of the lower Daintar valley is covered by active steep slate debris fans, which are deposited on the ground moraine terrace at the valley outlet (Photo 13). On the side valley outlet orographic right, ground moraine lines the valley flanks. The only place where it is not preserved is where the lower valley slopes are undercut in the narrow gorge and are thus excessively steepened.

In addition, the high debris production from outstanding slate components causes high material turnover along steep debris cones. The area of the valley outlet itself is filled by a thick ground moraine accumulation of the previous Daintar glacier, also referred to by Kuhle (2005, p. 16), who describes a 'well-preserved ground moraine pedestal of a thickness of 300–400 m' (Photo 13). The Daintar river has cut deep into this loose sediment over the course of the millennia. This terrace level can also be found in part on the orographic right Bar valley side above Torbuto Das. As a result of the virtually complete burial of glacial sediments by steep

debris cones in the lower flank areas, they only rarely come to light.

The lower Bar valley

The lower Bar valley downstream of the permanent settlement Torbuto Das down to the valley outlet at Chalt is characterised by a three-fold division of terraces orographic right. These involve rock-dependent structural forms, whose terrace surfaces are covered with ground moraine material (Photo 14). It is not possible to determine any previous glacier levels from this, but it proves a minimum ice filling up to the highest level. Kuhle (2005, p. 16) addresses these forms as late glacial lateral moraine ledges. Rock abrasions occur up to around 3700 m.

Ground moraine on the valley flanks orographic left up to 4000 m, orographic right up to 3900 m and flank polishings and abrasions up to 4200 m bear witness to a high ice level (Kuhle, 2005, p. 16).

The orographic right intermediate valley head, which separates the Bar valley from the neighbouring Chaprot valley to the west, forms a flat ridge at an altitude of 3500 m, declining to 2500 m. The elevation of the inflow of the Bar valley into the Hunza river is at 1765 m. The thick alluvial fan of Chalt, mainly formed from the Chaprot valley, runs around an isolated and moraine-covered full form, which rises up 250 m over the Hunza river on its right side in between the Bar- and Chaprot valley outlet. The Hunza river undercuts the glaciofluvial cone and the moraine-covered full form.

Summary of the results

In latest, historical times, the ice margin of a Kukuar/Satmaro glacier unified with the Baltar glaciers was still at 2560 m around 1915–1920. From this, a snowline can be calculated at 4168 m ($((5776 \text{ m} + 2560 \text{ m})/2 = 4168 \text{ m})$), which is 268 m below today's calculated average snowline of the two partial catchment areas at c. 4400 m.

That is a relatively high value, which here in view of the presence of the GLM 'c' and a level 'd' above it, marks a latest glacial maximum of a common glacier with the moraine level 'b'. The Baltar glacier had separated from the Kukuar glacier as early as 1933 and retreated 1.6 km into its side valley up to around 2800 m (Schomberg, 1933, p. 136).

These retreat moraines close to the recent glacier tongue of the Baltar glacier between 2800 and 2950 m mark the latest glacial maximum of the unified Baltar and Toltar glaciers in 1933 and enable the calculation of a snowline depression of 80–100 m.

This is consistent with the investigations of Paffen, Pillewitzer and Schneider (1956, p. 16), who state that the two glaciers Kukuar and Baltar extended several km further downstream and were visible from a permanent



← *Photo 1.* View from the intersection between the Toltar and Baltar glacier (36°28,3' N, 74°22' E) at 3420 m to the west over the debris-covered glacier tongue of the 24 km long Baltar glacier. The avalanche-fed glacier comes to an end at 3065 m ●. From orographic right, the 13 km long Toltar glacier ▲ flows in. In the area of confluence, a 90 m high ice-cliff has formed. The GLM (in the text 'c' ↓ ↓ ↓) limits the glacier to both sides. A debris margin roughly 15 m below the upper edge of the GLM ↑↑ reveals a more recent glacier level 'b'. In the background of the picture, the valley confluence with the Kukuar can be seen x. Photo S. Meiners, 19.07.2000.



↑ *Photo 2.* 180° panorama (viewpoint at 3930 m on the top of the GLM lateral moraine at the right side of the glacier, 36°28,05' N, 74°26' E) from NE to SW over the upper to middle catchment area of the Baltar glacier. The cross-sectional profile (see Figure 1) 2—2 in the left-hand picture and 3—3 in the right-hand picture on the orographic right side of the glacier are described in the text. Below the GLM 'c' at 4025 m are the subrecent lateral moraine 'a' and the historical moraine 'b'. Downstream in the cross-sectional profile 3—3, the moraine sequence from a to c is supplemented by the higher flat moraine terrace 'd'. The differentiation from the GLM (neoglacial) to the moraine terrace (late glacial) is marked here. In the picture on the right, the lateral moraine valley is interrupted by solid rock ↓. Photo S. Meiners, 16.07.2000.



↑ *Photo 3.* View downstream over the Baltar glacier terminus (36°27,05' N, 74°20,02' E) → and the orographic right valley flank. The meltwater of the strongly sunken Baltar glacier terminus (3065 m) incises the retreat moraines at 2800 – 2950 m Δ ▲. The trough profile is additionally disfigured by mudflows that are released from the wall and flow over the GLM or issue directly from the GLM moraine ■. The GLM moraine — — in part forms a thin debris veil on the steep valley flank. In the background of the picture is the valley confluence ↓ with the Kukuar glacier. Photo S. Meiners, 14.07.2000.



→ *Photo 5.* View from 2565 m (36°24.7' N, 74°17.5' E) upstream into the upper Bar valley to the Toltar col, whose meltwater has channelled the late glacial ground moraine lining. In the middle ground, the upper limit of the neoglacial moraine margin 'c' ↓ is visible. From the undifferentiated ground moraine material on the orographic left valley slope ▲, the historical moraine level (b) --- can be distinguished, which has built up a terminal moraine at 2560 m ● just before the settlement terrace of Hugue and thus represents the only ice margin of 1915 in the Bar valley. Photo S. Meiners, 24.07.2000.



← *Photo 4.* The photo panorama, taken at 2820 m stretches along the orographic left valley flank of the lower Baltar valley up to the valley confluence with the Kukuvar valley at 2740 m (36°27' N, 74°18' E). In the left-hand picture segment is the glacier terminus of the Baltar □. Here, it becomes clear that, under the towering GLM (c) ↓ the glacier level already described above (b) --- is preserved continuously up to the ice margin at 2560 m (see Photo 5). While an older mud fan ● has joined the upper edge of the level (b), a more recent mudflow ▲ has issued from the lateral moraine formation (b) onto the gravel bottom. O marks the area between 2800 – 2950 m, in which 2–3 glacier retreat moraines from 1933 are located. Photo S. Meiners, 19.07.2000.



→ *Photo 6.* Overview from 3000 m from the orographic right Bar valley flank (36°23' N, 74°16,7' E) upstream into the upper Bar valley. The main settlement of Bar at 2400 m ■ and Hugue at 2500 m ▲ are located on a ground moraine terrace, which represents the only flat area in the valley. The steep trough flanks are covered by slope debris fans, which are deposited over the high to late glacial moraine remnants. The four valley tributaries ↓ from the Toltar col mark the beginning of the channelling of the ground moraine ●. The line --- marks the neoglacial ice filling. o o shows the historical ice margin at 2560 m from 1915. During the High Glacial according to Kuhle (2005), the glacier ice filling was 1500–1600 m above the valley bottom, so the upper limit was at 4200 m. Photo S. Meiners, 24.07.2000.



↑ *Photo 7.* Panorama view from 3270 m (36°27, 6' N, 74°18, 2' E) over the Baltar- ↓/Kukuar valley confluence downstream. While the GLM moraine (c) --- and the deeper level (b) with an ice margin at 2560 m can be clearly distinguished, the level (d) □□ approx. 100 m above the GLM moraine corresponds to the latest late glacial earth pyramid level on the orographic left Kukuar valley side ▲, the location from which the photograph was taken. Schneider (1959) addressed level 'c' as the ice maximum around the turn of the century. Photo S. Meiners, 20.07.2000.



→ *Photo 8*. Photo taken from 3420 m (36°28' N, 74°17' E) to the north. The elevation of the GLM moraine --- along the Kukuar glacier declines glacier upstream. On the Satmaro glacier terminus at 3150 m →, the GLM towers over the glacier by 280–300 m. The historical level (b) is also visible here Above the GLM, the valley flanks are lined high up with ground moraine ▲. The cross marks the confluence of the Satmaro and Kukuar glacier partial streams. In front of the Satmaro glacier terminus, there is a gravel field currently containing dead ice. Photo S. Meiners, 21.07.2000.



← *Photo 9.* View from the opposite side of the Aldar Kash valley at 3420 m (36°28' N, 74°17' E). While the Satmaro glacier component ends at 3150 m ●, the end of the Kukuar glacier lies 6 km further downstream at 2800 m. In the middle ground of the picture, the Aldar Kash glacier valley ↓ drains from orographic right into the Kukuar valley. The Kukuar GLM moraine and the lateral moraine ▲ containing dead ice has recently been incised by meltwater from the Aldar Kash. The highest peak in the catchment area of the Aldar Kash is 5680 m high, the glacier ends at 3500 m ↓ and is thus 600 m above the valley bottom of the main valley. During the stage of the GLM, there was no contact with the Aldar Kash glacier. Photo S. Meiners, 21.07.2000.



← *Photo 11.* View from the Earth pyramid zone (36°27' N, 74°17' E) from the orographical left side down to the confluence area of the Baltar- and Kukuar meltwater streams. In the middle fluvio-glacial deposits and dead ice of the Kukuar glacier can be seen (x). The line^b marks the historical stage which leads to the ice margin at 2560 m of 1915 and younger. Line - - - - c marks the GLM level, where no ice margin can be seen further down. □ shows remnants of a higher moraine level (younger Late Glacial) on the true right Kukuar valley flank which is only preserved on individual localities. Photo S. Meiners, 21.07.2000.

← *Photo 10.* Panorama location (36°28' N, 74°15' E) on the orographic left side valley outlet of the Aldar Kash valley at 3135 m ◆ with view over the orographic left valley flank of the Kukuar glacier. Above the light-coloured debris margin of the GLM 'c' --- there is a 30–40 m higher moraine ledge 'd' ↓. ◆◆ marks the section that is strongly channelled into earth pyramids (see Photo 7). ← marks the Kukuar glacier terminus at 2800 m. In the left-hand picture segment, the ground moraine lined slopes are covered with debris cones ▲. In the Aldar Kash valley outlet, lake sediments have been exposed on the inner slope of a more recent terminal moraine ●, which proves the damming of a moraine lake in historical times. Photo S. Meiners, 24.07.2000.

→ *Photo 13.* In the lower Bar valley, the Daintar valley flows in from orographic right. In the confluence orographic left a 300-400 m high ground moraine pedestal has been deposited (36°20' N, 74°17' E), on which debris cones ↓ have developed. The settlement Torbuto Das ▲ at 2100 m irrigates the fields with water from the Daintar. The cross marks the Talmutz Pass, 3255 m, on which rounded blocks are found. Photo S. Meiners, 13.07.2000.



↓ *Photo 12.* In the central Bar valley (Photo taken from the left valley side at 2450 m), the debris cones hide the trough profile with moraine components. Above Hugue ▲, a small Bar hanging valley → with a small glacier flows into the Bar main valley. The meltwater is channelled to the fields and ground moraine terrace of Hugue for irrigation. A lateral moraine remnant (36°24'05" N, 74°17'03" E) with reversal of slope to the valley flank ← ← and upper edge inclining downstream belongs to a stage when the Bar hanging glacier must have flowed into the Bar main glacier during the Latest Late or Neoglacial. Photo S. Meiners, 13.07.2000.

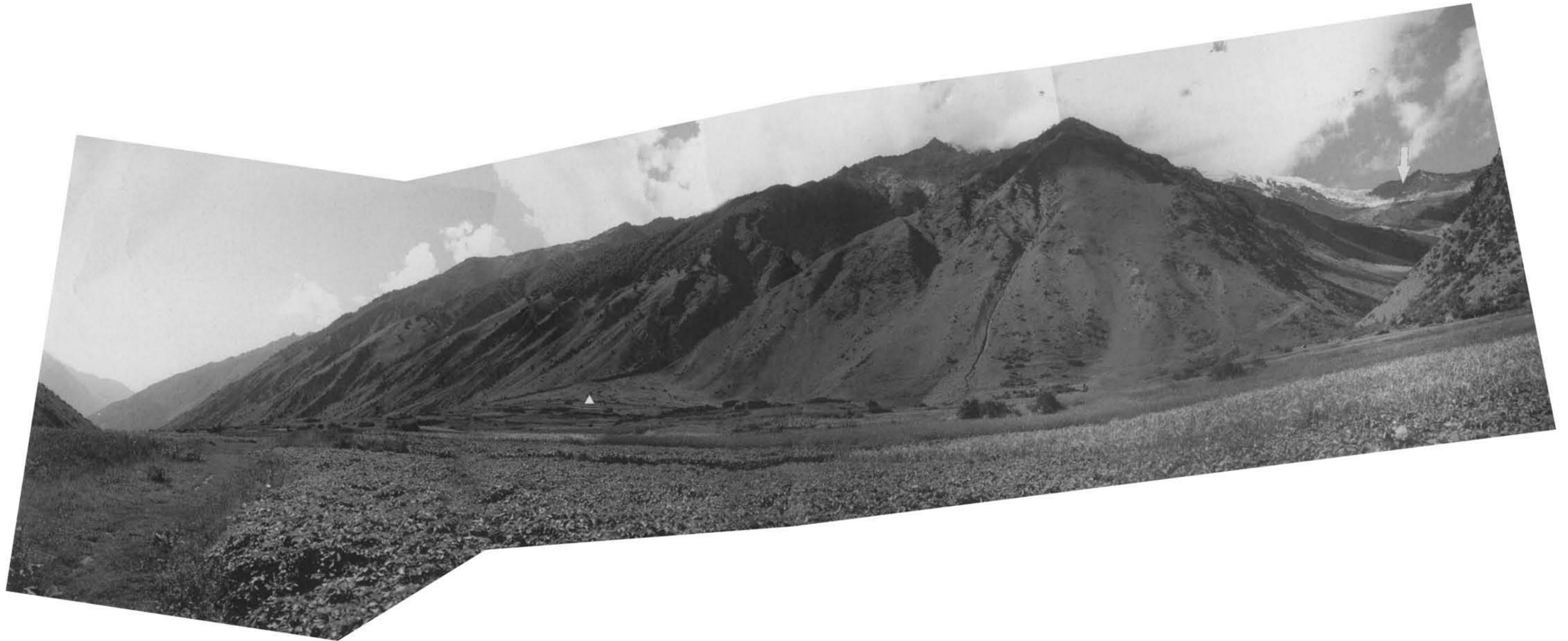




← *Photo 14.* View from the Talmutz Pass (3255 m, 36°20'06" N, 74°16'05" E) to the south down to the Hunza valley. The Rakaposhi (7788 m) \diamond rises up in the background. Three terrace levels $\downarrow\downarrow\downarrow$ are present, which are covered with ground moraine material. In the foreground lies Torbuto Das \blacksquare , in the background Budelas \blacktriangle . Flank polishings and abrasions up to 4200 m bear witness to a high glacial upper glacier margin (Kuhle, 2005, p. 16). Photo S. Meiners, 26.07.2000.

→ *Photo 15.* View from the wide alluvial fan at 3025 m, where the settlement place is named Taling (36°20'07" N, 74°10' 02" E). The orographic left valley flank of the Kerengi and Daintar valley is deeply incised by erosion channels several tens of metres thick \blacktriangle . A high to late glacial ice filling up to 4100- 4200 m is proved by the thick ground moraine. Photo S. Meiners, 27.07.2000.



