GeoJournal (2005) 62: 191
DOI 10.1007/s10708-005-2337-7
© Springer 2006

Guest editor's preface

The contributions presented here have been introduced in the scope of at least one, but mostly several of the following congresses and discussed in the circle of national and international colleagues: at the first workshop on 'Mountain Research in Germany' of the Bavarian Academy of Sciences in Munich (2001); at the 'Fifth International Conference on Geomorphology' in Tokyo (Japan) (2001), at the lecture series 'High Mountains of the Earth' on the occasion of the 'International Year of the Mountains', organized by the Marburg Geographical Society (MGG) (Germany) (2002), at the Geographical Colloquium of the University of Bern (Switzerland) (2002), at the 'International Conference on Mountain Environment and Development' in Chengdu (PR China) (2003), at the 'XVIth INQUA-CONGRESS in Reno (USA) (2003), at the 'Deutscher Geographentag' (German Geographers' Day) in Bern (Switzerland) (2003), at the Geographical Colloquium of the University of Mainz (Germany) (2004), at the '19th Himalaya-Karakoram-Tibet Workshop', Niseko (Japan) (2004), at the '4th International Symposium on the Tibetan Plateau', Lhasa, Tibet (PR China) (2004), in the "German Working Group for Geomorphology", Heidelberg (Germany) (2004) and the "Working Group for High Mountains", Berlin (Germany) (2005).

I wish to thank the authors Dr. L. Iturrizaga, Dr. S. Meiners and Dipl.Geographer M. Wagner for their trusting willingness to contribute with their newest research results to this GeoJournal Volume Tibet and High Asia VII.

My special thanks go to the founder editor of GeoJournal, Dr. Wolf Tietze, to the former managing editors Prof. H. van der Wusten and Prof. O.Gritsai and to the incumbent managing editor and editor-in-chief Prof. M. Barlow, who have encouraged and invited the guest editor to publish his newest relevant research results and those of his co-workers with regard to High Asia in a GeoJournal Volume at intervals of several years. Moreover, I thank Prof. Barlow for his obliging understanding as to the considerable size of the volume in hand.

Thanks are also due to the publishing editor Mrs. Renée de Boo and her successor, editorial director Myriam Poort, for their uncompromising care with which they have looked after the complicated printing of the book with numerous folded panorama– photographs, maps and figures and for all their efforts to attain highest technical quality.

Matthias Kuhle
Göttingen, February 2005

GeoJournal (2005) 62: 193–650
DOI: 10.1007/s10708-005-2338-6 © Springer 2006

The maximum Ice Age (Würmian, Last Ice Age, LGM) glaciation of the Himalaya – a glaciogeomorphological investigation of glacier trim-lines, ice thicknesses and lowest former ice margin positions in the Mt. Everest–Makalu–Cho Oyu massifs (Khumbu and Khumbakarna Himal) including informations on late-glacial, neoglacial, and historical glacier stages, their snow-line depressions and ages

Matthias Kuhle
Department of Geography and High Mountain Geomorphology, University of Göttingen, Goldschmidtstr. 5, 37077 Göttingen, Germany Tel.: +49-551-398067; Fax: +49-551-397614; E-mail: mkuhle@gwdg.de

Key words: Himalaya, Ice Age glaciation, last glacial period, paleoclimate, High Asia

Abstract

In the Khumbu- and Khumbakarna Himalaya an ice stream network and valley glacier system has been reconstructed for the last glacial period (Würmian, Last Ice Age, Isotope stage 4–2, 60–18 Ka BP, Stage 0) with glaciogeomorphological and sedimentological methods. It was a part of the glacier system of the Himalaya and has communicated across transfluence passes with the neighbouring ice stream networks toward the W and E. The ice stream network has also received inflow from the N, from a Tibetan ice stream network, by the Kyetrak–Nangpa–Bote Koshi Drangka in the W, by the W-Rongbuk glacier valley into the Ngozumpa Drangka, by the Central Rongbuk glacier valley into the Khumbu Drangka and by the antecedent Arun Nadi transverse-valley in the E of the investigation area. The ice thickness of the valley glacier sections, the surface of which was situated above the snow-line, amounted to 1000–1450 m. The most extended parent valley glaciers have measured approx. 70 km in length (Dudh Koshi glacier), 67 km (Barun–Arun glacier) and 80 km (Arun glacier). The tongue end of the Arun glacier has flowed down to ca. 500 m and that of the Dudh Koshi glacier to ca. 900 m a.s.l. At heights of the catchment areas of 8481 (or 8475) m (Makalu), i.e. 8848 (or 8872) m (Mt. Everest, Sagarmatha, Chogolungma) this is a vertical distance of the Ice Age glaciation of ca. 8000 m. The steep faces towering up to 2000 m above the névé areas of the 6000–7000 m-high surfaces of the ice stream network were located 2000–5000 m above the ELA. Accordingly, their temperatures were so low, that their rock surfaces were free of flank ice and ice balconies. From the maximum past glacier extension up to the current glacier margins, 13 (altogether 14) glacier stages have been differentiated and in part 14C-dated. They were four glacier stages of the late-glacial period, three of the neoglacial period and six of the historical period. By means of 130 medium-sized valley glaciers the corresponding ELA-depressions have been calculated in comparison with the current courses of the orographic snow-line. The number of the glacier stages since the maximum glaciation approx. agrees with that e.g. in the Alps and the Rocky Mountains since the last glacial period. Accordingly, it is interpreted as an indication of the Würmian age (last glacial period) of the lowest ice margin positions. The current climatic, i.e. average glacier snow-line in the research area runs about 5500 m a.s.l. The snow-line depression (ELA) of the last glacial period (Würm) calculated by four methods has run about 3870 m a.s.l., so that an ELA-depression of ca. 1630 m has been determined. This corresponds to a lowering of the annual temperature by ca. 8, i.e. 10 °C according to the specific humid conditions at that time.

1. Introduction, methods of evidence and characteristics of the investigation areas

Aim of this study was to find geomorphological and sedimentological indicators of a past glaciation. In addition to the reconstruction of the maximum extent of Ice Age glacier cover, field investigations combined with panorama photographs and laboratory analyses of samples were focused on the evidence of glacier trim-lines and thicknesses.

This is the regional continuation of a detailed and spatially extensive reconstruction of the Ice Age glaciation in High Asia. It completes the author's research on the past extent of ice and glacier thicknesses in High Asia carried out since 1973 (cf. Figure 1) and published since 1974 (Kuhle, 1974–2004a) by further observations