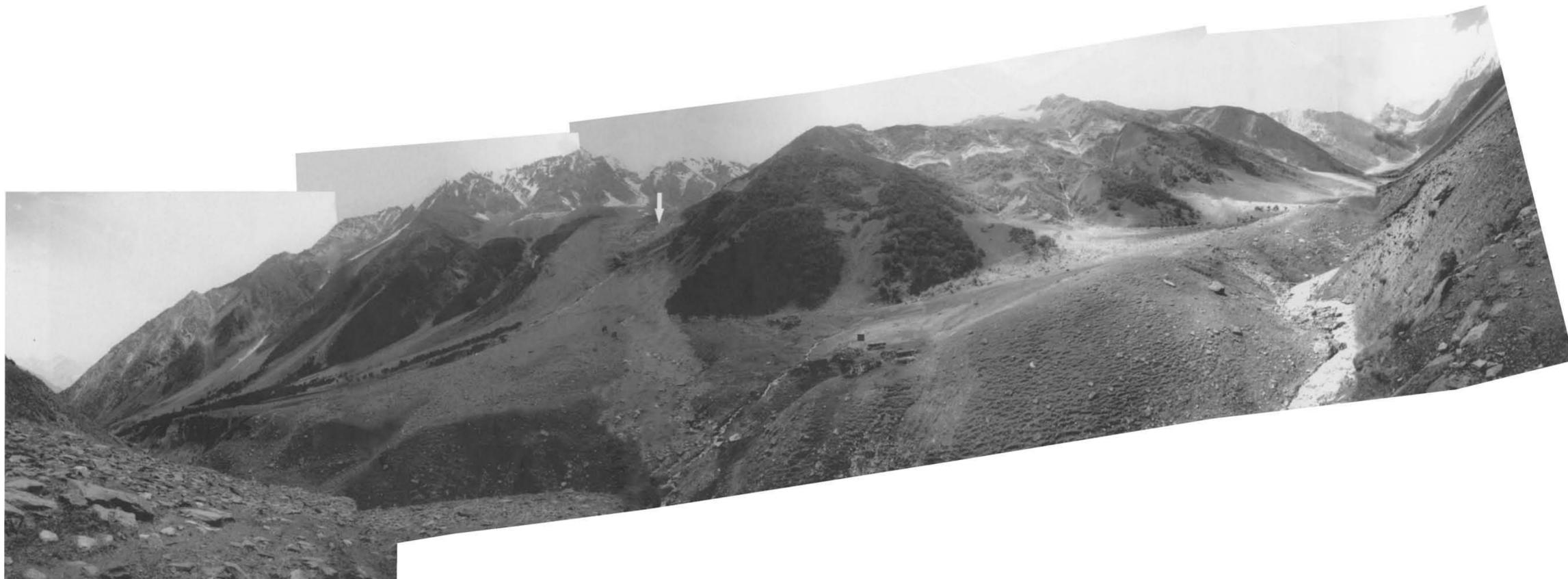


↑ *Photo 16.* West to East- Panorama from the Daintar West glacier ↓ over the orographic right valley flank. In the flat confluence area with the Kerengi valley running to the north ← a thick alluvial fan has been deposited ▲, on which the settlement Taling at 3025 m is located (36°20'07" N, 74°10'02" E). Here – in contrast to the opposite valley flank (see Photo 15) – the ground moraine only forms a thin coverage. Photo S. Meiners, 28.07.2000.

→ *Photo 17.* This photograph was taken on the top of a 150 m high terminal moraine at 3420 m (36°22'07" N, 74°09' E) from the year 1933 looking upstream to the Kerengi glacier. The arrow marks the glacier terminus at 3600 m, while the dots show the historical glacial maximum at 3400 m. The glacier tongue is completely covered by debris. The peak in the background ▲ is 5005 m high. Photo S. Meiners, 28.07.2000.



← *Photo 18.* View from the recent Kerengi glacier terminus at 3600 m (36°23'08" N, 74°08'08" E) to the south downstream. In the middle ground of the picture there is a roughly 150 m high terminal moraine ▲ rising above the valley bottom at 3270 m, the slopes of which are covered by mud fans from the recently glaciated, orographic right side valley. Also in the further course of the valley, alluvial fans line the lower valley flanks, so that deeper ice margins and lateral moraines are covered over. Photo S. Meiners, 27.07.2000.



† *Photo 19.* The panorama taken at 3375 m shows the recent minimally glaciated, orographic right flank of the Daintar West valley from West to East. The Tolaibar glacier ↓ apparently still advanced to the valley bottom 50 years ago. A roughly 30 m high ground moraine terrace is markedly incised by the Daintar river. Near to the edge of the terrace is the temporary high pasture settlement of Tolaibar ■. Photo S. Meiners, 28.07.2000.

settlement (by which Hugue is meant) before 1956. They justify this with research of the 'Baltit' map from the Quarter Inch Map, which refers to the presentation of a 'Hunza valley and Taghdumbash Pamir map' of 1915. On the basis of these data, the calculated snowline values must be relativised. Schomberg (1933, p. 138) points to the fact that the Kukuar was in retreat up to around 800 m after the side valley inflow of the Aldar Kush, but was still active, but then existed as dead ice up to the glacier terminus at 2560 m. In the area of confluence, dead ice could still be found within fluvio-glacial gravel, which underscores the chronological proximity of glacier disintegration. The lateral moraine of this last glacial maximum, described in the text as level 'b', could be mapped particularly clearly on the Baltar glacier.

The most prominent lateral moraine, which is to be found in all Karakorum glaciers, is the GLM 'c'. In the area of confluence of the Kukuar and Baltar, it achieves a height of up to 300 m over the valley bottom. Schneider (1959, p. 208) described the GLM on the orographic right side of the Kukuar as a light-coloured debris margin, which marks the ice maximum around the turn of the century. Further, he writes that the typical lateral moraine terraces on both sides of the glacier belong to the 'young' diluvial earth-pyramid series. This is contradictory, since the 'light-coloured debris margin' leads into the typical lateral moraine further upstream, which represents the large lateral moraine – referred to in the text as 'c'.

Visible on the orographic left valley slope, a further level could be mapped via the GLM – referred to in the text as 'd' – which is ultimately classified to the earth pyramid level and finds its counterpart on the opposite side of the valley. In view of the ice margin at 2560 m at the beginning of the 20th century, the pertinent glacier termini of the GLM and the earth pyramid moraine must have been located further downstream.

For both levels, which can be clearly distinguished from each other, no terminal moraine positions have been preserved in the Bar valley.

The somewhat minor glaciation of the Daintar valley in postglacial times is contrasted by a connection to the Bar glacier, revealed by a thick ground moraine pedestal at the valley outlet and a pronounced ground moraine lining of the valley slopes.

In the lower Bar valley downstream of the permanent settlement Torbuto Das, three ledges stepped on top of each other are preserved, which are covered by moraine material. Kuhle (2005) refers to them as late glacial moraine ledges. The Bar valley is characterised by a narrow trough profile, the valley slopes of which are lined high up with morainic fine material even below the settlement Torbuto Das. This means that glacier filling of the Bar valley up to the Hunza valley is indisputable. The moraine-covered rock bar at Chalt between the Bar- and the Chaprot valley outlet is discussed by Haserodt (1989, p. 195) as a late Pleistocene terminal moraine of the Bar valley, while Paffen et al. (1956, p. 14) already address the 'deepest moraine wall at Chalt at 2000 m' as

a 'late to postglacial terminal moraine of the side valley glacier advanced into the longitudinal valley.' On the basis of the glacial geomorphological indicators, Kuhle (2005, p.16) points to a connection of the Bar glacier (Tutu Uns) with the high glacial Hunza glacier, which had a glacier surface elevation of 3600–3700 m at this locality. It thus achieved a thickness of around 1800 m. The ice margin of a thick Hunza–Gilgit–Indus iceflow is stated in the Indus valley (after Kuhle, 1997, p.123) at 850 m.

While the height of the glacier surface was reconstructed at 3800 m between Torbuto Dhas (2100 m) and the Bar valley outlet (2000 m), the calculated prehistoric snowline (Last Glacial Maximum) at 3200 m – according to a snowline depression of 1200 m – would lay 600 m in height further downvalley.

References

- Baltit map NJ 43-14, Series U502, India and Pakistan 1: 250 000.
- Batura Investigation Group., 1979: The Batura Glacier in the Karakoram Mountains and its Variations *Scientia Sinica* 22(8): 958–974.
- Coward M.P., Jan Q.M., Rex D., Tarney J., Thirwall M. and Windley B.F., 1984: Geology of the South Central Karakoram and Kohistan. In: Miller K.J. (ed.), *International Karakoram Project*, Cambridge, Vol. 2, pp. 71–83.
- Dainelli G., 1922: *Studi sul Glaciale. Risultati Geologici e Geografici, Relazioni scientifiche della Spedizione Italiana De Fillipi nell' Himalaya, Caracorum e Turchestan Cinese (1913–1914)*. Vol. III, Ser. II., Bologna.
- Derbyshire E., Li Jijun, Perrott F.A., Xu Shuying and Waters, R.S., 1984: Quaternary glacial history of the Hunza Valley, Karakoram mountains, Pakistan. In: Miller, K.J. (ed), *International Karakoram Project*, Cambridge, Vol. 1, pp. 456–495.
- Ehlers, J. and Gibbard, P., (eds.), 2004: *Quaternary Glaciations- extent and chronology* Vol. III Elsevier, Amsterdam (u.a.).
- Haserodt K., 1989: Zur pleistozänen und postglazialen Vergletscherung zwischen Hindukusch, Karakorum und Westhimalaya *Beiträge und Materialien zur Regionalen Geographie* 2: 182–233.
- Höfer H.v., 1879: Gletscher und Eiszeitstudien *Sitzungsberichte der Akademie der Wissenschaften, Mathematisch-Naturwissenschaftliche Klasse* 1(79): 331–367.
- Hunza–Karakorum, 1995: Hunza–Karakorum. Topographische Ergebnisse der Deutsch–Österreichischen Himalaya–Karakorum–Expedition 1954 und der Deutschen Karakorum–Expedition 1959. Deutscher Alpenverein. Scale 1:100 000.
- Iturrizaga L., 2003: Distribution and genesis of lateroglacial valleys in the Karakoram Mountains (Pakistan). *Zeitschrift für Geomorphologie N.F.* (Suppl. 130): 51–74.
- Kick W., 1985: Geomorphologie und rezente Gletscheränderungen in Hochasien *Regensburger Geographische Schriften* 19(20): 53–77.
- Kuhle M., 1986: Schneegrenzberechnung und typologische Klassifikation von Gletschern anhand spezifischer Reliefparameter *Petermanns Geographische Mitteilungen* 130: 41–51.
- Kuhle M., 1988a: Topography as a Fundamental Element of Glacial Systems. A New Approach to ELA-Calculation and Typological Classification of Paleo- and Recent Glaciation *GeoJournal* 17: 545–568 (4, Tibet and High-Asia, Results of the Sino-German Joint Expeditions (I), eds: Kuhle, M. and Wang Wenjing).
- Kuhle M., 1988b: Geomorphological Findings on the Build-up of Pleistocene Glaciation in Southern Tibet, and on the Problem of Inland Ice. Results of the Shisha Pangma and Mt. Everest Expedition 1984 *GeoJournal* 17: 457–513 (4, Tibet and High-Asia, Results of the Sino-German Joint Expeditions (I), eds: Kuhle, M. and Wang Wenjing).
- Kuhle M., 1988c: The Pleistocene Glaciation of Tibet and the Onset of Ice Ages- An Autocycle Hypothesis *GeoJournal* 17: 581–596

- (4, Tibet and High-Asia. Results of the Sino-German Joint Expeditions (I), eds: Kuhle, M. and Wang Wenjing).
- Kuhle M., 1994: Present and Pleistocene Glaciation on the North-Western Margin of Tibet between the Karakorum Main Ridge and the Tarim Basin Supporting the Evidence of a Pleistocene Inland Glaciation in Tibet *GeoJournal* 33: 133–272 (2/3, Tibet and High Asia, Results of the Sino-German and Russian-German Joint Expeditions (III), ed: Kuhle, M.).
- Kuhle M., 1997: New Findings concerning the Ice Age (Last Glacial Maximum) Glacier Cover of the East-Pamir, of the Nanga Parbat up to the Central Himalaya and of Tibet, as well as the Age of the Tibetan Inland Ice *GeoJournal* 42: 87–257 (2–3, Tibet and High Asia. Results of Investigations into High Mountain Geomorphology, Paleo-Glaciology and Climatology of the Pleistocene (Ice Age Research) IV, ed: Kuhle, M.).
- Kuhle M., 2001: The maximum Ice Age (LGM) glaciation of the Central- and South Karakorum: an investigation of the heights of its glacier levels and ice thickness as well as lowest prehistoric ice margin positions in the Hindukush, Himalaya and in East-Tibet on the Minya Konka-massif *GeoJournal* 54: 109–396 (2–4, Glaciogeomorphology and Prehistoric Glaciation in the Karakorum and Himalaya. Tibet and High Asia (VI), ed: Kuhle, M.).
- Kuhle M., 2004: The High Glacial (Last Ice Age and LGM) ice cover in High and Central Asia *Development in Quaternary Science* 2: 175–199 (III, Quaternary Glaciation – Extent and Chronology, Part III: South America, Asia, Africa, Australia, Antarctica, eds: Ehlers, J. & Gibbard, P.L.).
- Kuhle M., 2005: The past Hunza Glacier in connection with a Pleistocene Karakoram ice stream network during the Last Ice Age (Würm). In: Kreuzmann H. (ed.), *Karakoram in Transition-The Hunza Valley* Oxford University Press, Oxford pp. in press, June 2005.
- Meiners S., 1996: Zur Rezenten, Historischen und Postglazialen Vergletscherung an ausgewählten Beispielen des Tien Shan und des Nord-West Karakorum *GeoAktuell* 2: 1–200.
- Meiners S., 1998: Preliminary Results concerning Historical to Post-Glacial Glacier stages in the N.-W.-Karakorum (Hispar Muztagh, Batura Muztagh, Rakaposhi Range). In: Stellrecht I. (ed), *Karakorum-Hindukush-Himalaya: Dynamics of Change, Culture Area Karakorum, Scientific Studies Vol. 4*, pp. 49–69. Rüdiger Köppe Verlag, Köln.
- Meiners S. (2001): The post to late glacial valley reconstruction on the Haramosh north side (Mani, Baska and Phuparash valleys). *GeoJournal* 54(nos.2–4)/55 (no. 1) (Glaciogeomorphology and Prehistoric Glaciation in the Karakorum and Himalaya. Tibet and High Asia (VI) ed: Kuhle, M): 429–450.
- Miller K.J., 1984: *The International Karakoram Project* Vol. 1, 2. 412 Cambridge University Press, London pp. 635.
- Owen L., Finkel R.C., Caffee M.W. and Gualtieri L., 2002: Timing of multiple late Quaternary glaciations in the Hunza Valley, Karakoram Mountains, northern Pakistan: Defined by cosmogenic radionuclide dating of moraines *Geological Society of America Bulletin* 15(5): 593–604.
- Paffen K.H., Pillewitzer W. and Schneider H.J., 1956: Forschungen im Hunza-Karakorum, vorläufiger Bericht über die wissenschaftlichen Arbeiten der Deutsch-Österreichischen Himalaya-Karakorum-Expedition 1954 *Erdkunde* 10(1): 1–33.
- Röthlisberger F., 1986: *10000 Jahre Gletschergeschichte der Erde*. Aarau, Frankfurt am Main, Salzburg.
- Schneider H.J., 1959: Zur diluvialen Geschichte des NW-Karakorum *Mitteilungen der Geographischen Gesellschaft München* 44: 201–216.
- Schomberg R.C.F., 1933: The Bar and Daintar Glaciers *The Alpine Journal: the Journal of the Alpine Club* 46: 131–142.
- Searle M.P., 1991: *Geology and Tectonics of the Karakoram Mountains (Includes Geological Map of the Central Karakoram, Scale 1:250.000)*, John Wiley & Sons, Chichester.
- Tahirkheli R.A.K. and Jan Q.M., 1984: The geographical and geological domains of the Karakoram. In: Miller K.J. (ed.), *The International Karakoram Projekt*. pp. 57–70. Vol. 2 Cambridge University Press, Cambridge.
- Visser P.C., 1938: *Glaciologie Wissenschaftliche Ergebnisse der niederländischen Expeditionen in den Karakorum und angrenzenden Gebieten 1922, 1925, 1929/30 und 1935 Vol 2 (Series eds: Visser, P.C. & Visser-Hoof, J.)*. E. J Leiden, Brill 216.

Geomorphological and pedological investigations on the glacial history of the Kali Gandaki (Nepal Himalaya)

Markus Wagner

Geography/High Mountain Geomorphology, Institute of Geography, University of Goettingen, Goldschmidtstr. 5, 37077, Goettingen, Germany (E-mail: mwagner4@gwdg.de)

Key words: glacial geomorphology, glacial history, Himalaya, ice age glaciation, relative dating, soil development

Abstract

In semi-arid orographic left tributaries of the Kali Gandaki at the northern and western flank of the Nilgiri Himal, glacio-geomorphological and pedological investigations were carried out on prehistoric moraines. Geomorphological relief analysis was derived from other literature and the own fieldwork of the author. The resulting glacial chronology was used as benchmark to explore the limits of different pedological dating methods regarding the degree of soil development. These methods are based on iron fractionation, total element contents and particle size distribution. In general the different glacial stages are mirrored correctly in the relative graduation of soil development. The ratio of well crystallised pedogenic iron-oxides to the total iron content and the ratio fine clay to total clay are most suitable, because they are almost independent from existing changes in the lithological composition. The total element based weathering indices are less suitable, because they react highly sensitive to the geology dependent shift to higher carbonate contents. Most of the grain size based weathering indices are inapplicable because of the typically high textural variability within till deposits.

Introduction

This paper deals with pedological relative dating methods supporting the geomorphological reconstruction of the glacial history in terms of Penck and Brückner (1909). This will give a more detailed view on the glacial chronology. The precondition of similar and constant soil development conditions makes it possible to derive the relative age of a soil from its weathering extent. Among others this principle is used to assign moraines to different stages of glaciation by estimating the relative age of the soil being developed on the moraine after the glacier retreated. In the Nepal Himalaya this relative dating technique was carried out at moraines in the Langtang Himal (Bäumler, et al., 1996b), Solu Khumbu Himal (Bäumler, 1993), Annapurna Himal (Zech, et al., 2001a, b) and Manaslu Himal (Zech, et al., 2003).