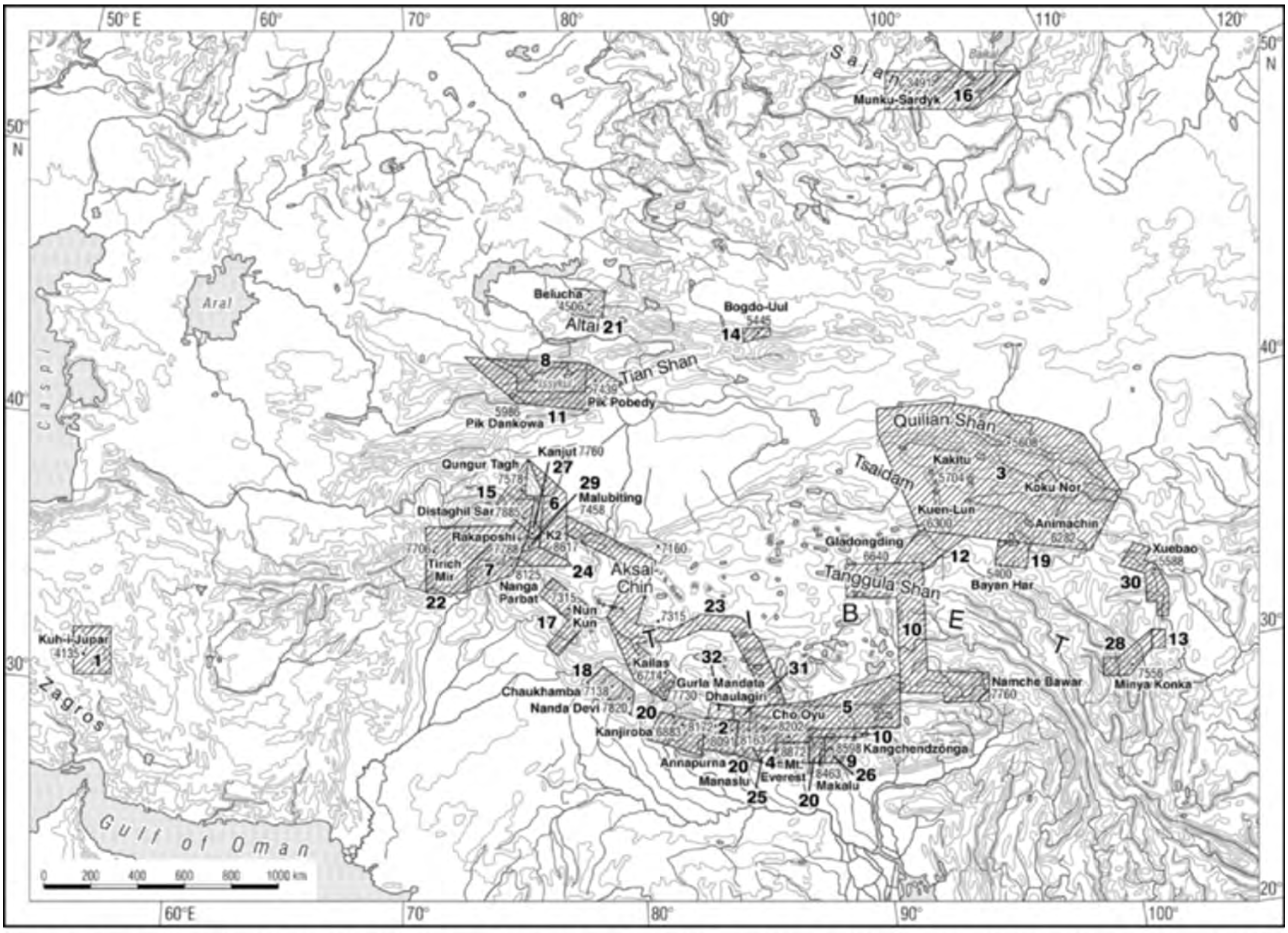
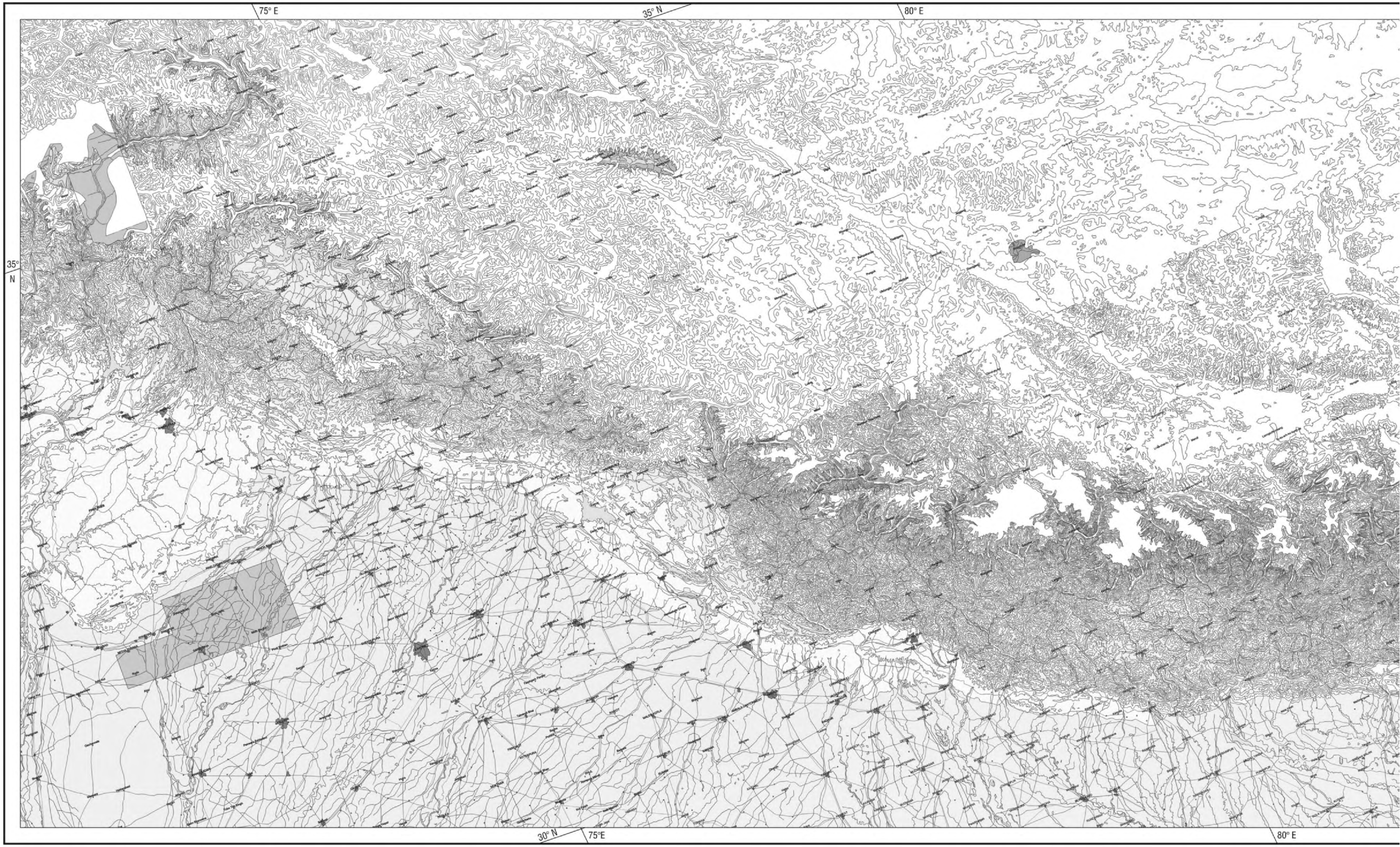


Figure 1. Research areas in Tibet and surrounding mountains visited by the author. The study presented here introduces new observations on the Ice Age glacier cover from area Nos. 4 and 20.

in areas which have already been studied earlier or which have not yet been visited (Figure 1, Nos. 4 and 20).

1.1. Methods

The geomorphological and Quaternary-geological methods applied in the field and laboratory have already been discussed in detail in the papers on empirical Ice Age research and the glaciation history of High Asia (Kuhle and Wang Wenjing, 1988; Kuhle and Xu Daoming, 1991; Kuhle, 1994, 1997a, 1999a, 2001a) published in the GeoJournal series "Tibet and High Asia – results of investigations into high mountain geomorphology, paleo-glaciology and climatology of the Pleistocene (Ice Age Research)" and "Glaciogeomorphology and prehistoric glaciation in the Karakorum and Himalaya" Volumes I (1988), II (1991), III (1994), IV (1997a), V (1999a) and VI (2001a). Accordingly, these scientifically common methods are only introduced here in general: Glaciogeomorphologic observations in the research area (Figure 2, No. 1) have been mapped. Locations of typologically unambiguous individual phenomena, i.e. glacier indicators, have been recorded with the help of 39 signatures (Figures 3, 11 and 19). The catalogue of signatures applied has especially been developed by the author for the base map 1:1 million (ONC H-9, 1978 and 1:50,000 Khumbu Himal Schneider, 1978). The locations of sediment samples, from which only a selection could be taken in consideration for this paper, has also been marked. All type localities are presented in Figures 3 and 11. They concern areas in which the arrangement of the position of the indicators provides unambiguous evidence of the Ice Age glacier cover. References to them are given in the text, in the photographs, photo-panoramas, tables and in the figures. In addition to the large-scale mappings and the recording of type localities – which do not only occur on the valley floors but partly also on remote slopes and mountain flanks – 34 geomorphologic profiles (Figures 7–10, 12–16, 20–36, 46, 52–57, 59), mainly valley cross-profiles distributed over the entire investigation area, have been recorded (Figures 3 and 4). These profiles are meant to give an impression of the three-dimensional proof-system based on the arrangement of the positions, so that they complete the glaciogeomorphologic map


75° E
35° N
80° E
35° N
30° N
75°E
80° E

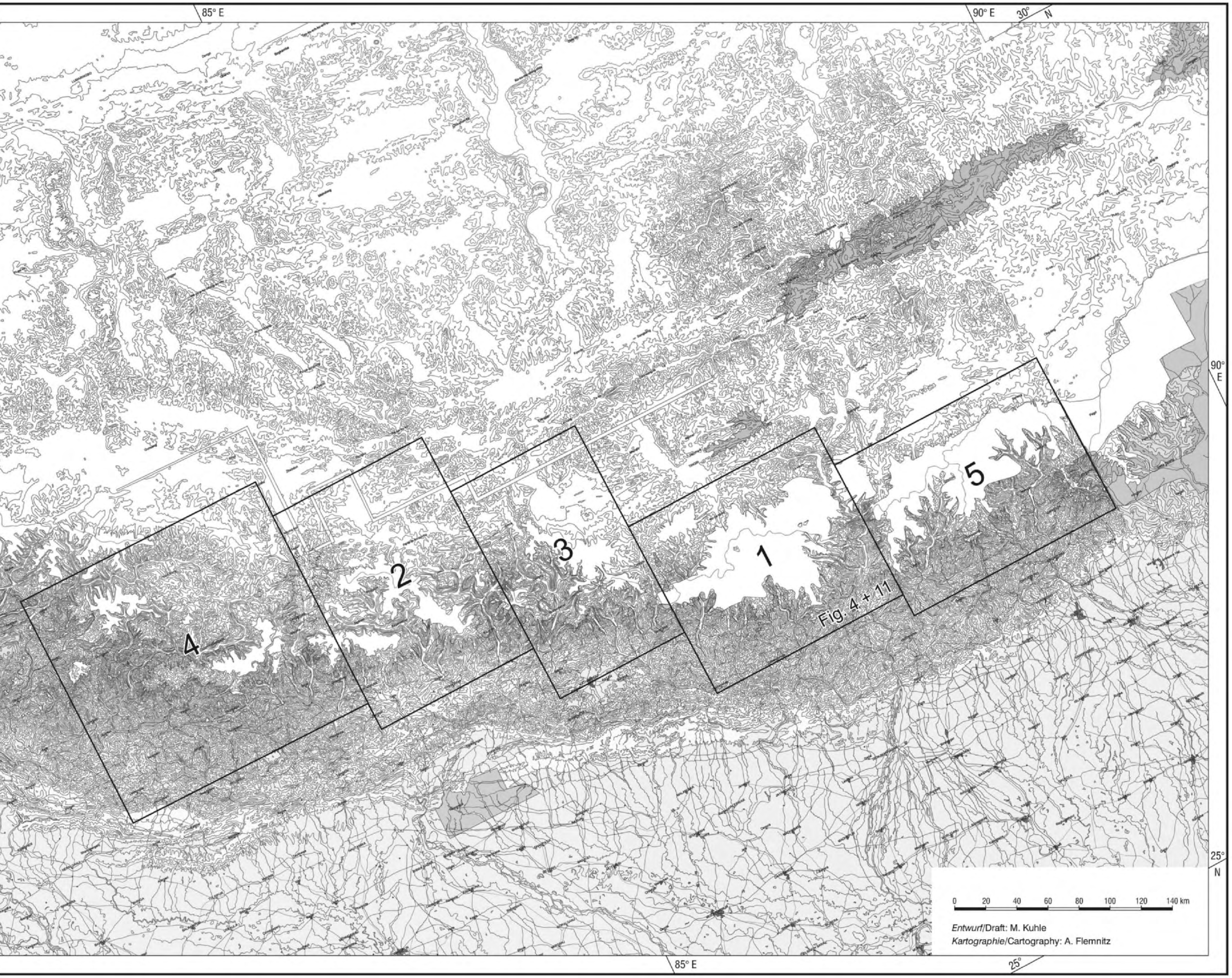


Figure 2. Map of the ice stream network of the Himalaya and South-Tibet during the last glacial period (Würm glaciation, Last Ice Age, Last High Glacial, Stage 0) ca. 60–18 Ka BP after Kuhle (2004a). Scale 1:2,400,000. No. 1: see Figures 3, 4, 11 and 19; Nos. 2 and 4: after Kuhle (1982, 1997b, 1998a, 2001c, 2005, in press); No. 3 after Kuhle (1988b, 1999b, 2001c); No. 5 after Kuhle (1990, 2001c). Draft: M. Kuhle; Scan: J. Ehlers.