The investigation areas are situated in the middle section of the Kali Gandaki catchment area, an antecedent valley between the Dhaulagiri and Annapurna Himal (Figure 1). The quaternary valley history of the Kali Gandaki is well determined even though the time and extent of glaciation is still contestable (Dollfus and Usselman, 1971; Hormann, 1974; Kuhle, 1982, 1983, 2001; Fort, 1985, 2000; Iwata, 1984). Comparing other publications with the own field experience the author uses geomorphological relief analysis as a benchmark to verify and adjust the different pedological dating meth-

ods. The short distance variation of the geological formations and climatic conditions in the Kali Gandaki offer further reasons for the adequacy of this valley to explore the limits of adaptability of the pedochronological approach.

The pedochronology cannot compensate absolute dating techniques like ^{14}C , OSL, TL or cosmogenic nuclides, but since the latter are very complex and not always accomplishable on glacio-geomorphological material in high mountain areas (Hallet and Putkonen, 1994), pedogenetic analysis offers an interesting addendum.

Material and methods

Glacial and glaciofluvial geomorphological features indicating erosional and depositional traces of glaciation, first need to be identified by detailed field investigation and sedimentological analysis. The resulting pattern of spatial distribution of these indicators allows the reconstruction of the glacial history through the medium of the "Glacial Series" established by Penck and Brückner (1909). Detailed methodological information about the specific glacio-geomorphological features and the significance of their relative arrangement and distribution within the landscape for the

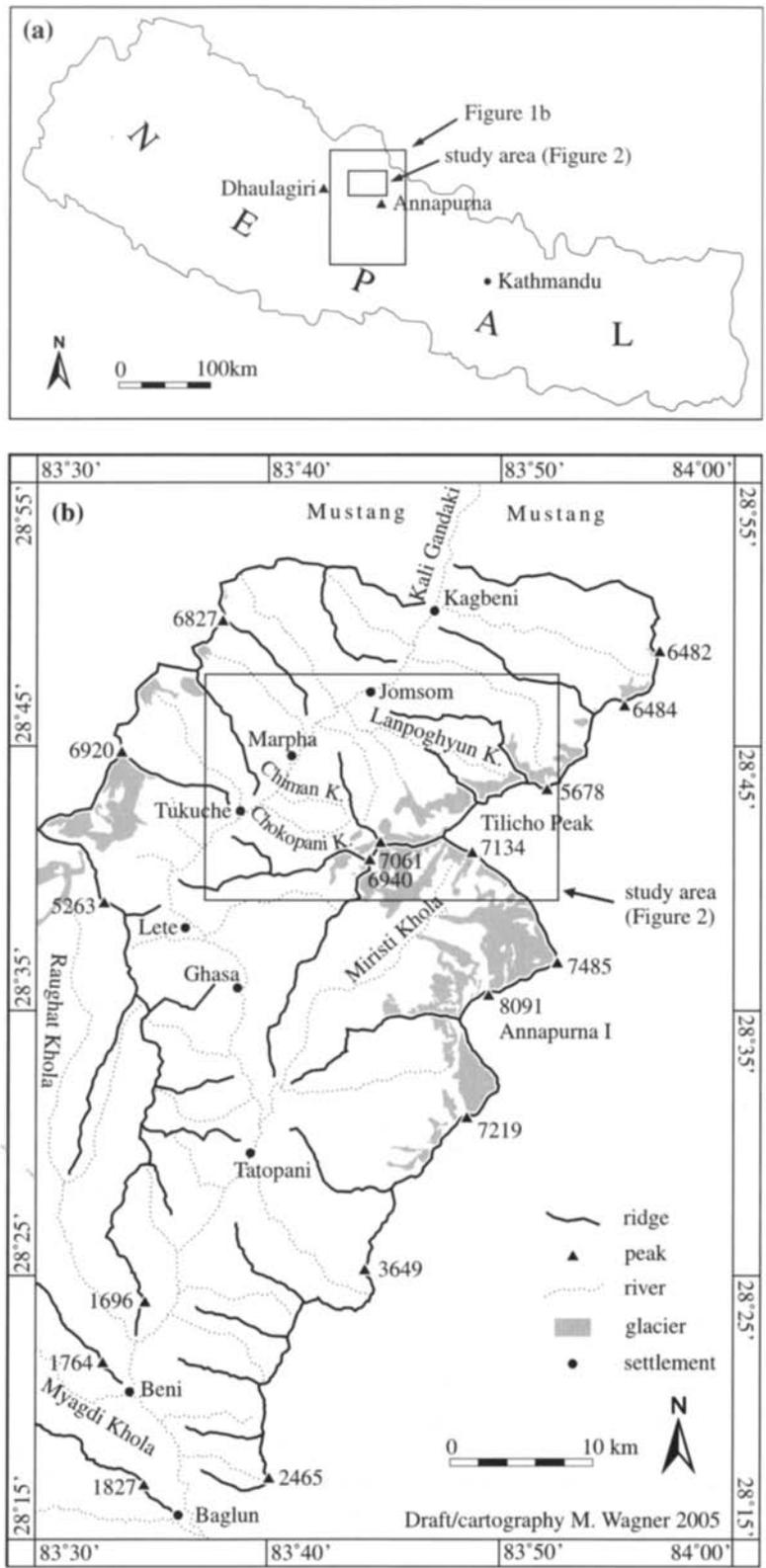


Figure 1. a and b. Location of the study area.

reconstruction of former glacier extent is given by Kuhle (1990, 1991).

As a result of glacio-geomorphological relief analysis and calculated equilibrium line altitude (ELA) depressions Kuhle (1982, 1983) reconstructed a very detailed succession of 14 glacial stages since the Last Glacial Maximum (LGM) for the Kali Gandaki. Later it was

approved at further investigation areas in High Asia (Meiners, 1999; Kuhle, 2004) and complemented by some absolute dating (Kuhle, 1987, p. 203, 1994, p. 264) (Table 1). Based on field observations of the landforms (Fort, 1985) and Iwata (1984) identified four glacial stages for the Kali Gandaki which are estimated to be Holocene, late Last Glacial (MIS 2), early Last Glacial

Table 1. Glacier stages of the mountains in High Asia from the pre-Last High Glacial (pre-LGM) to the present-day glacier margins and the pertinent sanders (glaciofluvial gravel fields and gravel field terraces) with their approximate age (Kuhle, 2004, p. 192, modified)

glacier stage	gravel field (Sander)	approximated age (YBP)	ELA-depression (m)
-I = Rib (pre-last high glacial maximum)	No. 6	150000–120000	c. 1400
0 = Würm (last High Glacial maximum)	No. 5	60000–18000	c. 1300
● 1, 2 = first and second Pre-Ghasa-Stagnation			
I–IV = Late Glacial	No. 4–No. 1	17000–13000 or 10000	c. 1100–700
I = Ghasa-Stage	No. 4	17000–15000	c. 1100
II = Taglung-Stage	No. 3	15000–14250	c. 1000
III = Dhampu-Stage	No. 2	14250–13500	c. 800–900
IV = Sirkung-Stage	No. 1	13500–13000 (older than 12870)	c. 700
V–VII = Neo-Glacial	No. –0 to No. –2	5500–1700 (older than 1 610)	c. 300–80
V = Nauri-Stage	No. –0	5500–4000 (4165)	c. 150–300
VI = older Dhaulagiri-Stage	No. –1	4000–2000 (2050)	c. 100–200
VII = middle Dhaulagiri-Stage	No. –2	2000–1700 (older than 1 610)	c. 80–150
VII–XI = historical glacier stages	No. –3 to No. –6	1700–0 (= 1950)	c. 80–20
VII = younger Dhaulagiri-Stage	No. –3	1700–400 (440 resp. older than 355)	c. 60–80
VIII = Stage VIII	No. –4	400–300 (320)	c. 50
IX = Stage IX	No. –5	300–180 (older than 155)	c. 40
X = Stage X	No. –6	180–30 (before 1950)	c. 30–40
XI = Stage XI	No. –7	30–0 (= 1950)	c. 20
XII = Stage XII = recent resp. present glacier stages	No. –8	+0 to +30 (1950–1980)	c. 10–20

Draft: M. Kuhle.

(MIS 4) and pre-Last Interglacial in age. So far only a few absolute dates of quaternary deposits are published concerning the Kali Gandaki area. The OSL age of the lacustrine sediments of the “Marpha Formation” in the middle section of the Kali Gandaki varies between 29 ± 4 and 79 ± 11 ka (Baade, 1998 cited in Fort, 2000, p. 107). Hurtado et al. (2001, p. 226) give an estimate age of 33–37 ka for the lowermost section of this formation derived from paleomagnetic analysis. The overall picture, which results from these different interpretations of the glacial history in addition to the authors’ field observation, was used to select key positions for digging soil profiles on moraines of various glacial stages. To assure consistent data the results of Kuhle (1982, 1983) are the main centre of reference as they offer a very clear documentation and the most detailed description of the glacial history including the calculation of ELA depressions. The latter are essential for a high resolution and comparability of the relative chronology of glacial stages. The method of Höfer (1879) was used to calculate the present and former ELA’s: the arithmetic mean of the mean altitude of the catchment area and the altitude of the glacier terminus.

The field description of the soil profiles and the interpretation of the pedophysical and pedochemical analysis of the horizon-wise taken air-dried bulk samples of fine-earth (diameter < 2 mm) are used to characterise the degree of soil formation. If the development conditions are homologous, the relative age of the soils and thus the relative age of the glacial deposits can be

derived. In most cases the small-scale variation of climate, vegetation and geology along the Kali Gandaki area allows the comparison of soils only within the same tributary.

Recorded soil profile field properties are the following: horizon sequence and thickness, bulk density, colour, texture, root penetration and site descriptions like altitude, geographical position, vegetation, moisture penetration, exposition and slope angle. The pH values of the soil samples were determined in 0.01 m CaCl_2 with a soil:solution ratio of 1:2.5. For particle size analysis the soil samples were treated with H_2O_2 to destroy organic matter and with $\text{Na}_4\text{P}_2\text{O}_7$ for dispersion. The coarse and medium sand fraction were determined by wet sieving, the finer fractions by laser analysis (Laser Particle Sizer “analysette 22” ECONOMY, Fritsch GmbH). Diameter limits of the fractions are shown in Figure 7. Organic matter content was measured by loss on ignition at 430 °C (Mehra and Jackson, 1960, p. 159). Total element analysis was carried out by X-ray fluorescence analysis (PW 1480, Philips). Pedogenic iron oxides (Fe_d) were extracted by dithionite-citrate-bicarbonate (DCB) solution (Mehra and Jackson, 1960, modified by Holmgren, 1967; Sparks, 1996). Non or poorly crystallised iron oxides, hydroxides and associated gels (Fe_o) were extracted by acid ammonium oxalate solution (Tamm, 1932; Schwertmann, 1964).

There are several possibilities to quantify the degree of soil weathering by calculating the ratio between unequal

mobile elements using total element contents. Kronberg and Nesbitt (1981) use a combination of two indices, where index A $[(\text{SiO}_2 + \text{CaO} + \text{Na}_2\text{O} + \text{K}_2\text{O})/(\text{Al}_2\text{O}_3 + \text{SiO}_2 + \text{CaO} + \text{Na}_2\text{O} + \text{K}_2\text{O})]$ describes the enrichment of Al (index becomes 0) and Si oxides (index becomes 1), while index B $[(\text{CaO} + \text{Na}_2\text{O} + \text{K}_2\text{O})/(\text{Al}_2\text{O}_3 + \text{CaO} + \text{Na}_2\text{O} + \text{K}_2\text{O})]$ indicates cation leaching (decrease of index B) during weathering. Feng (1997) uses a similar index, but the Ca content is factored out to avoid falsification in carbonate-rich sediments $[(\text{Al}_2\text{O}_3 + \text{Fe}_2\text{O}_3)/(\text{Na}_2\text{O} + \text{K}_2\text{O} + \text{MgO} + \text{P}_2\text{O}_5)]$. During soil development this index increases. A more selective indicator for leaching of the main alkali and alkaline earth cations is described by a decrease of the Parker-Index (Parker, 1970):

$$\text{Parker-Index} = \left(\frac{(\text{Na})_a}{0.35} + \frac{(\text{Mg})_a}{0.9} + \frac{(\text{K})_a}{0.25} + \frac{(\text{Ca})_a}{0.7} \right) \times 100$$

where X_a indicates the atomic proportion of element X, and the numbers in the denominators represent the specific bond strength of each element with oxygen. This bond strength characterises the different susceptibility to weathering for each element.

A decreasing Ca/Mg ratio in the surface horizons during weathering (Ahmad et al., 1977) provides a simple but effective indication.

Displacement in the proportion between different iron formations within the total iron content (Fe_t) is a common indicator for the degree of soil development. During soil ageing silicate-bound iron ($\text{Fe}_t - \text{Fe}_d$) decreases, while pedogenic iron oxides (Fe_d) are composed. Initially poorly crystallised pedogenic iron oxides, hydroxides and associated gels (Fe_o) are built, which are later transformed to crystalline forms ($\text{Fe}_d - \text{Fe}_o$). Alexander (1974) established the so-called Fe ratio (Fe_o/Fe_d) for estimating the age sequence of quaternary deposits. Later on the ratio $\text{Fe}_d - \text{Fe}_o/\text{Fe}_t$ was found to be more useful for pedogenic age differentiation (Arduino et al., 1984, p. 51).

Pedophysically the degree of soil development can be derived from the particle size distribution. During physical and chemical weathering the primary minerals are reduced to smaller pieces resulting in an increase of both the silt and clay fraction at the cost of the sand fraction (Protz, et al., 1984, p. 41). As weathering indicator the fine-clay/clay ratio FC/C (Levine and Ciolkosz, 1983) (fine-clay: below $0.2 \mu\text{m}$), the particle size median ratio $\text{Md}_{\text{sample}}/\text{Md}_{\text{clay}}$ (Langley Turnbaugh and Evans, 1994) and the (sand + silt)/clay ratio (S + Si)/C (Ahmad et al., 1977) are used.

Sudden changes of the vertical distribution of almost immobile elements within a profile may indicate inhomogeneity of the parent material. Common element ratios for testing the homogeneity are Zr/Sr (Evans and Adams, 1975), Ti/Zr (Bäumler et al., 1996a) or Y/Zr (Murad, 1978). Abrupt shifting of the grain size composition within a soil profile offers an alternative possibility to locate the change in sedimentation conditions. The ratio of coarse sand + medium sand to fine sand +

coarse silt $[(\text{CS} + \text{MS})/(\text{FS} + \text{CSi})]$ (Bäumler, 1996a) is used here.

To increase the comparability of different soil profiles, weighted means and the layer with the maximum extent of weathering are determined according to Bäumler (2001, p. 23). Thus the zone of maximum extent of weathering is derived from the maximum of $\text{Fe}_{d-o}/\text{Fe}_t$ within each soil profile. The weighted means are based on the horizon thickness and bulk density.

All the maps presented here as well as all place names are based on the topographical map series Nepal (His Majesty's Government of Nepal, 1994), sheet number 2883/03, 2883/04, 2883/07, 2883/08, 2883/11a, 2883/11b, 2883/11c, 2883/11d, 2883/12.

Areas under investigation

The Lanpoghyun Khola and its tributaries

The Lanpoghyun Khola is an orographic left tributary of the Kali Gandaki right to the north of the Great Himalayan Range (Figure 1). The valley is built up asymmetrically (Photo 1). The orographic right, south-facing slope belongs to the Muktinath Himal and culminates in only 5678 m. The north slope, on the other hand, is partly built by the Nilgiri Himal north face reaching a mean altitude at 6850 m asl with the Nilgiri North as the highest peak (7061 m asl). Therefore, the Nilgiri Himal on its orographic left slope mainly controls the glaciation of this valley. For the complete catchment area Kuhle (1982, p. 31) calculated a mean altitude at 6367 m asl. At present reconstituted glaciers are found along the steep north-facing wall down to 3960 m asl, representing an equilibrium line altitude (ELA) at 5330 m asl (Kuhle, 1982, p. 98). The Nilgiri Himal is composed of grey micritic limestone, gritty dolomite, black shale and limestone, whereas the southern part of the Muktinath Himal is composed of calcareous shale (Godin, 2003, p. 309). At Jomosom near the mouth of the Lanpoghyun Khola the mean annual precipitation is 257 mm (Miehe, 1991, p. 213), but Kuhle (1982, p. 9) assumes much higher values further up-valley. Kuhle (1982), Iwata (1984) and (Fort, 1985) agree that for a long time during the last glacial period a huge lake filled the Kali Gandaki from the mouth of the Chokopani Khola in the south up to Mustang in the north (Figure 1). It is not sure, how far the glaciers from the Lanpoghyun Khola flew into this paleo-lake during the LGM since no clear morphological evidence could be found within the main valley. While Kuhle (1982, p. 31), based on ELA calculations, made it likely that an LGM Lanpoghyun glacier even could have reached the lake damming glaciers of the Chokopani Khola and the Dhaulagiri east slope 9 km south of the Lanpoghyun Khola mouth, Iwata (1984, p. 30) correlates the moraines situated directly at the mouth of the Lanpoghyun Khola with the LGM (his Khingar stadium).

The Chokopani Khola and the Chimán Khola

The Chokopani Khola and the Chimán Khola are neighbouring orographic left tributaries of the Kali Gandaki (Figure 1, Photo 5). Their steep catchment areas are situated at the western flank of the Nilgiri Himal. The Chokopani Khola culminates in the Nilgiri North Peak at 7061 m asl. The mean altitude is 6855 m asl and a glacier terminus at 3785 m asl results in a present ELA at 5320 m asl (Kuhle, 1982, p. 89). Directly north to the Chokopani Khola the Chimán Khola reaches up to 5600 m asl with a mean altitude at 5300 m asl (Kuhle, 1982, p. 87). Geologically both valleys are composed of limestone, dolomitic sandstone, calcareous shale, siltstone, calcareous schist and phyllite (Godin, 2003, p. 309). The annual precipitation at Marpha is 367 mm, while at Lete 1079 mm were detected (Miehe, 1991, p. 213). According to Kuhle (1982) the Chokopani Khola glacier and the Chimán

Khola glacier extended into the Kali Gandaki during the LGM. By the early Late Glacial the Chimán Khola glacier retreated to the valley mouth. The Chokopani Khola glacier left the main valley around the late Late Glacial or early Holocene (Kuhle, 1982, p. 87).

Results and discussion

Results for the Lanpoghyun Khola and its tributaries

Four soil profiles were dug on deposits, which were allocated to four successional glacial stages by Kuhle (1982). The oldest one belongs to a recession stage (● 1,2) following the LGM, while the others represent three late glacial stages (I, II, III). Soil profile 12 is situated at 3140 m asl on a small moraine ridge (Photo 2 ▲, Figure 2) on the orographic left slope close to the valley exit. Its position 460 m above the present

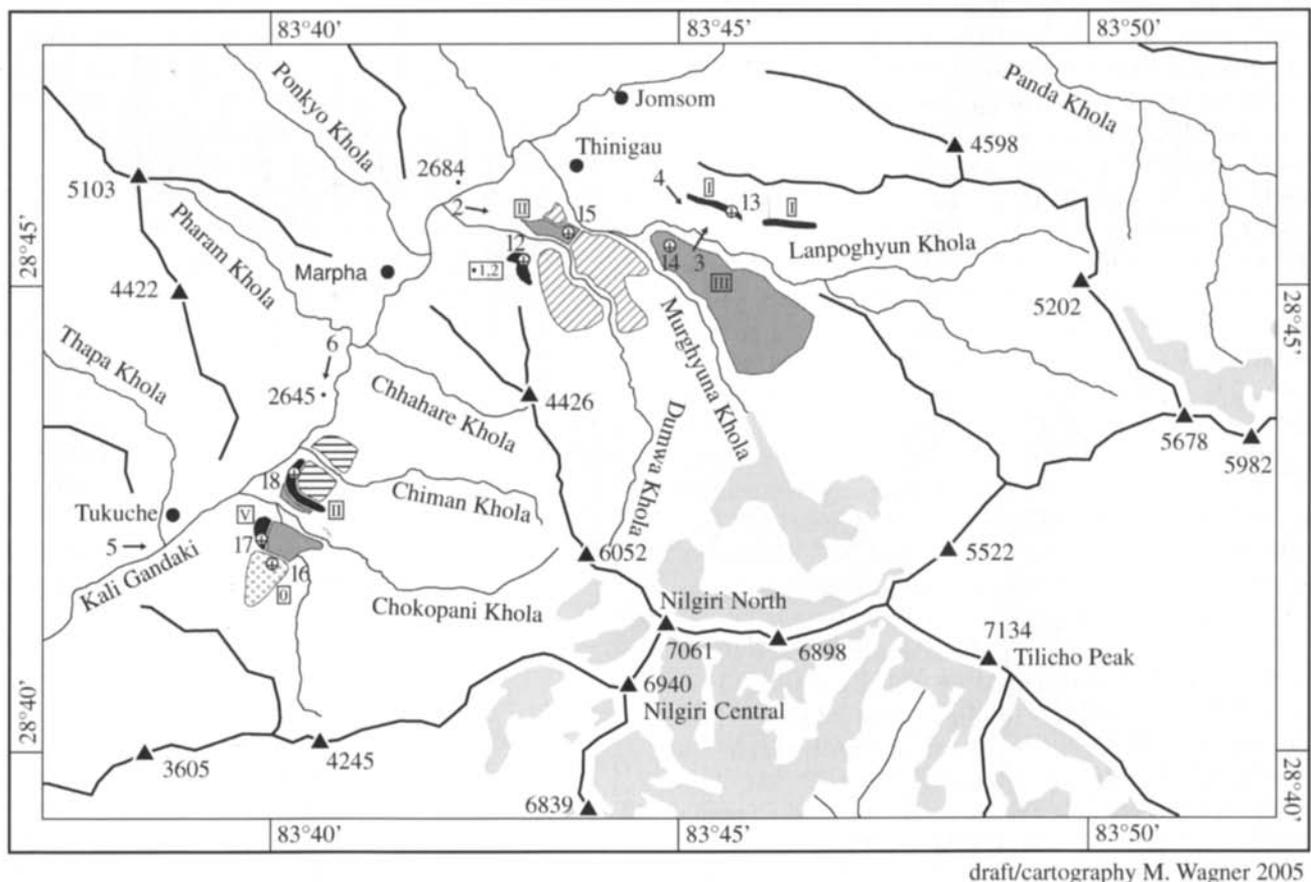


Figure 2. Map showing the relevant glacial and glaciofluvial key forms of the research area. Furthermore, the glacial stages of the moraines according to Kuhle (1982) and the soil profile localities are mapped. The arrows signalise position and line of sight of the photos.

valley bottom allows reconstructing the minimum glacier thickness. Since the ELA depression of a glacier that ends exactly at the mouth of the Lanpoghyun Khola is correlated rather to late glacial stages (Kuhle, 1982, p.31), the moraine must belong to an older stage. Soil profile 13 is located on a lateral moraine (Photo 3 ▲, Photo 4 ▲, Figure 2) at 3520 m asl at the orographic right flank about 4.5 km up-valley from the mouth and 360 m above the present thalweg. Taking into account that the associated glacier had its source mainly at the opposite valley slope, the moraine indicates a complete ice filling at this valley section of at least 360 m. Kuhle, 1982 (p. 31) derived a glacier termination reaching at least 2 km down the main valley (2650 m asl) wherefore a maximum ELA at 4509 m asl results in the classification as oldest late glacial stage (I). Iwata (1984, Figure 1) allocates this moraine to his early last high glacial Khingar stadium. Soil profile 15 is situated on a deposit (Photo 2 ■, Figure 2) of the next younger Taglung stage (II) (glacier termination at 2900 m asl, ELA at 4630 m asl, Kuhle, 1982, p. 96). It is located 1.5 km south of Thinigau next to the western end of a younger fluvial terrace (Photo 2 ◇, Figure 2) at 3040 m asl and 1.5 km up-valley from the mouth. Iwata (1984, p. 33) contrarily describes this accumulation as a fluvial terrace, buried by a 1–2 m thin glacier avalanche induced debris layer. Soil profile 14 at least was dug on top of the huge deposit (Photo 2 □, Photo 4 □, Figure 2) between the Murghyuna Khola and the upper Lanpoghyun Khola at 3440 m asl, 3 km from the valley mouth. Kuhle (1982, p. 97) defined it as a typical podestal ground moraine covered by supraglacial and englacial till belonging to his Late Glacial stage III (glacier termination at 2956 m asl, ELA at 4660 m). Iwata (1984, Figure 1) reconstructed the accumulation as a moraine as well, but he assigned it to the same early high glacial stage like the moraine at soil profile 13. Forests of *Pinus wallichiana* cover profile 12, 14 and 15, whereas a mountain pasture with only widespread single krummholz of *Juniperus indica* covers profile 13.

Concerning the general profile description, profile 12 is classified as skeletal-eutric Cambisol, profile 13 as eutric-haplic Cambisol, profile 14 as skeletal-eutric Regosol and profile 15 as eutric Regosol (Table 2). Comparing the two Cambisols, profile 12 shows a thicker Bw horizon and the boundary to the underlying horizon is clearer. Thus profile 13 might represent a less developed stage of a Cambisol. The Regosol at profile 14 is characterised by an early phase of soil development with only an initial A horizon, while the Regosol at profile 15 shows a well developed A horizon of 20 cm containing almost 6% of organic matter (Table 3). Because of the low thickness of the A horizon at profile 12, it could not be sampled adequately. Within each profile the pH values expectedly decrease with increasing soil depth (Table 3). The texture is characterised mainly by loam with a dominant silt component in profile 12 and 14 and a dominant sand component in the CBw horizon of profile 13 and the topsoil of profile 15

Table 2. Description of the soil profile sites

Profile no.	Subgroup (WRB, 1998)	Altitude [m]	Geographical position	Type of accumulation	Vegetation	Moisture penetration	Exposition	Geology of the catchment area	Glacial stage (Kuhle, 1982)
12	skeletal-eutric Cambisol	3140	83°42'49" E, 28°45'12" N	orographic left lateral moraine near valley exit, 460 m above the valley floor	coniferous forest	Medium	25° N	limestone, dolomite, shale	pre-ghasa-stadium
13	eutric-haplic Cambisol	3520	83°45'46" E, 28°45'36" N	orographic right lateral moraine, 360 m above the valley floor	mountain pasture	High	22° NNE	limestone, dolomite, shale	ghasa-stadium
14	skeletal-eutric Regosol	3440	83°45'27" E, 28°45'05" N	podestal ground moraine covered by supraglacial and englacial till	coniferous forest	Medium	9° NW	limestone, dolomite, shale	dhampu-stadium
15	eutric Regosol	3040	83°44'08" E, 28°45'24" N	ground moraine covered by supraglacial and englacial till	coniferous forest	High	5° NNW	limestone, dolomite, shale	taglung-stadium
16	eutric Cambisol	3165	83°39'54" E, 28°41'58" N	orographic left lateral moraine terrace, 525 m above the valley floor	coniferous forest	High	12° N	schist, phyllite, limestone, dolomite, shale	würmian (LGM)
17	skeletal-eutric Regosol	2900	83°39'55" E, 28°42'25" N	orographic left lateral/terminal moraine ridge, 260 m above the valley floor	coniferous forest	High	25° N	schist, phyllite, limestone, dolomite, shale	nauri-stadium
18	haplic Cambisol	2815	83°40'17" E, 28°43'00" N	lateral/terminal moraine at the valley mouth of the Chiman Khola, 215 m above the valley floor	coniferous forest	High	8° W	schist, phyllite, limestone, dolomite, shale	taglung-stadium

Table 3. Horizon-specifications and homogeneity indices of the soil profiles

Horizon	Depth [cm]	Bulk density [g cm ⁻³]	Colour	Coarse grain size fraction [%]	Clay, silt, sand [%]	Root penetration	pH (CaCl ₂)	Loss on ignition [%]	Zr/Sr *10	Ti/Zr	Y/Zr *100	(CS+MS)/(FS+CSI)
profile 12, skeletal-eutric Cambisol												
A	0-5											
Bw	5-30	1.65	10 YR 4/4 (6)	55	8.73, 51.62, 39.65	medium	7.00	4.08	25.36	37.88	10.88	0.36
2BC	30-70	1.35	10 YR 5/3	55	10.79, 55.68, 33.53	medium	7.14	3.76	4.03	47.43	12.34	0.93
2Cw	70+	1.3	10 YR 5/3	75+		low						
profile 13, eutric-haplic Cambisol												
A	0-15	1.3	10 YR 2/3	20	10.54, 42.47, 46.99	medium	7.08	4.77	8.49	42.88	11.30	0.30
Bw	15-25	1.5	2.5 Y 3/3	20	8.86, 45.61, 45.52	low	7.30	2.39	7.67	47.30	12.02	0.51
CBw	25-70	1.8	2.5 Y 4/4	15	5.80, 41.70, 52.50	low	7.39	1.72	5.44	55.18	13.43	0.57
Cw	70-100+	1.8	2.5 Y 5/4	20		low						
profile 14, skeletal-eutric Regosol												
A	0-5	1.1	2.5 Y 5/2	40	7.00, 58.88, 34.13	medium	7.10	1.70	2.87	46.88	11.98	0.82
Cw	5-70+	1.1	2.5 Y 6/2	75+	6.98, 50.56, 42.46	low	7.38	0.00	2.34	52.01	12.17	1.39
profile 15, eutric Regosol												
A	0-20	1.45	10 YR 3/3	30	5.36, 38.08, 56.56	low/medium	6.94	5.96	5.71	39.35	9.19	0.64
Cw	20-50+	1.2	2.5 Y 4/2	75+	8.30, 48.40, 43.30	very low	7.25	0.95	3.32	48.73	13.77	1.27
profile 16, eutric Cambisol												
A	0-20	1.35	10 YR 3/2	25	6.29, 59.19, 34.52	medium	7.05	5.65	17.97	35.69	9.33	0.21
2Bw	20-70	1.5	2.5 Y 4/4	30	3.64, 42.47, 53.89	low	7.29	1.12	3.44	52.47	17.57	0.57
2BC	70-90	1.6	2.5 Y 4/4	55	3.15, 37.96, 58.89	low	7.35	0.74	2.86	51.61	17.23	0.73
2Cw	90+	1.5	2.5 Y 4/4	75+		low						
profile 17, Skeletic-eutric Regosol												
A	0-20	1.2	10 YR 4/3	35	2.63, 29.66, 67.71	medium	7.14	2.89	2.85	41.99	12.17	0.92
Cw	20-70+	1.1	2.5 Y 4/6	50	1.09, 25.28, 73.63	medium	7.33	0.63	3.28	39.05	13.63	0.87
profile 18, typic Cambisol												
A	0-30	1.5	10 YR 3/3	10	6.72, 34.96, 58.33	medium	7.27	5.41	17.63	24.61	7.09	0.21
Bw	30-60	1.3	7.5 YR 4/4	25	8.88, 63.87, 27.25	medium	7.33	3.94	22.39	32.31	9.11	0.15
CBw	60-110	1.8	10 YR 3/4	40	10.92, 55.30, 33.78	low	7.42	2.38	11.37	28.17	7.65	0.23
Cw	110+	1.8	10 YR 4/4	55		low						

(Table 3). Except for the Zr/Sr ratio at profile 12 the chemical indices for homogeneity do not show abrupt changes within the profiles (Table 3). The texture based homogeneity index bears to these results. The higher proportion of fine sand and coarse silt in the upper 30 cm of profile 12 in combination with the clear break in the Zr/Sr ratio might be an indicator for a loess layer on top of the profile (Table 3).

Since the inhomogeneity of profile 12 might give rise to unrealistic mean profile values, the following results for the chemical and textural development indices (Table 4) are focusing on the zone of maximum extent of weathering. In addition the results for profile 12 are presented inclusive and exclusive the loess based topsoil. Agreeing with the field properties of the profiles, the total element based indices in consideration of the aeolian material generally reflect a graduation of soil development that approve the relative chronology given by Kuhle (1982) very well. The weathering index according to Kronberg and Nesbitt (1981) shows a clear decrease in its index B from the youngest to the oldest soils from 0.90 to 0.63 describing the cation leaching (Figure 3). According to the carbonate-rich parent material, the index of Feng (1997), factoring out Ca, was also calculated. The results are in accordance with the indices shown before, but profile 14 and 15 can be separated more clearly (Table 4, Figure 3). Decreasing

values for the index according to Parker (1970) approve the increasing soil development from profile 14 to 15, 13 and 12 as well (Figure 3). The Ca/Mg ratio within the topsoil expectedly decrease continuously with increasing soil development from 18.35 down to 10.50. If the loess layer is excluded, profile 12 drops from highest degree of weathering to one of the lowest, indicated by the indices of Kronberg and Nesbitt (1981) and Parker (1970) (Figure 3). Using the index of Feng (1997), it drops more slightly reflecting the second highest degree of weathering (Figure 3).

In consideration of the loess layer the increase of crystalline pedogenic Fe oxides during soil development is clearly arising in an increase of the Fe_{d-o}/Fe_t ratio from 0.03 and 0.12 in profile 14 and 15, to 0.34 and 0.45 in profile 13 and 12 (Figure 4). The time-dependent transformation of amorphous Fe_o into well-crystallised Fe_{d-o} is mirrored by the decrease in Fe_o/Fe_d from 0.91 and 0.61 in profile 14 and 15 to 0.15 and 0.10 in profile 13 and 12 (Figure 4). If the aeolian material is factored out, profile 12 gets approved as strongest weathered soil, but the difference to the next younger profile 13 is less obvious. In contrast to the total element based weathering indices, the pedogenetic Fe oxides reflect a strong degree of development within both the aeolian and the morainic material of profile 12 (Table 4).