86°35' E
86°40'
86°45'
86°50'
86°55'
87°00'
87°05'
28° 05' N
28° 00'
27° 55'
27° 50'
6.12.94/1 Probenentnahmestelle mit Datum der Probenentnahme oder Probennummer / Sampling locality with date or number
Photo 3 mit Aufnahmerichtung / Direction of Photo 3
Panoramaphoto 5 mit Aufnahmerichtung / Direction of panoramaphoto 5
360°-Panoramaphoto 9 / 360°-panorama-photo 9
(1200 m) Eismächtigkeit am Profil / Ice thickness at profile
•6940 Gipfelpunkt / peak
Kamm oder Gratverlauf / ridge
Fluß / river
Gletscher / glacier
0 2 4 6 8 10 km
Kartographie/Cartography: A. Flemnitz
Entwurf/Draft: M. Kuhle
Cho Oyu 8202
Ngozumpa Kang 7806
Gyachung Kang 7922
Nangpa La
Nangpai Gosum 7352
Lhabtshan
Gyazumpa
Nup La 5985 (5860)
West Rongbuk Glacier
Rongbuk Glacier
East Rongbuk Glacier
Chumbu 6870
Pumori 7145
Lingtren 6749
Khumbutse 6697
Lho La 6026
Changtse 7583
Chang La 7066
Rapiu La
Mount Everest 8848 (8872)
Nuptse 7879
Lhotse 8501
Shar Tse 7502
Cho Polu 6734
Makalu 8481
Baruntse 7220
West Col 6135
Chonku Chuli 6830
Ama Dablang 6856
Nyimagawa Drangka
Tshola Drangka
Bote Koshi
Machhermo D.
Luza D.
Dole D.
Khumbui Yul Lha D.
Khumjung
Pro. 1
Pro. 2
Pro. 3
Pro. 4
Pro. 10
Pro. 11
Pro. 12
Pro. 13
Pro. 14
Pro. 15
Pro. 16
Pro. 17
Pro. 18
Pro. 19
Pro. 20
Pro. 21
Pro. 22
Pro. 23
Pro. 24
Pro. 25
Pro. 26
Pro. 27
Pro. 34

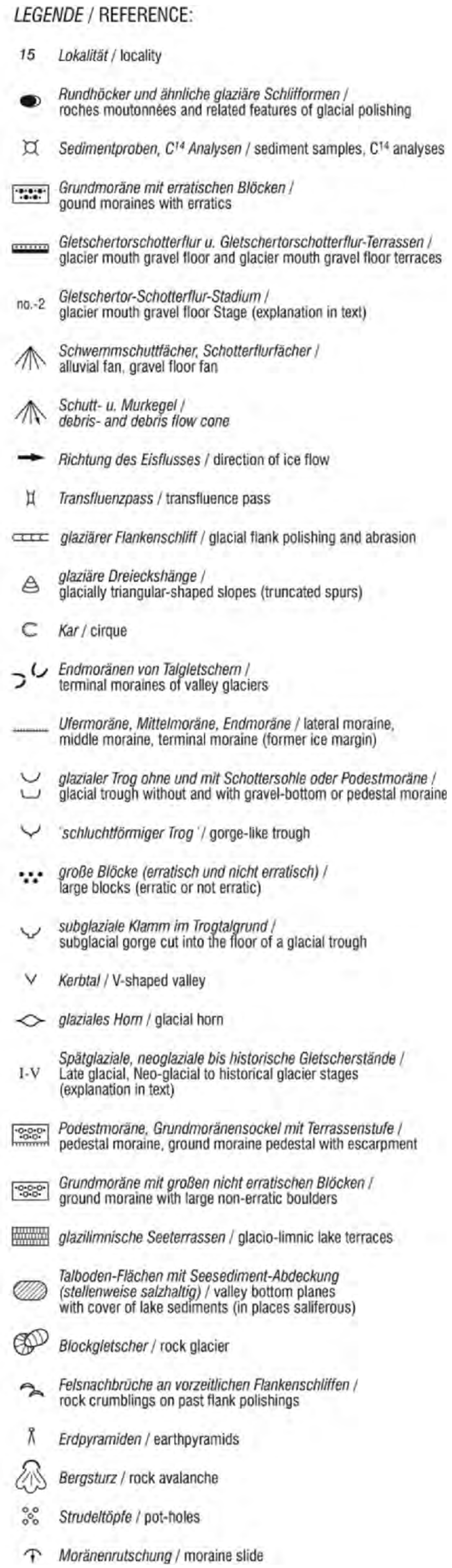


Figure 3. Quaternary-geological and glacio-geomorphological map 1:140,000 of the Khumbu- and Khumbakarna Himal (Cho Oyu-, Mt. Everest- (Chogolungma- i.e. Sagarmatha-) and Makalu massifs) in the Central Himalaya. Basic topographic map: Khumbu Himal 1:50,000, Schneider (1978).

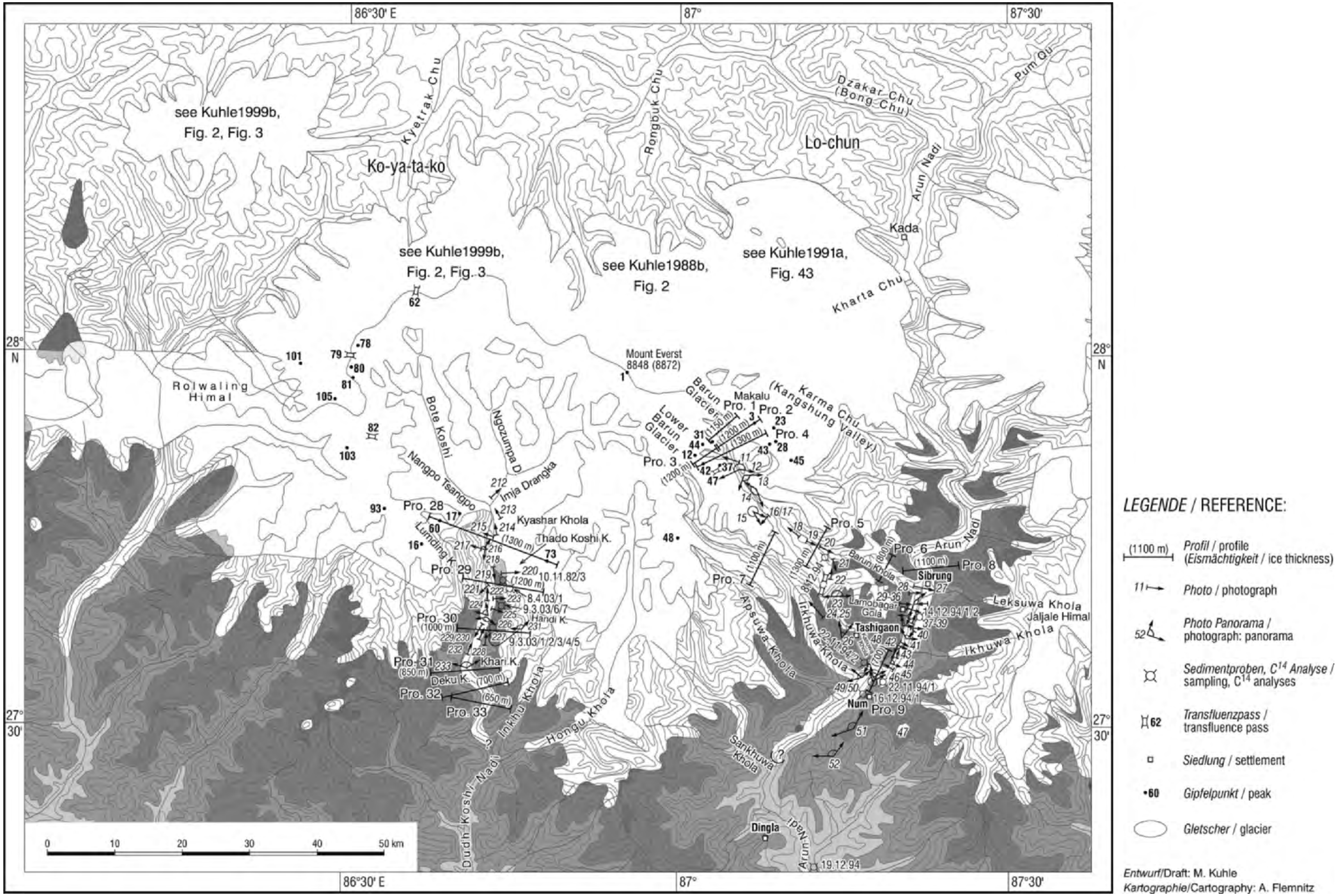


Figure 4. Map 1:700,000 with localities of the glacio-gemorphological and -sedimentological valley cross-profiles during the maximum Ice Age glaciation in the Khumbu- and Khumbakarna Himal between Makalu (8481 m) and Cho Oyu (8205 m) (Central Himalaya). See Figures 2,3,7–16.