Table 4. Analytic data and indices of soil development of the sampled soil horizons

horizon	Kronberg and Nesbitt (1981) ^a		Feng (1997) ^b	Ca/Mg	Parker-Index (1970)	Fe_t (g/kg)	Fe_d (g/kg)	Fe_o (g/kg)	Fe_o/Fe_d	Fe_{d-o}/Fe_t	(sand + silt)/clay	fine-clay/clay (%)	Md_{sample}/Md_{clay}
	Index A	Index B											
profile 12, skeletic-eutric Cambisol													
Bw	0.90	0.63	3.47	10.50	58.72	32.46	16.14	1.69	0.10	0.45	10.46	1.70	0.55
2BC	0.94	0.90	2.70	37.43	105.21	14.90	6.34	0.88	0.14	0.37	8.27	0.82	0.65
profile 13, eutric-haplic Cambisol													
A	0.92	0.76	2.95	12.99	68.81	26.44	11.07	2.76	0.25	0.31	8.49	1.13	0.48
Bw	0.91	0.77	3.16	15.04	76.01	29.24	11.63	1.69	0.15	0.34	10.28	1.00	0.50
CBw	0.91	0.78	3.30	14.80	77.65	30.78	9.51	1.24	0.13	0.27	16.25	0.86	0.43
profile 14, skeletic-eutric Regosol													
A	0.94	0.90	1.86	18.35	106.06	15.25	5.64	5.12	0.91	0.03	13.29	0.88	0.59
Cw	0.94	0.91	1.84	19.13	109.71	15.32	5.58	5.12	0.92	0.03	13.32	0.94	0.54
Profile 15, eutric Regosol													
A	0.93	0.85	2.47	17.10	82.19	20.43	6.38	3.91	0.61	0.12	17.66	0.89	0.40
Cw	0.93	0.88	2.28	17.49	99.21	19.94	6.51	6.75	1.04	-0.012	11.05	0.61	0.55
profile 16, eutric Cambisol													
A	0.92	0.66	2.44	6.73	59.64	23.29	13.95	5.29	0.38	0.37	14.89	1.58	0.55
2Bw	0.93	0.85	2.75	23.35	94.60	26.02	15.58	4.07	0.26	0.44	26.46	1.24	0.42
2BC	0.94	0.88	2.60	24.91	101.65	24.90	14.44	3.22	0.22	0.45	30.76	1.40	0.38
profile 17, skeletic-eutric Regosol													
A	0.95	0.92	2.23	28.08	105.03	15.46	6.53	1.67	0.25	0.31	36.97	0.71	0.33
Cw	0.95	0.91	2.29	24.82	102.08	16.16	7.50	2.53	0.34	0.31	90.87	1.69	0.31
profile 18, typic Cambisol													
A	0.94	0.78	3.03	16.38	60.08	22.18	8.93	3.06	0.34	0.26	13.89	0.65	0.41
Bw	0.92	0.71	3.15	12.88	63.10	27.77	13.91	3.16	0.23	0.39	10.27	1.10	0.65
CBw	0.93	0.83	2.97	19.38	80.32	23.71	9.93	2.57	0.26	0.31	8.16	1.32	0.61

^a Index A: $(SiO_2 + CaO + Na_2O + K_2O)/(Al_2O_3 + SiO_2 + CaO + Na_2O + K_2O)$; Index B: $(CaO + Na_2O + K_2O)/(Al_2O_3 + CaO + Na_2O + K_2O)$.

^b $(Al_2O_3 + Fe_2O_3)/(Na_2O + K_2O + MgO + P_2O_5)$.

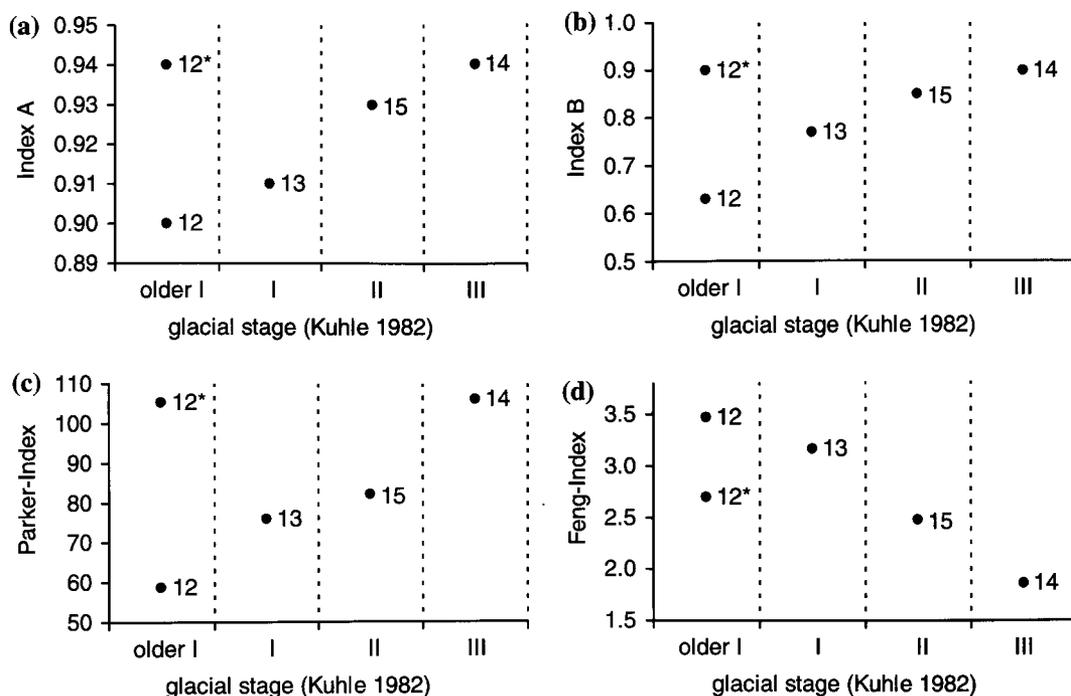


Figure 3. Results of pedochemical weathering indices for soil profile no. 12, 13, 14 and 15 from the Lanpoghyun Khola in relation to the glacial stages according to Kuhle (1982). The results belong to the zone of maximum extent of weathering. In case of 12* the aeolian layer is excluded. Diagram a and b show Index A and B according to Kronberg and Nesbitt (1981). Diagram c shows the index according to Parker (1970). Diagram d shows the index according to Feng (1997).

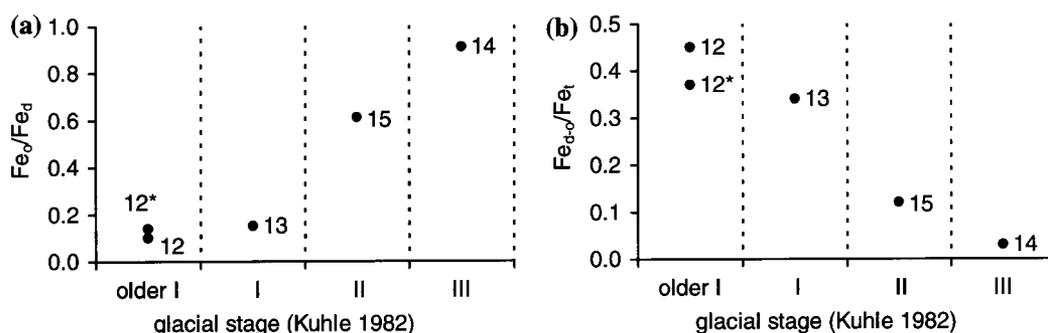


Figure 4. Results of weathering indices based on pedogenic iron oxides for profile 12, 13, 14 and 15 from the Lanpoghyun Khola in relation to the glacial stages according to Kuhle (1982). The results belong to the zone of maximum extent of weathering. In case of 12* the aeolian layer is excluded. In diagram a the ratio of well-crystallised pedogenic iron oxide to the total pedogenic iron oxide is shown (Fe_o/Fe_d). In diagram b the ratio of poorly crystallised pedogenic iron oxides to well-crystallised pedogenic iron oxides is shown (Fe_{d-o}/Fe_t).

The texture indices are less appropriate for detecting the degree of soil development within the Lanpoghyun Khola. The parent material dependent dominance of sand in profile 13 and 15 and silt in profile 12 and 14 (Table 3) superposes the weathering dependent reduction of the grain size diameters. Therefore, the median ratio Md_{sample}/Md_{clay} does not reveal any weathering trend (Figure 5). The $(S+Si)/C$ ratio and the FC/C ratio (Figure 5) allow to differentiate correctly between the older (12, 13) and the younger profiles (14, 15), if the aeolian layer is included. For the FC/C ratio this is not true, if the aeolian layer is excluded. Similar to most of the total element based indices, the FC/C ratio indicates the lowest degree of weathering for the morainic material at profile 12 (0.82), while the loess layer indicates the strongest development (1.70) (Table 4).

Discussion for the Lanpoghyun Khola and its tributaries

In contradiction to Kuhle (1982), Iwata (1984) and (Fort, 1985) did not calculate ELA depressions to reconstruct a chronology of the glacial glacier extension. According to their state of preservation, the moraines are classified into one holocene stage, two last glacial stages and one pre-last glacial stage. This classification does not allow differentiating between the deposits, where the soil profiles are located. Furthermore Iwata (1984) as well as (Fort, 1985) reconstruct a minor high glacial glacier extension for the Lanpoghyun Khola in relation to Kuhle (1982). The narrowness of the High Himalaya causing a small glacier accumulation area is given as main reason for this by Fort (2000, p. 114). The narrowness of the catchment area needs to be considered more detailed. Above 4600 m asl the orographic left

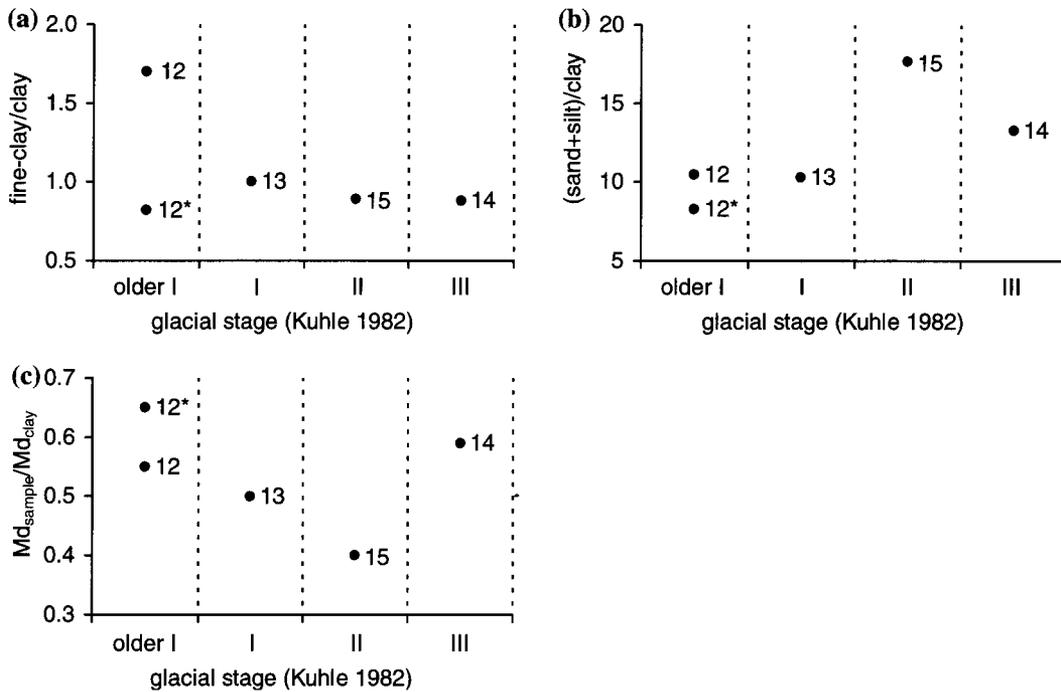


Figure 5. Results of the weathering indices based on particle size distribution for profile 12, 13, 14 and 15 from the Lanpoghyun Khola in relation to the glacial stages according to Kuhle (1982). The results belong to the zone of maximum extent of weathering. In case of 12* the aeolian layer is excluded. In diagram a the ratio fine-clay/clay is shown. In diagram b the ratio (sand + silt)/clay is shown. In diagram c the ratio of the sample-based median to the median of poor clay is shown (Md_{sample}/Md_{clay}).

slope of the Lanpoghyun Khola is very steep, while the inclination below 4600 m asl is getting more and more gently. At present the ELA is situated in the steep part of the valley flank resulting in an accordingly small accumulation area (Figure 6). But for the late glacial lateral moraine at the opposite slope (soil profile 13,

Photo 4 ▲) an ELA at 4509 m asl can be calculated (Kuhle, 1982, p. 96). Further on the high position of this moraine above the valley bottom demonstrates a complete ice filling of the valley of more than 360 m further up-valley. This glacier surface additionally expanded the accumulation area (cf. König, 1999, p. 375, 2002,

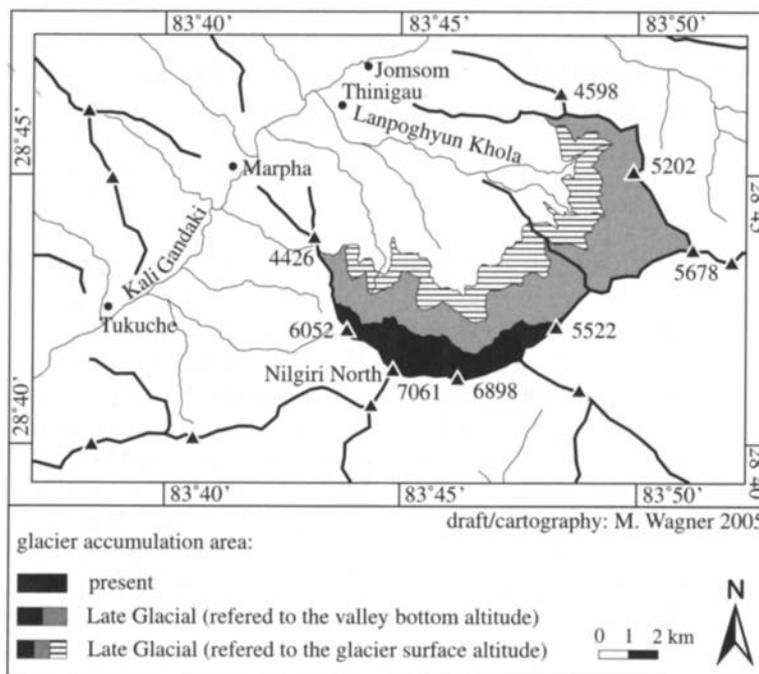


Figure 6. Effect of ELA depression on the dimension of the glacier accumulation area (AA) within the Lanpoghyun Khola. At present an ELA at 5330 m asl results in the black coloured AA. The grey coloured area shows the expansion of the AA for the Late Glacial, if an ELA of 4510 m asl is assumed (Kuhle, 1982, p. 96). The late glacial altitude level of the valley surface was increased by at least 360 m because of the thickness of the overlying glacier itself. This results in a further expansion of the AA represented by the line-textured area.

p. 134). As a result, the accumulation area of this past glacier was distinctly increased in relation to the present (Figure 6). According to the questionable reasons for a lower high glacial glacier extension in the Lanpoghyun Khola, the chronological order given by Kuhle (1982) seems to be more likely. Comparatively low ELA depressions might be the consequence of a to low calculated present ELA resulting from the reconstititional character of the present glacier. The lack of bigger boulders within the parent material of profile 13 does not contradict to its interpretation as lateral moraine. The dominance of sand (52.50%) and the low portion of clay (5.80%) (Figure 7) interdict aeolian or limnic origin, while the low degree of sorting ($S_o = 4.04$) of the fine-earth excludes fluvial transport (cf. Müller, 1964, p. 103; Kuhle, 2001).

At profile 12 the Zr/Sr ratio and the $(CS+MS)/(FS+CSi)$ ratio (Table 3) made it likely that the moraine was covered by an aeolian layer of at least 30 cm. Such a deposition attends plausible from a topographical and climatological point of view. Profile 12 is already situated in the sphere of the dry Kali Gandaki, where strong diurnal valley winds depending on the transitional valley characteristic are causing strong sandstorms at present (Egger et al., 1998).

Derived from the field properties, the soils could already be divided into the stronger developed Cambisols at profiles 12 and 13 and the less developed Regosols at profiles 14 and 15. This distinct graduation got approved clearly by all chemistry based weathering indices as well as the $(S+Si)/C$ and FC/C ratio considering the loess based topsoil of profile 12. Furthermore these analytic development indices (except for $(S+Si)/C$) were appropriate to distinguish within the Cambisols and Regosols. The derived relative succession of soil development agrees with the reconstructed chronological order of deposition of the parent material given by Kuhle (1982). The pH value as well as the proportion of organic matter did not show any accordance with the degree of soil development and thus they are inappli-

cable as weathering indices. Similar conclusions can be found in Markewich et al. (1989, p. D12) and Walker and Green (1976, p. 298).

Within the moraine based 2BC horizon of profile 12 the different weathering indices show inconsistent results. Expectedly the pedogenic iron oxides signalise the strongest weathering besides the Bw horizon of profile 12, while the total element based indices show a weak development which is closer related to the younger soils at profile 14 and 15. Because this phenomenon is limited to the morainic material at profile 12, a change in the lithological composition of the till within the Lanpoghyun Khola might be the reason. This lithological change is effected by the glacial stage dependent changing amount of ELA depression, resulting in changing accumulation areas of the glaciers (cf. Bäumler, 2001, p. 37) (Figure 6). Since Fe_o/Fe_d and Fe_{d-o}/Fe_t are limited to pedological referred adjustments within Fe_t , these ratios are independent from a change in lithology and supposed to deliver more realistic results for the degree of weathering within profile 12 as the other indices (cf. Arduino et al., 1984, p. 51; Bäumler et al., 1996a, p. 69). The FC/C ratio should also be independent from the lithology, since the fine clay fraction mostly results from pedological clay creation and recreation (Levine and Ciolkosz, 1983, p. 93). But the high difference of the values within profile 12 disagrees to this assumption (Figure 5). Derived from the pedogenic Fe oxides the moraine based 2BC horizon of profile 12 is only slightly less weathered than the overlying loess based Bw horizon. Most likely the soil development of the entire profile (12) results out of *in situ* weathering and hence its degree of weathering is suitable for relative dating of the underlying moraine.

Contrary to the relative chronological order derived from the degree of soil development, the absolute graduation of soil development does not always fit to the geomorphological derived classification according to Kuhle (1982). Taking into account the carbonate-rich parent material and the low amount of precipitation, the absolute degree of soil weathering allows it to assign profile 13, agreeing with Kuhle (1982), to the Late Glacial (cf. Ahmad et al., 1977). Though profile 12 is stronger weathered than profile 13, a classification as late High Glacial is not constraining from a pedogenetical point of view. But Semmel (1989, p. 156) emphasised that late glacial soils might be pre-weathered and thus being developed similar like high glacial soils. An indicator for a high glacial age of profile 12 can also be found at Alonso, et al. (1994, p. 305) who describe a negative correlation of soil development and soil age. The soils at profile 14 and 15, situated on moraines of the middle Late Glacial, are characterised by a distinctly lower degree of development. The reason for this might be found in the particularly short distance variation of the precipitation amounts within the valley cross section (Meurer, 1984). According to the diurnal valley wind system, convective cloudiness at the valley slopes causes a strong upslope precipitation gradient. In the Kali

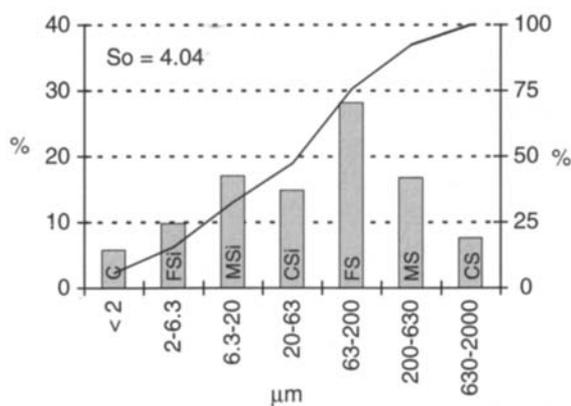


Figure 7. Grain size distribution (percent and cumulative percent) of the fine-earth in the CBw horizon of soil profile 13. The profile is situated at an orographic right late glacial lateral moraine in the Lanpoghyun Khola. The degree of sorting (S_o) is low according to Müller (1964, p. 103) and Kuhle (2001).

Gandaki Meurer (1984, p. 194) detected an increase of precipitation from about 320 mm at the valley bottom at 2485 m asl up to about 850 mm at 4160 m asl. Therefrom the soil profiles 12 and 13, which are located 420 and 360 m upslope the valley bottom, receive much more precipitation than profile 14 and 15, which are situated almost in the centre of the valley cross section (Photo 2). Another reason for a minor soil development on the deposits of profile 14 and 15 arises from their characteristic as bouldery ablation till. Gellatly et al. (1985, p. 272) estimated a delay in the establishment of soil of more than 500 years for such moraines. The lower soil development might also be a consequence of post-glacial mass movement events causing an overlay of the morainic deposits on the valley bottom. Regarding Iwata (1984) such an overlay of a glacier avalanche induced debris layer cannot be ruled out for profile 15. But the isolated position of the moraine at profile 14 clearly separated from the valley flanks by deep incised river beds (Photo 2□) exclude the possibility of a post glacial overlay. Accordingly neither Kuhle (1982) nor Iwata (1984) found any evidence for such a young overlay. Erosion processes are supposed to be marginal because the limestone causes a high consolidation of the deposits (Iwata, 1984, p. 34).

Results for the Chokopani Khola and the Chimán Khola

Because of the steepness and inaccessibility of the upper parts of the tributaries, the soil profiles were dug around the estuaries. Three profiles were excavated, which are located on moraines assigned by Kuhle (1982) to the LGM (stage 0), the Late Glacial (stage II) and the early Holocene (stage V). Profile 16 is located on an orographic left lateral moraine terrace (Photo 6 ▲, Figure 2) of the Chokopani Khola glacier at 3165 m asl, about 1 km up-valley from the mouth, 525 m above the present valley bottom and 290 m above a ground moraine (Photo 5 ■, Figure 2) preserved at the valley bottom (Kuhle, 1982, p. 43). The high glacial age of the lateral moraine is estimated from the reconstructed glacier thickness of 290 m. Iwata (1984, p. 27) characterises the deposit as alluvial fan, but the almost upright front of the accumulation is inconsistent with this interpretation. It therefore appears reasonably to classify the deposit as a combination of a lateral moraine with a kame accumulation as described in Kuhle (1991, p. 150). Iturrizaga (2001, p. 403) calls this kind of kame accumulation came cone, since the supply area is a tributary of the glaciated valley. Profile 18 is situated on the orographic left lateral/terminal moraine (Photo 5 ●, Photo 6 ●, Figure 2) of the Chimán Khola glacier at 2815 m asl close to the valley mouth and 215 m above the thalweg (Kuhle, 1982, p. 88). The related tongue basin (Photo 6◇, Figure 2) is well preserved, while the orographic right part of the terminal moraine is eroded completely. Kuhle (1982, p. 88) assigned the moraine to his late glacial Taglung Stage (II, glacier termination at 2635 m asl, ELA at 3970 m asl). Iwata (1984, p. 27) on the other

hand mapped the assumed moraine and tongue basin as high glacial and late glacial river terraces. According to the spatial distribution of the deposits the interpretation as glacial accumulation is more probable. The mixture of diamicitic and limnic sediments within the terminal moraine indicates that the Late Glacial glacier advanced into a lake, which still existed within the Kali Gandaki. Profile 17 is located at 2900 m asl on a small terminal moraine (Photo 6 ○, Figure 2) of the Chokopani Khola glacier directly below the moraine on which profile 16 is situated. Kuhle (1982, p. 89) classified the moraine to his early neoglacial Nauri Stage (V, glacier termination at 2804 m asl, ELA at 4830 m asl). Forests of *Pinus wallichiana*, *Picea smithiana*, *Cupressus torulosa* and *Juniperus indica* cover all three profile sites.

Profile 16 and 18 are classified as eutric Cambisol and haplic Cambisol, whereas the clearly less developed profile 17 is classified as skeletic-eutric Regosol (Table 2). According to the field properties a further differentiation between the Cambisols is not possible. Similar to the soils in the Lanpoghyun Khola the pH values and the portion of organic matter in all profiles show a typical positive and respectively negative correlation with soil depth, but do not allow any statement about the degree of soil development (Table 3). The loamy texture is sand dominated in profile 17, the subsoil of profile 16 and the topsoil of profile 18, while the silt class dominates in the topsoil of profile 16 and the subsoil of profile 18 (Table 3). The homogeneity indices (Table 3) do not show clear breaks within the profiles, except for profile 16. The Zr/Sr ratio as well as the Ti/Zr and Y/Zr ratio indicates a change in the parent material below the A-horizon. In agreement with soil profile 12, the low (CS + MS)/(FS + CSi) ratio alludes to a loess layer at the topsoil of profile 16.

In respect to the inhomogeneity of profile 16 the results of the chemical and textural weathering indices are related to the horizon of maximum extent of weathering again. The low development of soil profile 17 in relation to the strong weathered profile 18 is reflected clearly in all total element based weathering indices (Table 4, Figure 8). According to the pedogenic Fe oxides the results also approve a lower developed profile 17 in relation to profile 18, but the difference is less pronounced (Figure 9). The Fe_o/Fe_d ratio is similar in both profiles (0.25 and 0.23), but it shows high amplitudes within each profile (Table 4). Because of the textural variation of the parent material between and even within the profiles, the texture based weathering indices are not very meaningful, though they mostly show a correct trend between the profiles 17 and 18 (Figure 10). The dominating influence of the parent material gets apparent in the (S + Si)/C ratio, where the values at the Cw horizon of profile 17 and the CBw horizon of profile 18 show an extreme range between 90.87 and 8.16 (Table 4). The FC/C ratio, which should be independent from the general grain size distribution, shows a correct increase from 0.71 in profile 17 to 1.10 in profile 18. But it needs to be considered that within profile 17 the lowest

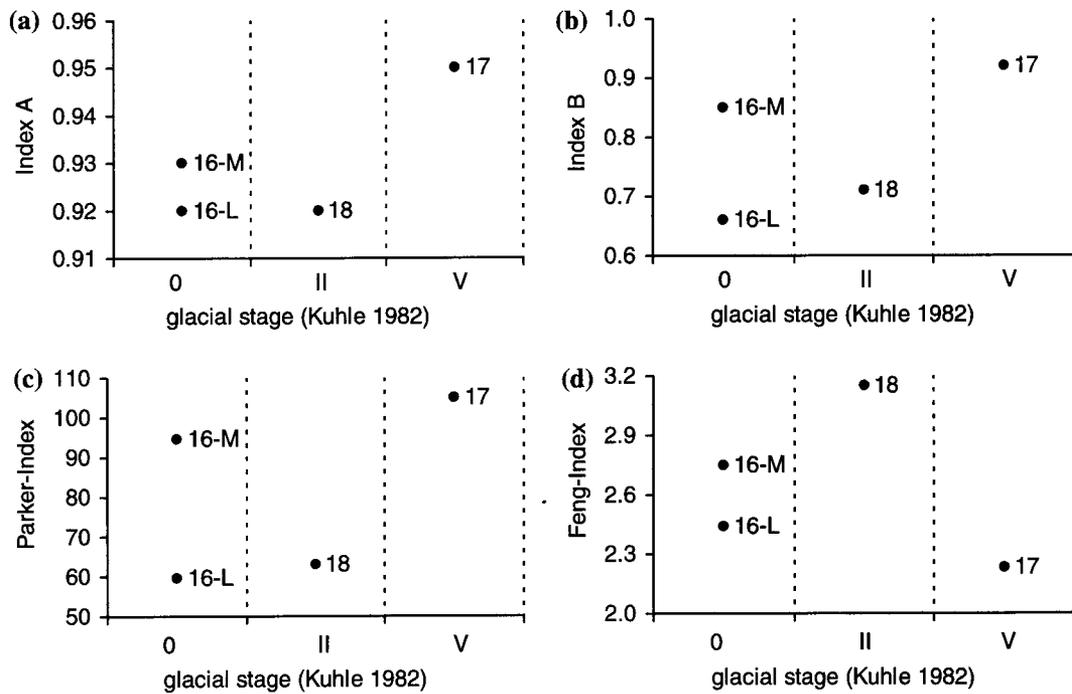


Figure 8. Results of pedochemical weathering indices for soil profile no. 16, 17 and 18 from the Chokopani Khola and Chimani Khola in relation to the glacial stages according to Kuhle (1982). The results belong to the zone of maximum extent of weathering. In the case of 16M the results are limited to the morainic subsoil of profile 16; 16L represents the loess-based topsoil of profile 16. Diagram a and b show Index A and B according to Kronberg and Nesbitt (1981). Diagram c shows the index according to Parker (1970). Diagram d shows the index according to Feng (1997).

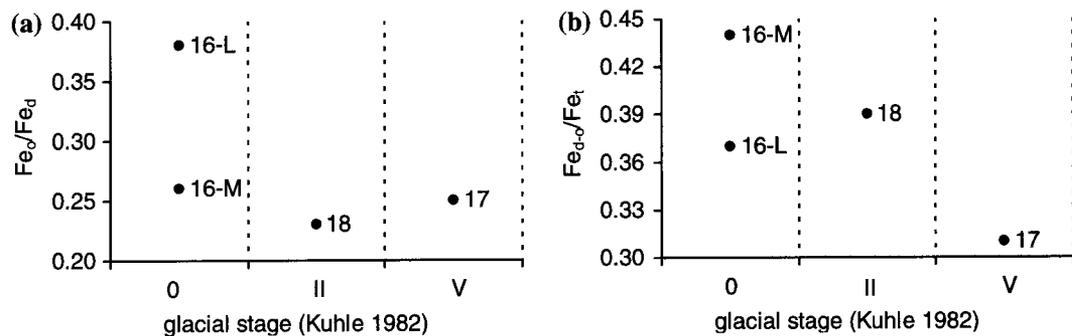


Figure 9. Results of weathering indices based on pedogenic iron oxides for soil profile no. 16, 17 and 18 from the Chokopani Khola and Chimani Khola in relation to the glacial stages according to Kuhle (1982). The results belong to the zone of maximum extent of weathering. In the case of 16M the results are limited to the morainic subsoil of profile 16; 16L represents the loess-based topsoil of profile 16. In diagram a the ratio of well-crystallised pedogenic iron oxide to the total pedogenic iron oxide is shown (Fe_o/Fe_d). In diagram b the ratio of poorly crystallised pedogenic iron oxides to well-crystallised pedogenic iron oxides is shown (Fe_{d-o}/Fe_t).

and the highest FC/C ratio of all three profiles are contained (0.71 and 1.69) (Table 4). The extreme difference follows the very low clay content at profile 17, as the values for the FC/fine-earth ratio are almost equal within the profile (0.0187% and 0.0184%).

The analytical results for profile 16 were factored out so far because they show similar antagonisms as described for profile 12 in the Lanpoghyun Khola. For this reason, the results will be described separately for the loess based topsoil and the moraine based subsoil of the profile. In relation to the other profiles, the topsoil of profile 16 is characterised as strongest developed soil according to the indices of Kronberg and Nesbitt (1981) and Parker (1970) (Figure 8), the Fe_{d-o}/Fe_t ratio (Figure 9) and the FC/C ratio (Figure 10). It ranges between profile 17 and 18 according to the total element

based index of Feng (1997) (Figure 8) and the remaining texture based indices (Figure 10). On the other hand, the subsoil is characterised as strongest developed soil according to the iron oxide indices (Figure 9) and the FC/C ratio (Figure 10), while it ranges between profile 17 and 18 according to the other texture based indices (Figure 10) and the total element based indices (Figure 8).

Discussion for the Chokopani Khola and the Chimani Khola

The Chokopani Khola and Chimani Khola are characterised by a constantly steep downhill grade. Therefore, a sudden change in the dimension of the glacier accumulation area as a consequence of a decreasing ELA can

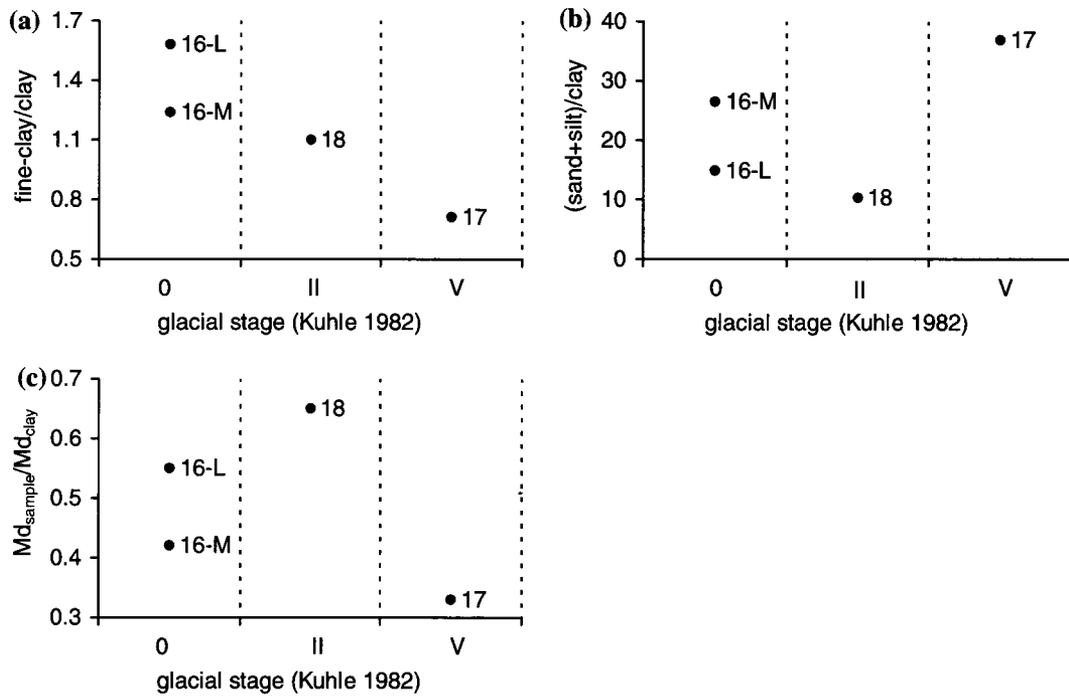


Figure 10. Results of the weathering indices based on particle size distribution for profile no. 16, 17 and 18 from the Chokopani Khola and Chiman Khola in relation to the glacial stages according to Kuhle (1982). The results belong to the zone of maximum extent of weathering. In the case of 16M the results are limited to the morainic subsoil of profile 16; 16L represents the loess-based topsoil of profile 16. In diagram a the ratio of fine-clay/clay is shown. In diagram b the ratio (sand + silt)/clay is shown. In diagram c the ratio of the sample-based median to the median of poor clay is shown (Md_{sample}/Md_{clay}).

be ruled out. Kuhle (1982) as well as Iwata (1984) and Fort (2000) reconstruct a high glacial glacier extending to the Kali Gandaki, but according to Kuhle's research the glacier went further down. None the less Iwata (1984) did not find moraines around the snout of the Chokopani Khola and Chiman Khola. The deposits, which Kuhle (1982) classified as moraines (Figure 2, Photo 6) are assigned as alluvial fan or fluvial terrace by Iwata (1984, p. 27). As mentioned before the spatial distribution and the morphology of the deposits coactively assign them rather as glacial than as fluvial deposits. Therefore, the genetical and chronological classification given by Kuhle (1982) seems to be an appropriate base for pedochronological investigations. Comparatively strong ELA depressions are a result of the very steep catchment area.