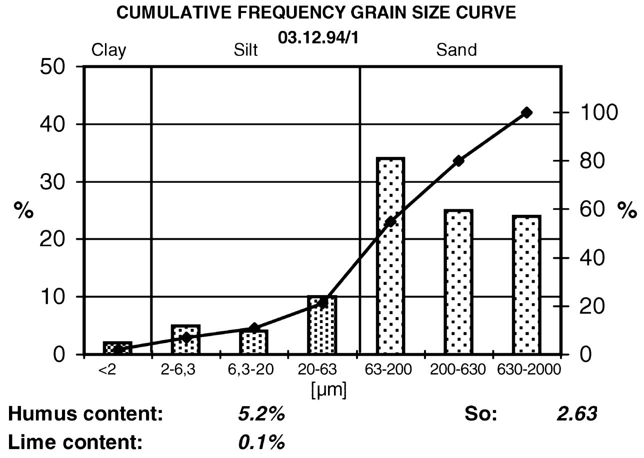


Figure 5. (Diagram of the grain sizes 03.12.1994/1). At 5240 m a.s.l., on the orographic left flank of the Barun valley, lateral moraine matrix (Photo 9 foreground in the middle; 10 IV) taken 500 m above the current valley bottom near the Shershon alpine pasture from a depth of 0.3 m. This lateral, i.e. medial moraine surface has been sedimentated during Stage IV (Table 1). The primary maximum is relatively coarse-grained, i.e. it lies with 34% in the fine sand; the secondary maximum with ca. 6% fine silt determines the bimodal course of the cumulative curve typical of moraine matrix; sorting coefficient calculated according to Engelhardt (1973, p. 133) So = 2.63 (So $=\sqrt{Q3/Q1}$). Here, the grain sizes of the first quartile Q1 of the grain size distribution curve are compared with those of the third quartile Q3 in order to differentiate the fluvial and morainic accumulations. Locality: Figure 3: 3.12.94/1 (27°49′30″ N/87°05′15″ E); see also Figure 6, Sample No. 7. Sampling: M. Kuhle.

(Figure 3, 11 and 19). Especially the indicators of the past-glacier thickness can be inferred from these profiles. All indicators marked in the maps and profiles have been documented on the spot by photographs and photo-panoramas (Figures 3 and 4) in a medium-sized format. All these photos are analogue photos, so that in contrast to digital photos – the content and validity of which can be changed without having any possibility of checking – the authenticity of the photos in the field is verifiable by negative films and prints.

For purposes of a detailed diagnose and additional reassurance as to the occurrence of real ground moraine (lodgement till) in these high topographic positions testifying to past-glacier trim-lines, representative samples have been taken in order to be analysed in the laboratory (Figures 3, 4 and 19). The analyse data of 65 moraine samples are for the most part presented in Figures 5, 6, 37, 38–45, 47–51, 58, 60–95. The sediment analyses: Ct/NT-determination (Elementar Analyser Leco CHN 1000), lime content determination (after Scheibler; DIN 19684 Teil 5, 1977), grain size analysis (‘Combined screen - and pipette analysis’ after Köhn, 1928, DIN 19683 Blatt 2, 1973), determination of the sorting coefficient in the matrix spectrum (after the method of Engelhardt, 1973) (see Figures 5, 38–45, 47–51, 58, 60–95) and morphoscopic quartz grain analysis (after the method of Mahaney, 1995) (see Figures 6 and 37) are able to support and complete the proof of a huge former glacigenic landscape. Glacially crushed or freshly weathered material cannot immediately be recognized by morphoscopic quartz grain analyses (Figures 6 and 37), but by petrographic analyse in the field, i.e. by the content of erratic material – in places also by the lime content of the debris covers – can be proved that glacially crushed and not freshly weathered material *in situ* is concerned.

The sorting coefficient So $(=\sqrt{Q3/Q1})$ compares the ratio of the grain sizes of the first quarter $Q1$ of the grain size distribution curve with that of the third quarter $Q3$ and provides an additional reliable proof as to mainly the differentiation of fluvial and morainic accumulations. If only one grain size appears in the sediment, then So = 1. The greater the coefficient, the stronger the intermixing of different grain sizes, which is typical of moraine matrix. Accordingly, the insignificant C-portion, the bi/trimodal and quadramodal grain size distribution, the lack in sorting and the very high percentage of glacially crushed quartz grains provide evidence of lodgement till (ground moraine) even up to very high positions in this steep valley relief. Owing to this, these analyses are further accumulation indicators of the former ice cover as well as of the glacier thickness and – in some places – even of the minimum altitudes of the glacier trim-line.

The geomorphological maps as to the glacier reconstruction of the last glacial period (Würmian, Isotope Stages 4 to 2, Stage 0 in Table 1 and in the photos) (Figures 3 and 11) as well as the text of the paper consider the late glacial, holocene (neoglacial) and historical glacier stages (Tables 1, 3 and 4), even though they are not the true subject of this investigation. The existence of these younger glacier indicators is important, because they render the differentiation of 7 late glacial- to neoglacial and 6 historical glacier stages possible, aligned between the lowest past (high glacial of the last glacial period, Stage 0) and the lowest current glacier margins. They are marked by the numbers I–XII as being of late glacial to historical age (Tables 1, 3, 4; Figures 3, 11 and 19). According to 15 14C-datings (Table 2) and measurements of the lichen-diameters their age has been determined, i.e. limited (Figures 3 and 19). The number of 13 late glacial to historical glacier stages since the last glacial period corresponds with that of the number of glacier stages of the post-last glacial period diagnosed worldwide. So, these younger evidences of ice margin positions are important indications of the correctness of our dating of the lowest past ice margin positions as belonging to the last glacial period (Stage 0 = Isotope Stage 4–2).

1.2. Areas of investigation

During two 4-months expeditions in 1976 and 1977 (Kuhle, 1980, 1982, 1983a) the author has evidenced an Ice Age glaciation in the Dhaulagiri- and Annapurna-Himalaya (Figure 1, No. 2) that was clearly more important than it had been suggested for the Himalaya before (cf. v. Wissmann, 1959). As an area of reference

sample No. / *Proben-nummer*	Date / *Datum*	counted quartz grains of the medium sand/ *ausgezählte Quarzkörner der Mittel-sandfraktion*	Freshly weathered/ glacially crushed / *frisch verwittert/ glazigen gebroch* *[%]*	lustrous (fluvially polished) / *fluvial poliert* *[%]*	dull (aeolian) / *äolisch mattiert* *[%]*	remarks / *Anmerkungen* analysed grain size/ *analysierte Korngröße: 200-630 μm*
1	22.11.94/1	201	80,1	19,9	0,0	very high portion of muskovite, many iron-oxide crusts, perhaps pyrite; partly fluvially polished / *Sehr hoher Anteil von Muskovit und viele Eisenoxidkrusten, vielleicht Pyrit. Teils fluviale Überpolitur*
2	22.11.94/2	261	89,6	9,6	0,8	large part of grains freshly weathered; small portion rounded at the edges / *Körner größtenteils deutlich frisch verwittert, kleiner Prozentanteil mit Kantenrundung*
3	29.11.94/1	213	57,3	23,9	18,8	quartz grains clearly rounded (aeolian with percussion depressions); many grainy-stalked feldspars / *Deutliche Rundung der Quarzkörner (äolisch mit Percussionstrichtern). Viele körnig-stengelige Feldspäte*
4	29.11.94/2	232	63,4	23,7	12,9	edges are rounded; portion of dull (aeolian) grains may be higher, because dullness of the grain surface sets in before its rounding (only round and dull grains can be analysed) / *Kantenrundung, Anteil äolisch-mattierter Körner eventuell höher, da Mattierung der Kornoberfläche vor Kornrundung einsetzt, jedoch nur runde & matte Körner zugewiesen werden können*
5	02.12.94/1	220	59,1	27,3	13,6	heterogeneous sample: rounded to rounded at edges, but also very fresh and sharp-edged; partly very nice conchoidal fractures / *Heterogen, teils gerundet bis kantengerundet, aber auch sehr frisch & scharfkantig. Zum Teil sehr schöne muschelige Brüche*
6	02.12.94/2	249	72,3	22,1	5,6	high portion of muskovite; grains markedly stronger-edged than 5 / *Hoher Muskovit-Anteil, Körner deutlich kantiger als 5*
7	03.12.94/1	168	54,8	40,5	4,7	small portion of quartz, partly reddish-oxidized; for the most part freshly weathered to slightly rounded / *Geringer Quarzanteil, teils rötlich oxidiert, größtenteils frisch verwittert bis angerundet*
8	04.12.94	237	38,8	29,5	31,7	very high portion of quartz, clearly glaciofluvial character / *Sehr hoher Quarzanteil, deutlich (glazi-)fluvial geprägt*
9	06.12.94/1	221	64,3	21,3	14,4	relatively high portion of muskovite, edges often rounded / *Relativ hoher Muskovit-Anteil, oftmals Kantenrundung*
10	06.12.94 /2	221	42,5	28,1	29,4	substrate nearly pure quartz sand; heterogeneous with all transitions; exemplary character at magnification 1.6 / *Substrat erscheint als fast reiner Quarzsand. Heterogene Probe – alle Übergänge vorhanden. Exemplarischer Charakter bei Vergrößerungsstufe 1.6*
11	08.12.94	227	67,4	28,6	4,0	many quartz grains slightly rounded at the edges - probably minor recent fluvial reshaping, i.e. glaciofluvial displacement / *Leichte Kantenrundung vieler Quarzkörner spricht für eine geringfügige rezente fluviatile Überformung bzw. glazifluviale Umlagerung*
12	14.12.94/1	232	43,1	38,8	18,1	very high portion of quartz / *Sehr hoher Quarzanteil*
13	14.12.94/2	224	57,1	30,4	12,5	very high portion of quartz similar to 12, but somewhat more edged / *Sehr hoher Quarzanteil, ähnlich zu 12, nur etwas kantiger*
14	16.12.94/1	208	74,5	24,0	1,5	very high portion of mica, often covered with iron-oxide crusts; all transition forms (freshly edged, rounded at edges, round) / *Sehr hoher Glimmer-Anteil, vielfach mit Eisenoxidkrusten überzogen; alle Übergangsformen von kantig-frisch zu kantengerundet-rund*
15	19.12.94	234	49,1	46,6	4,3	character of sample obviously fluvially superimposed / *Deutlich fluvial überprägt*

Figure 6. Morphometric quartz grain analysis of 15 representative samples from the Khumbakarna Himal with the Barun- and Arun valley (cf. Figures 3 and 4).