In agreement with the chronological classification resulting from the geomorphological approach, the soil field properties as well as the different chemical and textural weathering indices clearly separate the low developed profile 17 from the stronger developed profiles 16 and 18. A further differentiation of the latter is not that distinct since the weathering indices offer contrary results at soil profile 16. One reason can be found in the inhomogeneity of the profile. Since the degree of weathering of the moraine based material is crucial for the relative dating, the results of the loess based topsoil will be factored out. The aeolian overlay should not have caused an interruption of the weathering processes in the underlying morainic horizons due to its low thickness (cf. Bäumler, 2001, p. 102). The Fe oxide

based indices and the FC/C ratio definitely reflect a stronger degree of soil development at profile 16 in relation to profile 18. This is in accordance with the geomorphological indications. These indices are less sensitive for changes in the lithological composition (Arduino et al., 1984, p. 37; Bäumler et al., 1996a, p. 69). The contradictory lower degree of weathering at profile 16 indicated by the total element based indices therefore is assumed to be a consequence of changing lithology (cf. profile 12 in the Lanpoghyun Khola). This becomes obvious, if the Ca excluding index of Feng (1997) is compared to the other total element based indices within profile 16 (Table 4). While all other indices signalise a stronger weathering of the loess horizon, the index of Feng (1997) shows a stronger weathering of the moraine based subsoil and hence it suits the Fe oxide indices and the FC/C ratio.

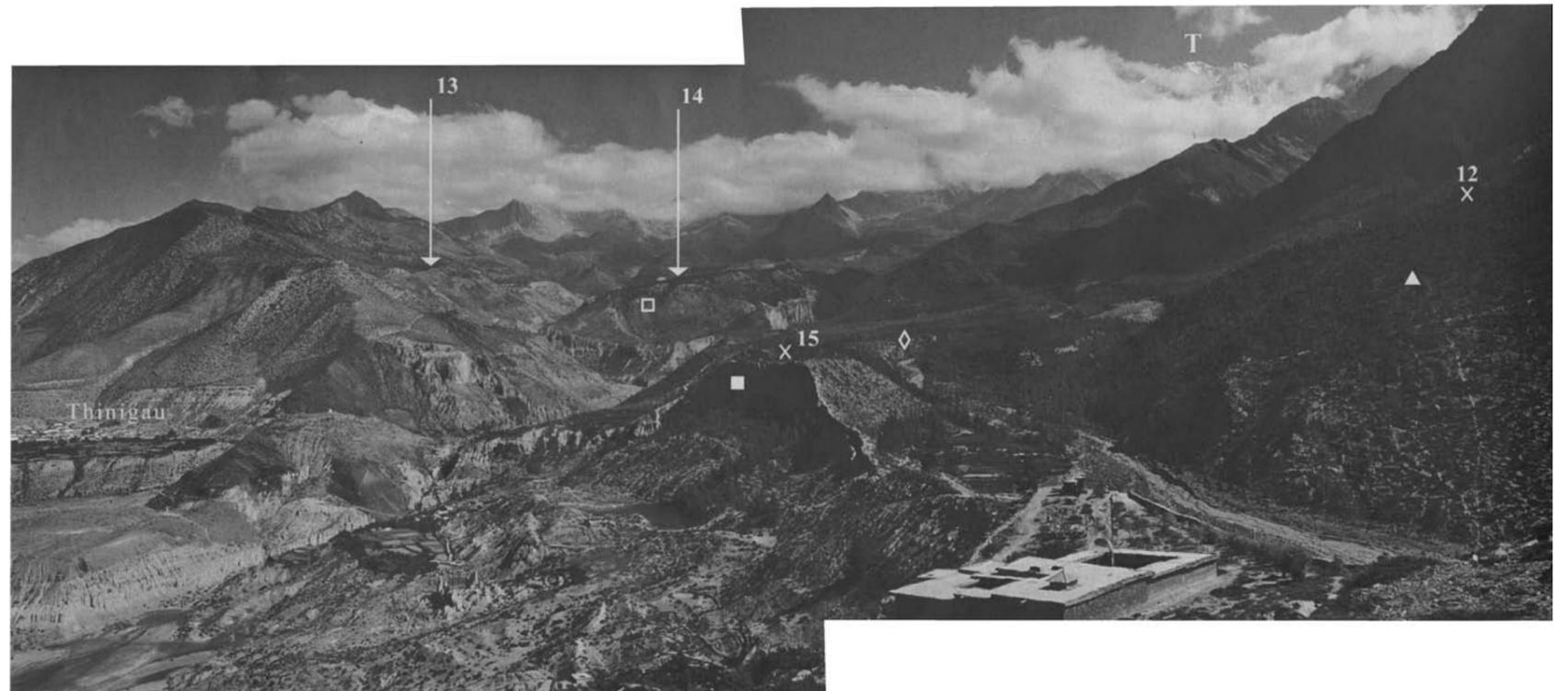
Though the Fe_{d-o}/Fe_t ratio shows the lowest degree of weathering for profile 17, the difference to the older profiles is less distinct than expected. It cannot be ruled out that the deposition is a reaccumulated moraine and the parent material is pre-weathered. The high variability of the Fe_o/Fe_d ratio within the profiles and the low differences between the profiles hampers its significance as weathering index in agreement with Bäumler (2001, p. 19). The unwanted extraction of magnetite or easy weatherable iron minerals might have falsified the results for Fe_o (cf. McKeague et al., 1971, p. 35).

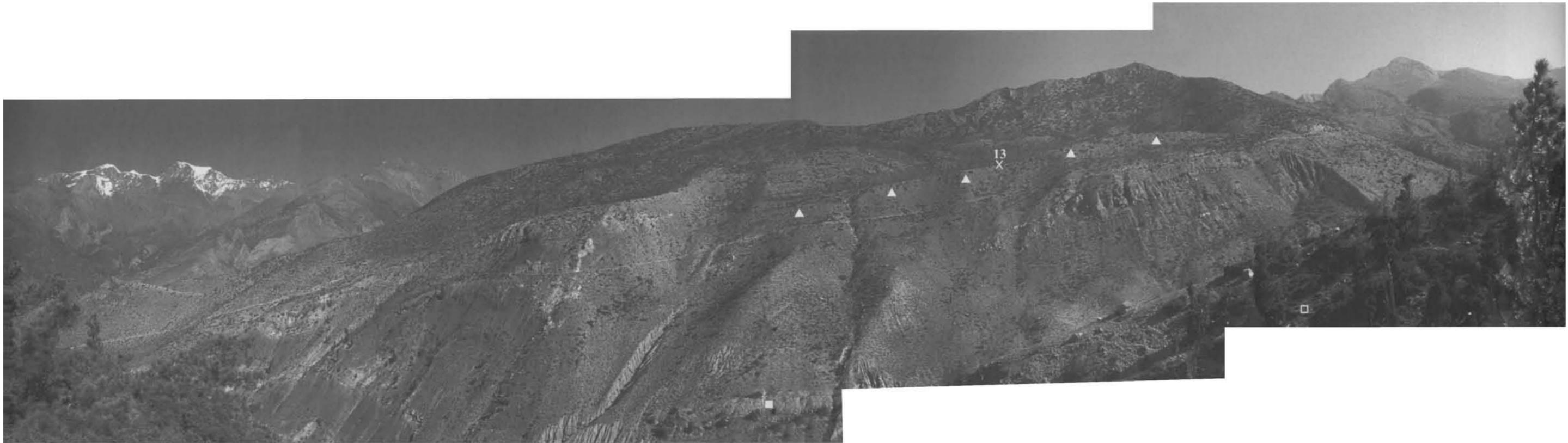
The texture based indices for the profiles in the Chokopani Khola and Chiman Khola showed that the grain size distribution mostly is an inappropriate indi-



← *Photo 1.* Looking from the Lumbuk Khola at 3520 m asl to the SE towards the Nilgiri Himal north face. It culminates in the Tilicho Peak (T, 7134 m asl) and the Nilgiri North Peak (N, 7061 m asl). Behind↑↑↑ the Lanpoghyun Khola is located. The asymmetrically shape of the valley is getting obvious in this picture (Photo: M. Wagner, 10.10.2001).

→ *Photo 2.* View from the exposed accumulation at the valley mouth up-valley into the Lanpoghyun Khola (at 2940 m asl, 220 m above the valley floor). The position of all soil profiles (X12, ↓ 13, ↓ 14, X15) and of the related moraines (▲, below ↓ 13, □, ■) in this valley can be seen ▲ marks the oldest moraine preserved in this valley (Kuhle, 1982, p. 31). It indicates a glacier-thickness of 420 m near the valley exit. The next younger moraine is a lateral moraine on the orographic right valley flank (below ↓ 13) 360 m above the valley floor (Kuhle, 1982, p. 31). ■ marks ground moraine of the next younger glacial stage (Kuhle, 1982, p. 96). A younger fluvial terrace (◇) behind the moraine is situated at a lower altitude level. The youngest deposit under investigation is a podestal ground moraine (□) (Kuhle, 1982, p. 97). Between the clouds the Tilicho Peak is visible (T, 7134 m asl) (Photo: M. Wagner, 17.10.2001).

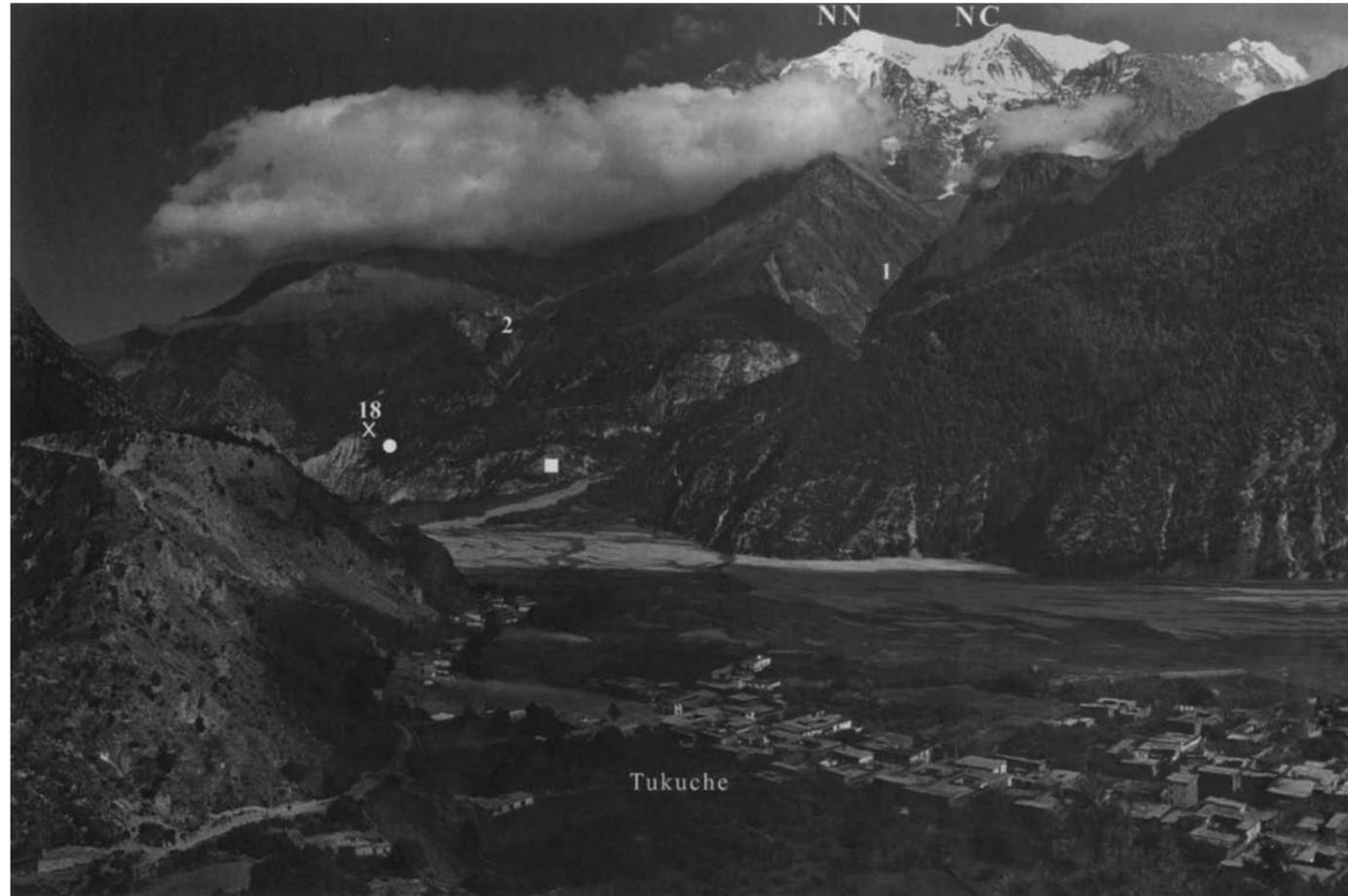




↑ *Photo 3.* The picture was taken from the podestal moraine (□) at profile 14 (3440 m asl, 3 km SE of Thinigau) to the N onto the orographic right flank of the Lanpoghyun Khola. The ridge of the late glacial lateral moraine (above ▲) (Kuhle, 1982, p. 96) at profile 13 (X13) is preserved very well and can be traced for more than 2 km. Down-slope the flank is mantled by morainic material partly combined with lacustrine sediments (■) (Photo: M. Wagner, 16.10.2001).



← *Photo 4.* Looking up-valley to the E-SE from the orographic right slope of the Lanpoghyun Khola 2.8 km E of Thinigau at 3500 m asl. The picture offers a more detailed view on the position of soil profile 13 and 14 (X13, X14) and the related moraines (▲, □) (cf. photo 2; Kuhle, 1982). Above 14 directly below the clouds the present glacier can be seen. Between the clouds the Tilicho Peak is visible (T, 7134 m asl) (Photo: M. Wagner, 15.10.2001).



← *Photo 5.* The steep tributaries Chiman Khola (2) and Chokopani Khola (1) as seen from the orographic right slope of the Kali Gandaki (at 2720 m asl, 0.3 km W of Tukuche) to the W across the river bed. The Chokopani Khola (1) culminates in the Nilgiri North Peak (NN, 7061 m) and the Nilgiri Central Peak (NC, 6940 m). ■ marks the remnant of a ground moraine in the Chokopani Khola (Kuhle, 1982, p. 43). ● marks the outer slope of a terminal moraine of the former Chiman Khola Glacier (Kuhle, 1982, p. 88). At this moraine soil profile 18 is located (X18) (Photo: M. Wagner, 18.10.2001).

→ *Photo 6.* View from the orographic right bank of the Kali Gandaki (at 2640 m asl, 1 km SW of Marpha) across the river bed onto the accumulations at the valley mouth of the orographic left tributaries Chiman Khola (2) and Chokopani Khola (1). The positions of the soil profiles 16, 17, 18 (↓ 16, ↓ 17, X18) and of the related moraines (▲, ○, ●) can be seen. Soil profile 16 (↓ 16) is located on a lateral moraine (▲) (Kuhle, 1982, p. 43) on the orographic left slope of the Chokopani Khola (1). Right below this moraine soil profile 17 (↓ 17) is situated on a small terminal moraine ridge (○) (Kuhle, 1982, p.89). Soil profile 18 (X18) is located on a partly preserved terminal moraine (●) (Kuhle, 1982, p.88) in the mouth of the Chiman Khola (2). A well-preserved corresponding tongue basin filling (◇) approves the classification as terminal moraine (Photo: M. Wagner, 27.09.2001).



cator for the degree of soil development, if these soils are situated on typically inconsistent glacial deposits. Even within a profile that is developed completely in the same parent material a high variability of the chemical composition and grain size distribution can be found (Bäumler, 2001, p. 62). An exception can be made for the lithologically more independent FC/C ratio again. This ratio is applicable especially in older soils, where the content of clay and fine clay is high enough to provide assured results (Levine and Ciolkosz, 1983, p. 93). According to this, the soils in this study contain less amounts of clay and fine clay, but the results are mostly agreeing with the degree of soil development. Only in event of the very low clay contents at profile 17 (Table 4) the application of the results as weathering index is not possible.