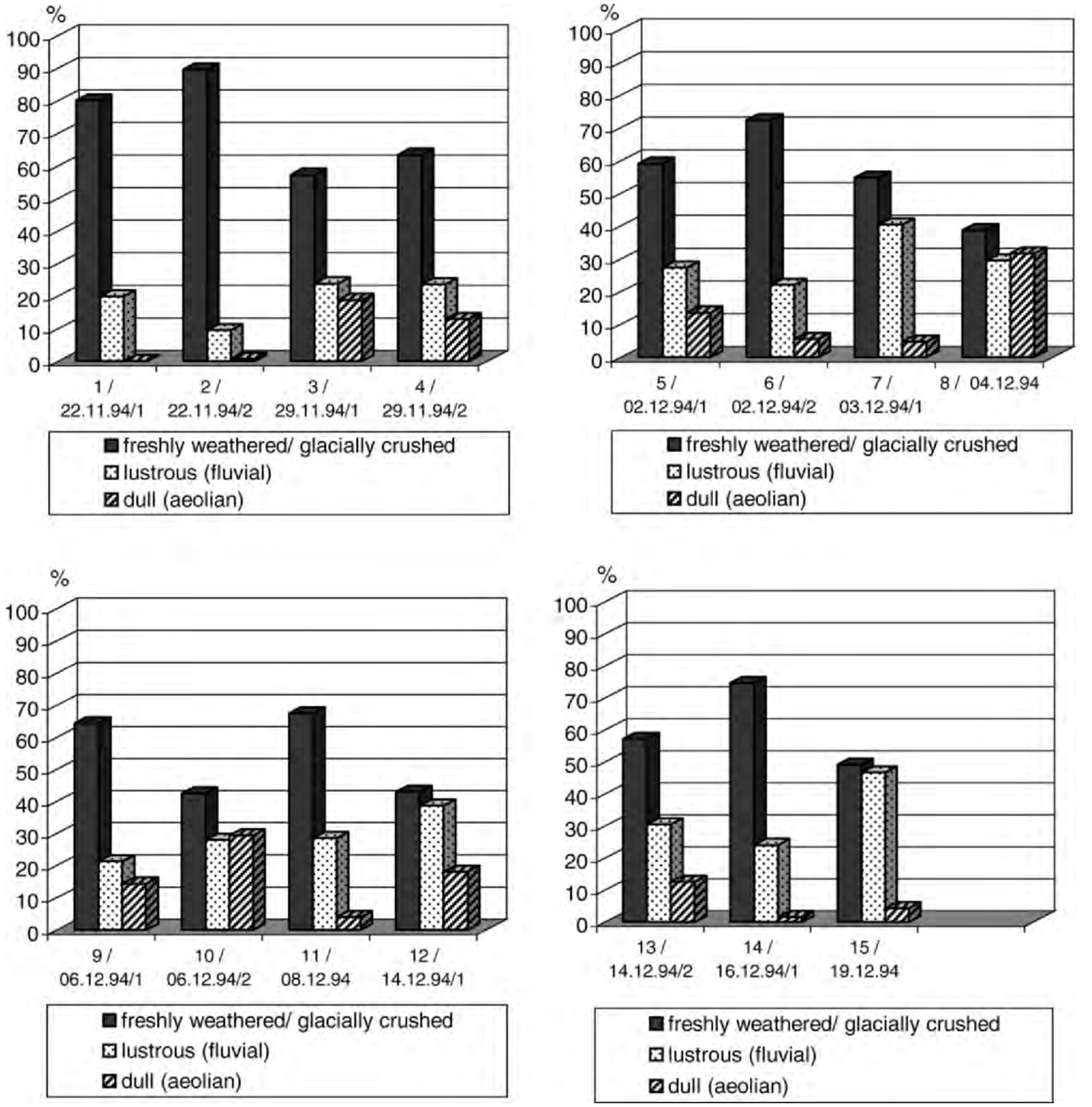


Figure 6. Continued.

the Dhaulagiri- and Annapurna-Himal were especially appropriate for these observations, because the author could visit both, the Tibetan N-slope and the transverse valleys as well as the S-slope. In order to substantiate the findings, further research areas as e.g. the Cho Oyu-, Mt. Everest- (Chogolungma- or Sagarmatha-) and Makalu-groups, i.e. the Khumbakarna Himal have been observed, too. During three expeditions up to 3 months in 1984, 1989 and 1996 leading to altitudes up to over 7000 m a.s.l., the N-slopes of these three mountains and the Mt. Everest E-slope were investigated (Figure 1, Nos. 5, 10, 23). The results as to a past glaciation which here, too, was very extensive – what seems to be inconsistent with respect to the subtropic latitude at 27° N and the semiarid climate – has already been published in detail (Kuhle, 1984a, 1985a, 1985b, 1986a, 1986b, 1986c, 1986d, 1986e, 1986f, 1987a, 1988a, 1988b, 1988c, 1988d, 1988e, 1991a, 1998a, 1998b, 1998c, 1999b, 2001b, 2002a). These research areas are immediately N-adjacent to those treated in this paper (Figure 1 Nos. 4 and 20). Considering the very important ice thicknesses, the topographic connection over high passes across the Himalaya main-ridge and also through it along transverse valleys, it becomes clear that the Ice Age glacier cover of the N-slope must have been connected with

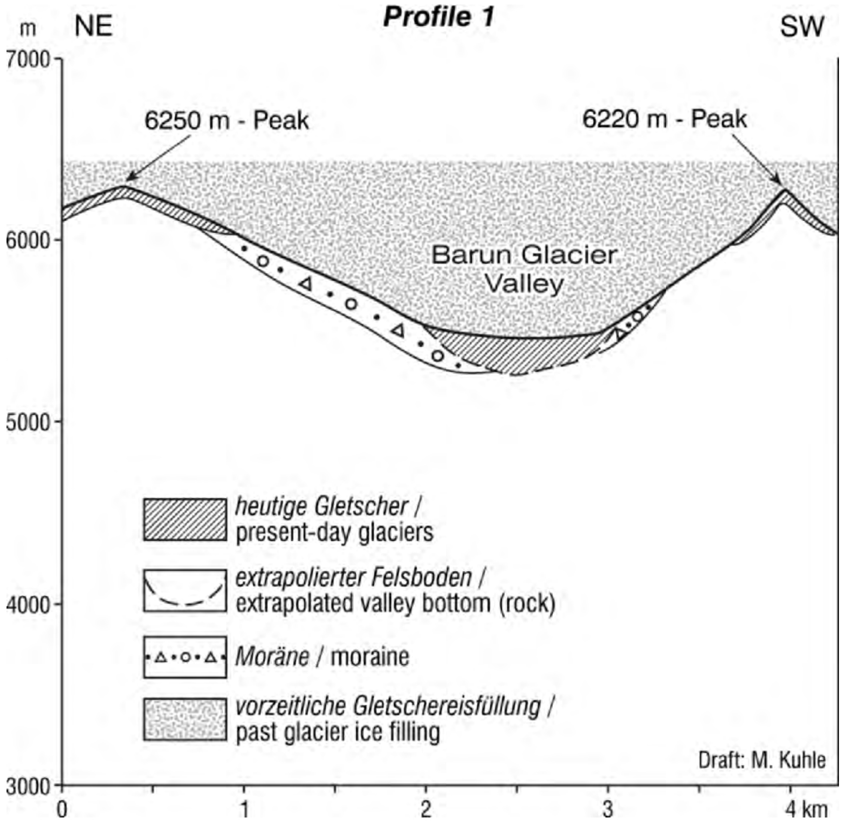


Figure 7. (Profile 1) Cross-section (not exaggerated) across the upper Barun glacier valley from the 6250 m-peak (NE of Baruntse, No. 13, Figure 3) in the orographic left valley flank as far as the 6220 m-peak (W of Makalu, No. 3, Figure 3) in the right valley flank with its minimum glacier ice filling reconstructed for the last glacial period (ca. 60–18 Ka). Locality: Figure 4.

that of the S-slope and that the heights of the glacier trim-lines were communicating. Accordingly, the Ice Age valley glaciers reconstructed here, formed the outlet glaciers of the ice cover north of the Himalaya main-ridge and in S-Tibet (cf. Kuhle, 1988b, 1998b, 1998c, 1999b, 2001b, 2002a). In the research area under discussion, situated S of the main-ridge, the outlet glaciers from Tibet as well as the valley glaciers flowing down from the S-flanks of the Himalaya mountains, have developed the lowest Ice Age glacier margins and tongue ends in High- i.e. South-Asia. They reached down to less than 1000 m a.s.l. and, correspondingly, into a climate which was completely different and even then relatively warm-humid. The lowest glacier terminals of the Nanda Devi- and Kamet-group, of the Dhaulagiri-, Annapurna- and Manaslu-group, of the Langtang- and Rolwaling-group but also of the Kangchendzönga Himalaya flowed down just as low (cf. Kuhle, 1980–2001c; König, 1999).

How far the outlet glacier has flowed down the Arun valley from S-Tibet and how substantial the glacier inflow from the Barun- and Iswa Khola (Chamlang valley) (Makalu S-side; Figure 1, No. 20) might have been, is treated in the first section based on data of a 1-month expedition in 1994. For the reconstruction of the maximum Ice Age glacier filling and cover of this mountain area the determination of the then ice thicknesses and trim-lines in these valleys is absolutely necessary. On the data base of two research expeditions in 1982 and 2003 over a period of all together 4.5 months these questions will be treated with regard to the Khumbu area, the upper catchment area of the Dudh Koshi Nadi (Cho Oyu- and Everest-S-slope; Figure 1, No. 4).

2. The highest former trim-lines and glacier thicknesses in the Makalu- and Chamlang-Himalaya- (Khumbakarna Himal-) S-slopes and the lowest glacier terminus in the Arun valley

2.1. The Ice Age Barun glacier

The two source branches of the Barun valley belong to the catchment area of the present and past Barun glacier: the northern Barun glacier valley leading down from Cho Polu (6734 m, Photo 1 and Figure 3, No. 29) and Shar Tse (or Peak 38; 7502 m; Photo 1 and Figure 3, No. 10) and the southern lower Barun glacier valley coming down from the Baruntse SE-satellite (6730 m; Figure 3, No. 30) and the 6830 m peak (Photo 11 and Figure 3, No. 44) (Figure 9). Both the valleys join in the valley chamber of the Shershon alpine pasture at 4700 m a.s.l. (Photo 9 next to □). The current E-exposed lower Barun glacier reaches somewhat farther down, i.e. to 4600 m a.s.l. (aneroid measurement 4400 m a.s.l.), that is up to the Mera (Sedua) alpine pasture (Photo 12). It is the lowest present-day ice stream in the Barun valley.

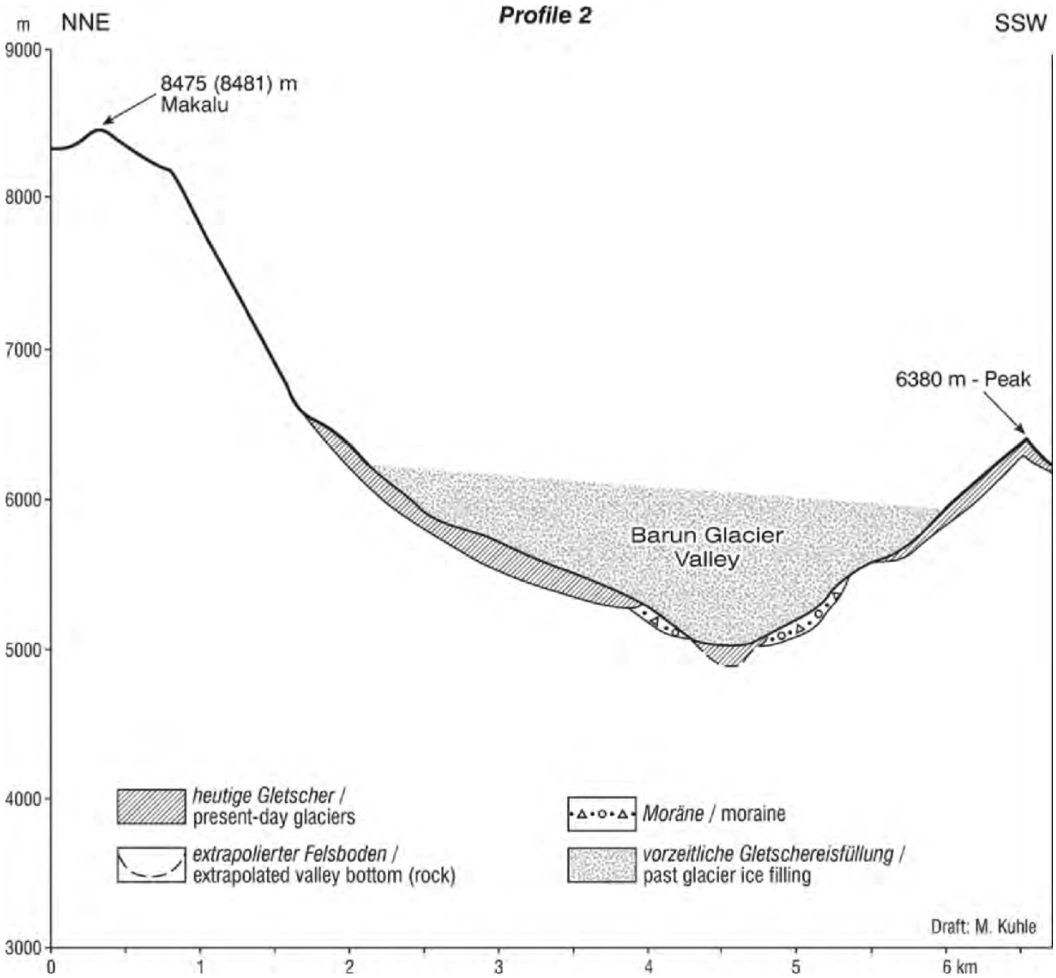


Figure 8. (Profile 2) Cross-section (not exaggerated) across the upper Barun glacier valley from the Makalu (No. 3, Figure 3) in the orographic left valley flank as far as the 6380 m-peak (NE-satellite of the 6550 m-peak, No. 39, Figure 3) in the right valley flank with its minimum glacier ice filling reconstructed for the last glacial period (ca. 60–18 Ka). Locality: Figure 4.

On the orographic left flank of the northern Barun valley the highest past ground moraine remnants reach an altitude of 5800 m a.s.l. (Photo 1, two ■; Figure 3 on the left of No. 3). They have been remoulded by the historic to current S- to SW-exposed hanging glaciers and their meltwaters, but have primarily been deposited by the Ice Age Barun main glacier. Glacigenic flank abrasions in a longitudinal direction of the valley have even been evidenced up to ca. 6200 m a.s.l. in this orographic left-hand flank (Photo 1 the two ∩ on the right); 5 the right ∩; 6∩; 7∩ on the left; 8∩ below Nos. 1–3; 9 second to fourth ∩ from the right). Their upper polish lines mark the High Glacial trim-line (Photo 1: 0 – – –; 5 – – – white; 6 – – – white on the left; 8 … white; 9 – – – on the left and right below No. 3).

The abrasions are modified by gullies of avalanches and rock falls (Photo 1⇩; Figure 3 half-left below No. 3), the development of which is forced by the present-day hanging glaciation above and the increasing frost weathering due to infiltrating glacier meltwater. These have led to crumblings of the polishing and abrasion faces. But the three modern, altogether 5.5 km-wide hanging glaciers on the 3500 m-high Makalu S-flank (Photos 6 and 7 below No. 3) have also undercut the Barun valley flanks rounded by the Ice Age valley glacier. They have dispersed them into rock pillars and glacigenic triangle-shaped faces (Figure 3 below and up to the left below No. 3) (Photo 5, on the right and left below No. 3; 8 the three ∩ from the right), so that they have reshaped the Ice Age flank polishing at a right angle. A corresponding occurrence of post- i.e. interglacial glacigenic reshaping of the High Glacial work of the parent glacier through altogether nine right tributary glaciers can be observed on the orographic right side of the Barun valley flank (Photo 3 e.g. tributary glacier □ above and on the right below No. 39). In addition, glacigenically rounded triangle-shaped slopes lying in between (Figure 3 on the right of No. 29, half-right above Nos. 13, 30, 41 and 39) are evidence of the Ice Age flank abrasion (Photo 1, the three ∩ from the left; Photo 2, below the trim-line ... on the left and ∩; Photo 3∩; Photo 4∩; Photo 5, the two ∩ from the left). Naturally, on these polished mountain spurs or triangle-shaped slopes it has only been formed or preserved up to the uppermost sharpening, that means up to an altitude of ca. 6220 m (Photo 2 trim-line ... on the left). There are also triangle-shaped slopes bearing the characteristics of roches moutonneés (Photo 2∩). Here, the polyglacial-

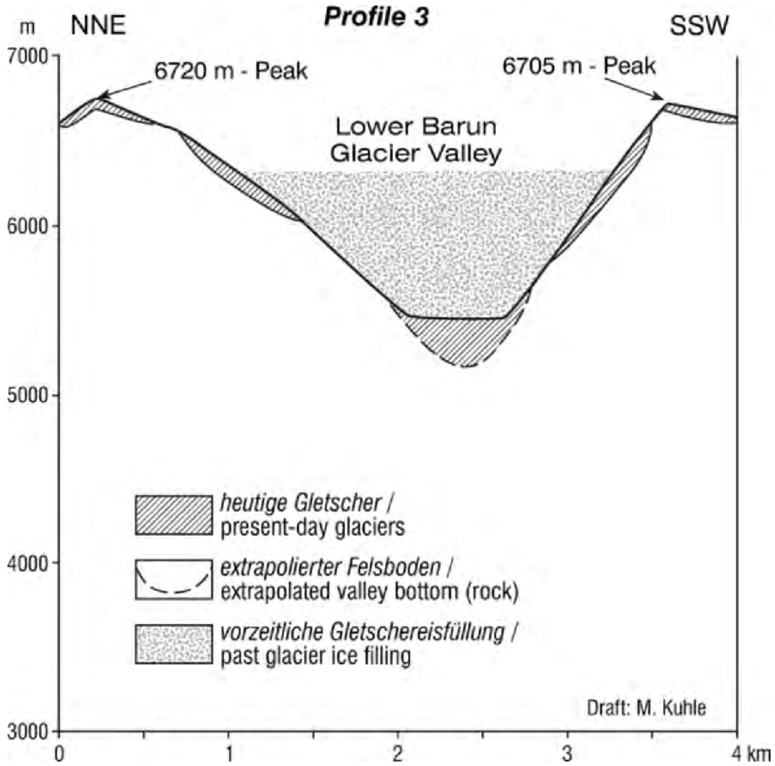


Figure 9. (Profile 3) Cross-section (not exaggerated) across the lower Barun glacier valley from the 6720 m-peak (No. 31, Figure 3) in the orographic left valley flank as far as the 6705 m-peak (Chamlang NE-satellite, No. 12, Figure 3) in the right valley flank with its minimum glacier ice filling reconstructed for the last glacial period (ca. 60–18 Ka). Locality: Figure 4.

classic forms of valley flanks are concerned (Davis, 1912: 417 – Figure 149 between G and C; 453 – Figure 175 between P, M and G; 454 – Figure 176 from T and B to C; 459 – Figures 178 and 179; Kuhle, 1991b) typical of high mountains heavily glaciated at glacial times and still glaciated interglacially. On these orographic right triangle-shaped slopes flank polishings and High Glacial abrasion surfaces are preserved only at a small-scale (Photo 4 ∩). Mostly they have been late- to postglacially reshaped by crumblings, local erosion of meltwater and denudation by rock fall (▽; Photo 2 below of *** on the left). In many places surfaces of block debris typical of postglacial frost weathering (Photo 3 above ∩; 5 above ∩ on the very right) known from the mountainous Scandinavian past inland ice areas, have been developed. The slope-faces, which become broader and flatter toward the slope foot, are covered with ground moraines the thickness of which