Analogue to the cognition at the Lanpoghyun Khola, the pH value and the content of organic matter did not show any correlation with the degree of soil weathering for the profiles at the Chokopani Khola and Chimani Khola.

The absolute chronological classification of the moraine at profile 17 as neoglacial stage seems to be adequate concerning the low degree of soil development. Profile 16 and 18 are distinctly stronger developed and in respect of the semi-arid climatic conditions, the carbonate-rich parent material and the position in an altitudinal belt which is typical for Cambisols (cf. Bäumler et al., 1996a, p. 7), a correlation with the Late Glacial is justifiable. A correlation of profile 16 with the High Glacial is doubtful concerning the slightly stronger soil development, but it cannot be ruled out as mentioned before for profile 12.

Conclusion

To review the possibility of relative dating through the medium of soil development, seven soil profiles were dug on moraines, which were geomorphologically classified to different glacial stages (Kuhle, 1982). The moraines at profile 17, 18 and 16 in the Chokopani Khola and Chimani Khola belong to chronologically clear separated neoglacial, late glacial and high glacial stages. The moraines at profile 14, 15, 13 and 12 in the Lanpoghyun Khola on the other hand belong to chronologically closer related late glacial to post high glacial stages. In this context, the influence of the calcareous parent material and the semi-arid climate on the soil development is of special interest.

The deposits, where the soil profiles were dug, could clearly be identified as moraines agreeing with the geomorphological results of Kuhle (1982). Alternative interpretations as alluvial fan or fluvial terrace (Iwata, 1984) for some of the deposits could not be affirmed according to the geomorphological structure, their arrangement within the landscape and their sedimentological composition. Only the accumulation at profile 15

can also be classified as glacier avalanche induced debris layer (Iwata, 1984).

Steep gradients in the content of almost immobile elements reflect inhomogeneity within profile 12 and 16 and higher fractions of medium silt and fine silt in the topsoil indicate a loess layer on top of these moraines. The thin aeolian layers did not interrupt the soil development on the moraines.

Despite the assumed slower soil development as a consequence of the semi-arid climatic conditions and the carbonate-rich parent material, the different glacial stages are mirrored correctly in the relative graduation of soil development. According to the absolute chronology, profile 14 and 15 show a very low degree of soil development in respect to the assumed late glacial age of the moraines. The main reason for this can be found in the orographically induced extreme low amounts of precipitation at these profile sites. While the pedochronological differentiation of neoglacial and late glacial stages is very clear, the difference between late glacial and high glacial or post high glacial stages is less pronounced. This might be provoked by changes in the lithological composition of high and late glacial moraines or by pre-weathering of the late glacial deposits (cf. Semmel, 1989, p. 156).

For estimating relative soil ages on high glacial to neoglacial moraines in semi-arid orographic left tributaries of the Kali Gandaki at the northern and western flank of the Nilgiri Himal, the Fe_{d-o}/Fe_t ratio and the FC/C ratio are found to be most suitable, because they are almost independent from existing changes in the lithological composition. The total element based weathering indices are less suitable, because they react highly sensitive to the geology dependent shift to higher carbonate contents. Except for FC/C all weathering indices according to the distribution of grain size fractions are inapplicable because of the typically high textural variability within till deposits.

Acknowledgements

This paper presents preliminary results of a doctoral thesis kindly supervised by Prof. Kuhle at the University of Göttingen. The author would like to thank the Federal State of *Niedersachsen* (Graduiertenförderung), the *Deutscher Akademischer Austauschdienst* (DAAD) and the *Universitätsbund Göttingen e.V.* for financial support. The Author also wishes to thank Diplom-Geographin Gabriele Kehr for the linguistic reworking of the English manuscript.

References

- Ahmad M., Ryan J. and Paeth R.C., 1977: Soil development as a function of time in the Punjab River Plains of Pakistan *Soil Science Society of America Journal* **41**: 1162–1166.

- Alexander E.B., 1974: Extractable iron in relation to soil age on terraces along the Truckee River, Nevada *Soil Science Society of America Proceedings* **38**: 121–124.
- Alonso P., Sierra C., Ortega E. and Dorronsoro C., 1994: Soil development indices of soils developed on fluvial terraces (Penaranda de Bracamonte, Salamanca, Spain) *Catena* **23**: 295–308.
- Arduino E., Barberis E., Carraro F. and Forno M.G., 1984: Estimating relative ages from iron-oxide/total-iron ratios of soils in the western Po Valley, Italy *Geoderma* **33**: 39–52.
- Bäumler R., 1993: Bodenbildung und Verwitterungsintensität auf Moränen und Gletscherablagerungen im Khumbu Himal und oberen Solu-Tal, Ostnepal *Innsbrucker Geographische Schriften* **20**: 29–45.
- Bäumler R., 2001: Vergleichende bodenkundliche Untersuchungen in Hochasien und Kamtschatka. Böden als Zeugen der quartären Landschafts- und Klimageschichte. Relief Boden Paläoklima **16**: 1–217. Gebrüder Bornträger, Berlin, Stuttgart.
- Bäumler R., Kemp-Oberhettinger M. and Zech W., 1996a: Bodengenese Untersuchungen zur Moränenstratigraphie im Langtang-Tal (Zentralnepal) und im Solu/Khumbu (Ostnepal) *Bayreuther Bodenkundliche Berichte* **51**: 1–91.
- Bäumler R., Kemp-Oberhettinger M., Zech W., Heuberger H., Siebert A., Madhikarmi D.P. and Poudel K.P., 1996b: Soil weathering on glacial and glaciofluvial deposits in the Langtang Valley (Central Nepal) and its relation to the glacial history *Zeitschrift für Geomorphologie N.F.* **103**(Suppl.): 373–387.
- Dollfus O. and Usselman P., 1971: *Recherches géomorphologiques dans la centre-ouest du Népal. (Cahiers népalais)*. 56 pp. Centre d'Etudes Népalaises, Musée de l'Homme, Paris.
- Egger J., Bajrachaya S., Egger U., Heinrich R., Shakya P., Wendt H. and Wirth V., 1998: Diurnal winds in the Himalayan Kali Gandaki valley. Part I: Observations *Monthly Weather Review* **128**: 1106–1122.
- Evans L.J. and Adams W.A., 1975: Quantitative pedological studies on soils derived from silurian mudstones. IV. Uniformity of the parent material and evaluation of internal standards *Journal of Soil Science* **26**(3): 319–326.
- Feng Z.-D., 1997: Geochemical characteristics of a loess-soil sequence in central Kansas *Soil Science Society of America Journal* **61**: 534–541.
- Fort M., 1985: Contribution of sedimentary and geomorphic data to the knowledge of paleoclimates in Nepal Himalayas *Current Trends in Geology* **4**: 159–189 (Climate and Geology of Kashmir).
- Fort M., 2000: Glaciers and mass wasting processes: their influence on the shaping of the Kali Gandaki valley (higher Himalaya of Nepal) *Quaternary International* **65/66**: 101–119.
- Gellatly A.F., Röthlisberger F. and Geyh M.A., 1985: Holocene glacier variations in New Zealand (South Island) *Zeitschrift für Gletscherkunde und Glazialgeologie* **21**: 265–273.
- Godin L., 2003: Structural evolution of the Tethyan sedimentary sequence in the Annapurna area, central Nepal Himalaya *Journal of Asian Earth Science* **22**: 307–328.
- Hallet B. and Putkonen J., 1994: Surface dating of dynamic landforms: young boulders on aging Moraines *Science* **265**(12): 937–940.
- His Majesty's Government of Nepal Survey Department, 1994–2002: Nepal. 1:25000/1:50000. HMG Nepal, Survey Department, Kathmandu.
- Höfer H.v., 1879: Gletscher und Eiszeitstudien. Sitzungsbericht der Akademie der Wissenschaften Wien *Mathematisch-physikalische Klasse I* **79**: 331–367.
- Holmgren G.G.S., 1967: A rapid citrate-dithionite extractable iron procedure *Soil Science Society of America Proceedings* **31**: 210–211.
- Hormann K., 1974: Die Terrassen an der Seti Khola – ein Beitrag zur Quartären Morphogenese in Zentralnepal *Erdkunde* **28**(3): 161–176.
- Hurtado J.M., Hodges K.V. and Whipple K.X., 2001: Neotectonics of the Thakkhola graben and implications for recent activity on the South Tibetan fault system in the central Nepal Himalaya *Geological Society of America Bulletin* **113**(2): 222–240.
- Iturrizaga L., 2001: Lateroglacial valleys and landforms in the Karakoram Mountains (Pakistan). *GeoJournal* **54**(2-4) (Kuhle M. (ed.), Tibet and High Asia VII): 397–428.
- Iwata S., 1984: Geomorphology of the Thakkhola-Muktinath region, Central Nepal, and its late quaternary history *Geographical Reports of Tokyo Metropolitan University* **19**: 25–42.
- König O., 1999: Preliminary results on the last high-glacial glaciation of the Rolwaling Himal and the Kangchenjunga Himal (Nepal, East-Himalaya). *GeoJournal* **47**(1/2) (Kuhle M. (ed.), Tibet and High Asia V): 373–384.
- König O., 2002: Zur Vergletscherungsgeschichte des Rolwaling Himal und des Kangchenjunga Himal (Nepal, Himalaya Südabdachung). PhD thesis, Universität Göttingen, 267 pp.
- Kronberg B.I. and Nesbitt H.W., 1981: Quantification of weathering, soil geochemistry and soil fertility *Journal of Soil Science* **32**: 453–459.
- Kuhle M., 1982: Der Dhaulagiri- und Annapurna-Himalaya. Ein Beitrag zur Geomorphologie extremer Hochgebirge. *Zeitschrift für Geomorphologie Supplement* Vol. 41 (Bd. I (Text): 1–229; Bd. II (Abb.): 1–183 und Geomorph. Karte 1:85 000).
- Kuhle M., 1983: Der Dhaulagiri- und Annapurna-Himalaya. Ein Beitrag zur Geomorphologie extremer Hochgebirge. *Empirische Grundlage. Zeitschr. f. Geomorphologie Supplement* **41** (Ergänzungsband III): 1–383.
- Kuhle M., 1987: Absolute Datierungen zur jüngeren Gletscher Geschichte im Mt Everest-Gebiet und die mathematische Korrektur von Schneegrenzberechnungen. In: Hütteroth W.-D. (ed.), Tagungsbericht und wissenschaftliche Abhandlungen des 45. Deutschen Geographentages Berlin 1985, Steiner, Stuttgart, pp. 200–208.
- Kuhle M., 1990: The probability of proof in geomorphology – an example of the application of information theory to a new kind of glacialic morphological type, the ice-marginal ramp (Bortensander) *GeoJournal* **21**(3): 195–222.
- Kuhle M., 1991: *Glazialgeomorphologie*. Wissenschaftliche Buchgesellschaft, Darmstadt 213 pp.
- Kuhle M., 1994: Present and Pleistocene Glaciation on the North-Western Margin of Tibet between the Karakorum Main Ridge and the Tarim Basin Supporting the Evidence of a Pleistocene Inland Glaciation in Tibet. *GeoJournal* **33**(2/3) (Kuhle M. (ed.), Tibet and High Asia (III), Results of the Sino-German and Russian-German Joint Expeditions): 133–272.
- Kuhle M., 2001: The maximum Ice Age (LGM) glaciation of the Central- and South Karakorum: an investigation of the heights of its glacier levels and ice thickness as well as lowest prehistoric ice margin positions in the Hindukush, Himalaya and in East-Tibet on the Minya Konka-massif. *GeoJournal* **54** (2–4) (Kuhle M. (ed.), Tibet and High Asia VI, Glaciogeomorphology and Prehistoric Glaciation in the Karakorum and Himalaya): 109–396.
- Kuhle M., 2004: The High Glacial (Last Ice Age and LGM) ice cover in High and Central Asia. In: Ehlers J. and Gibbard P.L. (eds.), *Development in Quaternary Science 2* (Quaternary Glaciation – Extent and Chronology, Part III: South America, Asia, Africa, Australia, Antarctica), pp. 175–199.
- Langley Turmbaugh S.J. and Evans C.V., 1994: A determinative soil development index for pedo-stratigraphic studies *Geoderma* **61**: 39–59.
- Levine E.R. and Ciolkosz E.J., 1983: Soil development in till of various ages in Northeastern Pennsylvania *Quaternary Research* **19**: 85–99.
- Markewich H.W., Pavich M.J., Mausbach R.G., Johnson R.G. and Gonzalez V.M., 1989: A guide for using soil and weathering profile data in chronosequence studies of the coastal plain of the eastern United States *U.S. Geological Survey Bulletin* **1589**(4): 1–39 (Pedologic studies in the Eastern United States Relations to geology).
- McKeague J.A., Brydon J.E. and Miles N.M., 1971: Differentiation of forms of extractable iron and aluminium in soils *Soil Science Society of America Proceedings* **35**: 33–38.
- Mehra O.P. and Jackson M.L., 1960: Iron oxide removal from soils and clays by dithionite-citrate systems buffered with sodium bicarbonate *Clays and Clay Minerals* **7**: 317–327.
- Meiners S., 1999: The history of glaciation of the Rolwaling and Kangchenjunga Himalayas. *GeoJournal* **47**(1/2) (Kuhle M. (ed.), Tibet and High Asia V): 341–372.
- Meurer M., 1984: Geoökologische Untersuchungen im Kali-Gandaki-Tal (Nepal): I. Die klimatischen Verhältnisse. *Verhandlungen der Gesellschaft für Ökologie* (Bern 1982) **XII**, pp. 185–196.
- Miehe G., 1991: Der Himalaya – eine multizonale Gebirgsregion. In: Walter H. and Breckle W. (eds.), *Ökologie der Erde (4)*, Spezielle Ökologie der Gemäßigten und Arktischen Zonen außerhalb Euro-Nordasiens. Gustav Fischer Verlag, Stuttgart, pp. 181–230.

- Müller G., 1964: Sediment-Petrologie (1), Methoden der Sediment-Untersuchung. In: Engelhardt W.v., Füchtbauer H. and Müller, G. (eds.), *Sediment-Petrologie (1)*, E. Schweizerbart'sche Verlagsbuchhandlung, Stuttgart, 303 pp.
- Murad E., 1978: Yttrium and zirconium as geochemical guide elements in soil and stream sediment sequences *Journal of Soil Science* **29**: 219–223.
- Parker A., 1970: An index of weathering for silicate rocks *Geological Magazine* **107**: 501–504.
- Penck A. and Brückner E., 1909: Die Alpen im Eiszeitalter (1–3), Leipzig, 1199 pp.
- Protz R., Ross G.J., Martini I.P. and Terasmae J., 1984: Rate of podzolic soil formation near Hudson Bay, Ontario *Canadian Journal of Soil Science* **64**: 31–49.
- Schwertmann U., 1964: Differenzierung der Eisenoxide des Bodens durch Extraktion mit Ammoniumoxalat-Lösung *Zeitschrift für Pflanzenernährung, Düngung, Bodenkunde* **105**: 194–202.
- Semmel A., 1989: Paleopedology and geomorphology: examples from the eastern part of Central Europe *Catena Suppl.* **16**: 143–162.
- Sparks D.L. (ed.) 1996: *Methods of Soil Analysis, Part 3, Chemical Methods*. SSSA/ASA, Madison, 1390 pp.
- Tamm O., 1932: Über die Oxalmethode in der chemischen Bodenanalyse *Meddelingen for Statens Skofogsforsöksanstalt* **27**: 1–50.
- Walker P.H. and Green P., 1976: Soil trends in two valley fill sequences *Australian Journal of Soil Research* **14**: 291–303.
- WRB, 1998: World reference base for soil resources. World Soil Resources Reports. Vol. 84, ISSS, FAO, Rome, 88 pp.
- Zech W., Bäumler R., Madhikarmi D., Gerl T. and Beck E., 2001a: Zur pleistozänen und holozänen Landschaftsgeschichte des Modi Khola-Tals (Annapurna, Nepal) *Zeitschrift für Gletscherkunde und Glazialgeologie* **37**(2): 159–190.
- Zech W., Madhikarmi D., Gerl T. and Beck E., 2001b: Rekonstruktion der spätglazialen und holozänen Vergletscherung des Annapurna III-Nordgletschers unter besonderer Berücksichtigung der Böden als Indikatoren für Klimaschwankungen *Zeitschrift für Gletscherkunde und Glazialgeologie* **37**(2): 141–158.
- Zech W., Glaser B., Abramowski U., Dittmar C. and Kubik P.W., 2003: Reconstruction of the Late Quaternary Glaciation of the Macha Khola valley (Gorkha Himal, Nepal) using relative and absolute (14-C, 10-Be, dendrochronology) dating techniques *Quaternary Science Reviews* **22**: 2253–2265.