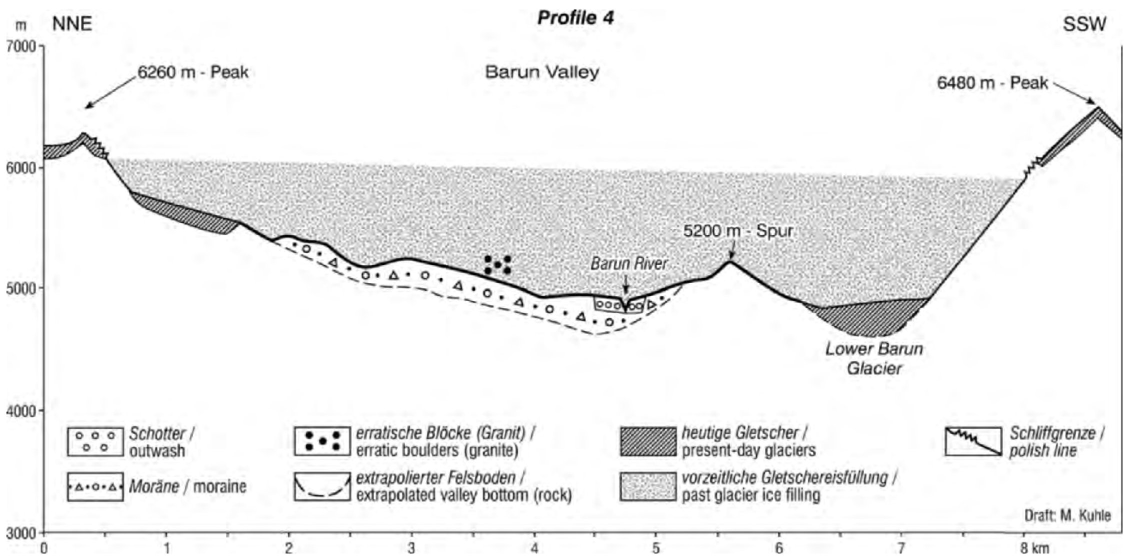
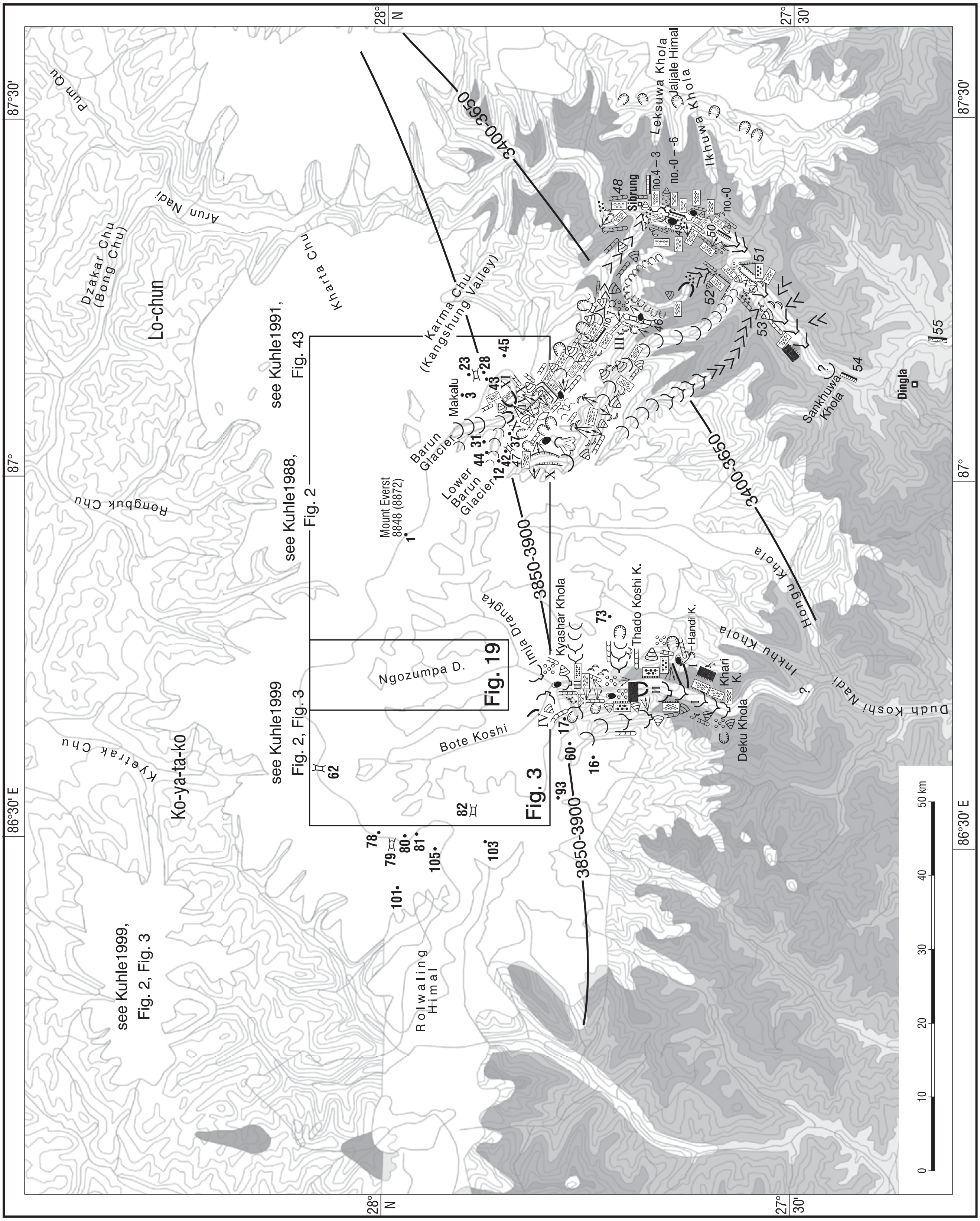


Figure 10. (Profile 4) Cross-section (not exaggerated) across the Barun valley in the confluence area of the upper and lower Barun glacier valley from the 6260 m-peak (SE-satellite of the 6825 m-peak, No. 23, Figure 3) in the orographic left valley flank as far as the 6480 m-peak (No. 42, Figure 3) in the right valley flank with its minimum glacier ice filling reconstructed for the last glacial period (ca. 60–18 Ka). Locality: Figure 4.


28° N
27° 30'
86°30' E
87°
87°30'
Pum Qu
Dzakar Chu (Bong Chu)
Arun Nadi
Lo-chun
Kharta Chu
Karma Chu (Kangshung Valley)
see Kuhle1991, Fig. 43
see Kuhle1988, Fig. 2
see Kuhle1999 Fig. 2, Fig. 3
see Kuhle1999, Fig. 2, Fig. 3
Rongbuk Chu
Kyetrak Chu
Ko-ya-ta-ko
Rolwaling Himal
Mount Everst 8848 (8872)
Makalu
Barun Glacier
Lower Barun Glacier
Ngozumpa D.
Fig. 19
Fig. 3
Bote Koshi
Imja Drangka
Kyashar Khola
Thado Koshi K.
Handi K.
Khari K.
Deku Khola
Inkhu Khola
Hongu Khola
Dudh Koshi Nadi
Sankhuwa Khola
Dingla
Ikhuwa Khola
Leksuwa Khola
Jaljale Himal
Sibrung
3400-3650
3850-3900
0 10 20 30 40 50 km

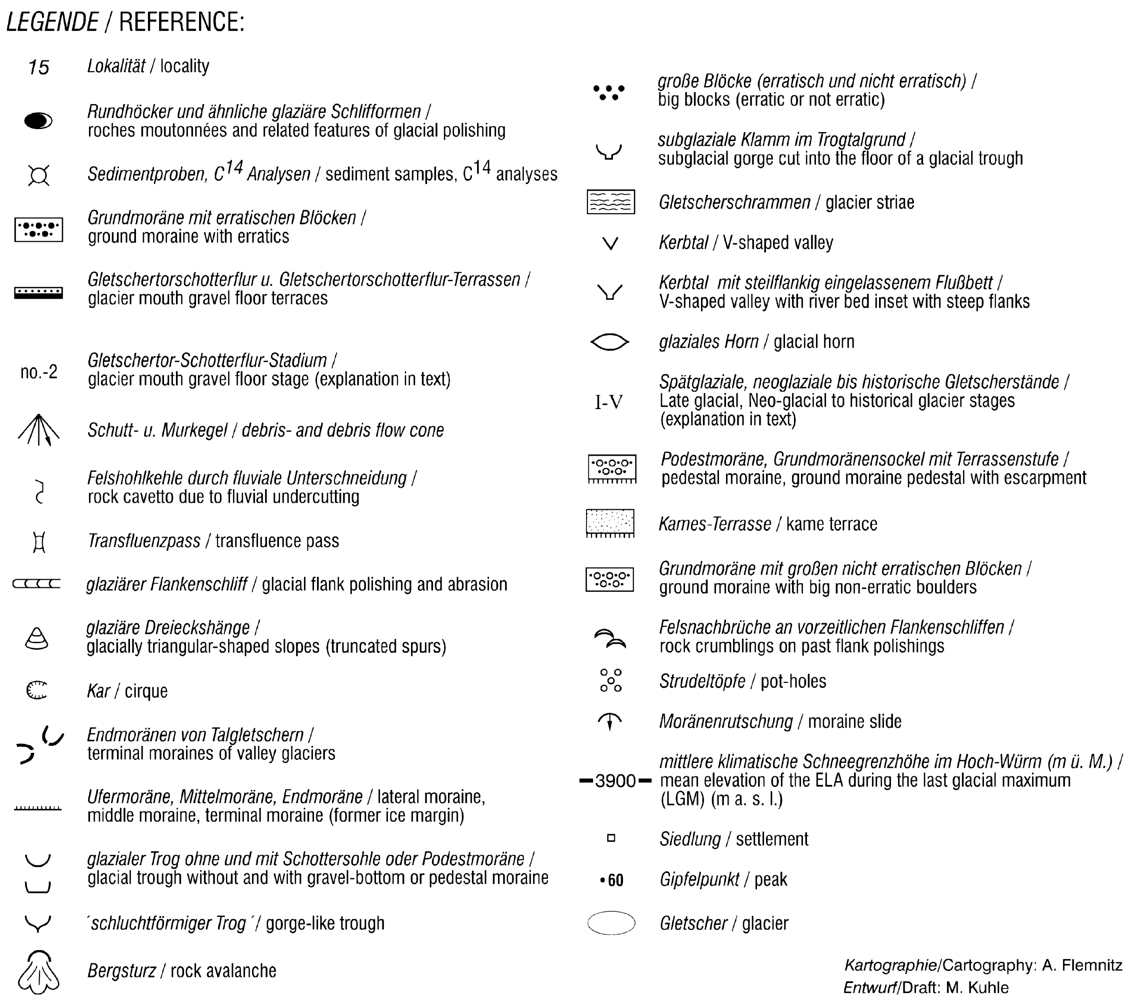


Figure 11. Quaternary-geological and glacio-geomorphological map 1:700,000 of the Khumbu- and Khumbakarna Himal (Cho Oyu-, Mt. Everest- (Chogolungma- i.e. Sagarmatha-) and Makalu massifs) in the Central Himalaya. See Figures 2–4.

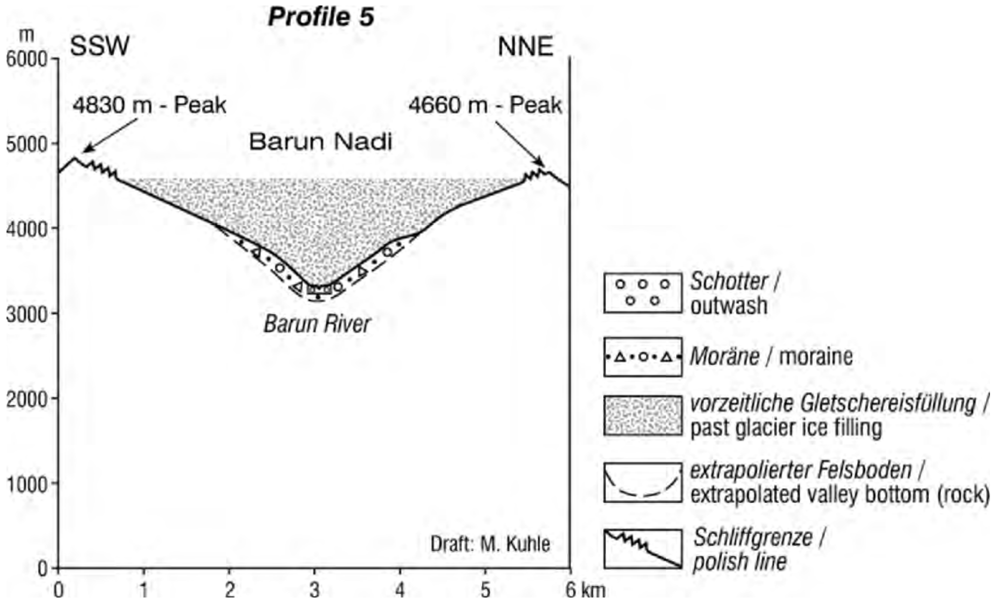


Figure 12. (Profile 5) Cross-section (not exaggerated) across the middle Barun Nadi (valley), looking up from the 4830 m-peak or spur-summit in the orographic right valley flank as far as the 4660 m-spur-summit in the left valley flank with its minimum glacier ice filling reconstructed for the last glacial period (ca. 60–18 Ka). Locality: Figure 4.

increases in a downward direction (Photo 2 ■ small on the left; Photo 3 ■ small; Photo 4 ■; Figure 7). Since the melting down of the Barun parent glacier, rills of melt-water erosion, fluvial redepositions (Photo 4 below and on the right of ■ white) and angular rock boulders (○) deriving from wall-crumblings (▽), which took place after the deglaciation of the upper slopes, are to be observed besides moraine boulders. Neoglacial and historical up to contemporary (Stage V–XII, see Table 1) lateral moraine ledges have been attached to these covers of ground moraine by the Barun glacier (Figure 3; Photos 1–6). The orographic right lateral moraine of the Stages VII–X partly forms a clear-cut crest. The fine material matrix ($\leq$2000 μm) of the moraine preserved *in situ* at 5150 m a.s.l. (sample 6.12.94/2, locality see Figure 3; right margin of Photo 5, foreground) shows a primary grain size maximum in the fine sand and a secondary one in the clay. 57.5% of the morphoscopically analysed quartz grains of the sample have already been reshaped fluvially and eolianly (Figure 6 No. 10). A comparative sample, taken from the surface moraine of the current Barun glacier at 5200 m a.s.l. (sample 6.12.94/1, locality see Figure 3; Photo 3 foreground) shows – at the same petrographic catchment area – a much higher proportion of musco-vite grains, which have not yet been washed out, and not quite 36% quartz grains reworked fluvially and eolianly (Figure 6, No. 9). At a corresponding geological catch-

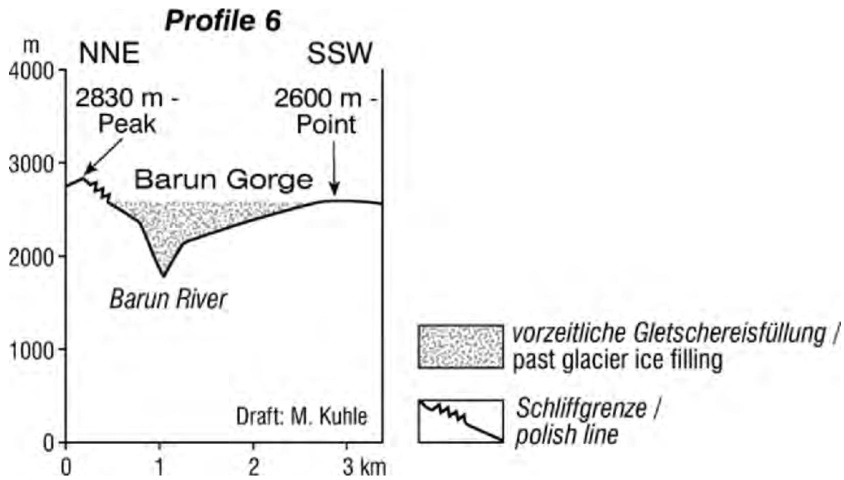


Figure 13. (Profile 6) Cross-section (not exaggerated) across the lower Barun Nadi (valley) looking down from the 2830 m-peak or spur-summit into the orographic left valley flank as far as the 2600 m-point in the right valley flank with its minimum glacier ice filling reconstructed for the last glacial period (ca. 60–18 Ka). Here, the interlocking of two valley profiles is concerned: an upper, trough-shaped profile down to the talweg at 2150 m (see orographic right profile-bend above the steeply sloping flank of the gorge) and a lower narrow gorge-shaped V-profile down to 1800 m a.s.l. Owing to a faulting followed by its incision, the profile of the gorge shifted from the original centre of the valley 500 m to the left (NNE). Locality: Figure 4.

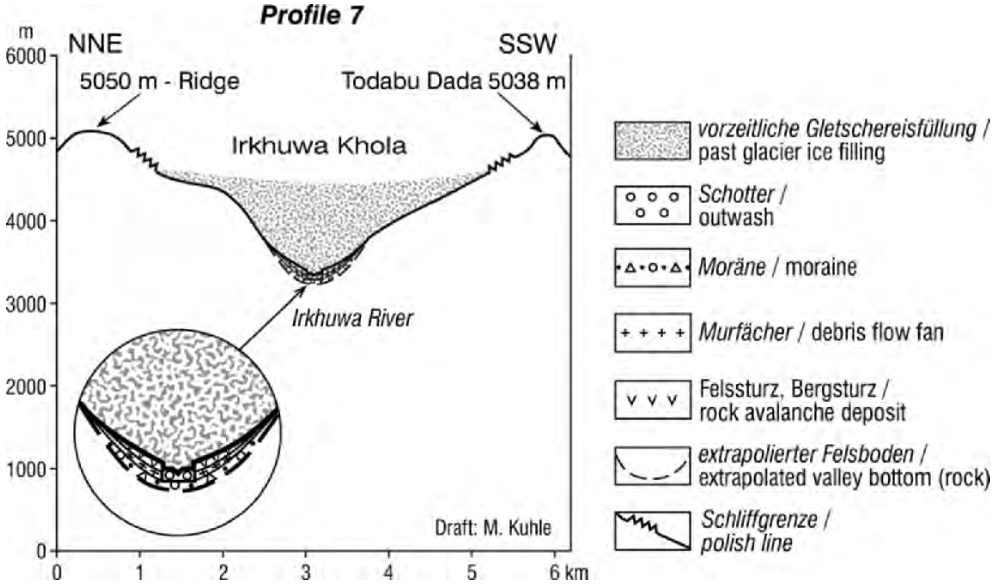


Figure 14. (Profile 7) Cross-section (not exaggerated) across the Irkhuwa or Isuwa Khola (valley), looking down from the 5050 m-ridge or spur-summit in the orographic left valley flank as far as the 5038 m-high Todabu Dada on top of the right valley flank with its minimum glacier ice filling reconstructed for the last glacial period (ca. 60–18 Ka). Here, a classic trough valley profile is concerned, which, on the orographic left side at a level of ca. 4400 m, toward above is brought to an end by a convex transition into a cirque terrace (cf. Photos 24, 25, right halves). This cirque terrace has been developed on an old surface level. It has been – and still is – formed from the late Late Glacial (Stage IV, Table 1) up to the historical cirque glaciation, i.e. mainly during interglacial periods. Cirque terraces such as these are typical of the European Alps, whilst in the Himalaya they are rarer. The Ice Age glacier surface lay ca. 1000 m above the snow-line. Due to the marginal accumulation of avalanches and the increasing velocity of discharge in the middle of the valley the centre of the glacier was lower than the margins (the glacier surface sagged). The trough shape has been favoured by a tectonic graben, on which the Irkhuwa Khola developed. Locality: Figure 4.

ment area these samples provide an appropriate base of comparison for the down-valley past Late- to Last High Glacial moraines from which samples have been taken. Kalvoda (1992) describes and documents bedrocks of the upper catchment area in the upper Barun Nadi, which turn up again in the samples taken from these moraines. So, for instance, he introduces the Miocene leucocratic granite intrusions in the lower high intensity injection zone of the Makalu Formation above 6250 m a.s.l. in the south-western face of the Makalu as being biotite-muscovite granite and originally Precambrian paragneisses (ibid.: 96–97, Plate IX/1/2–XI), from which the light granite boulders and dark-banded gneiss boulders, as well as the light and dark mica grains and the morphoscopically analysed quartz grains, originate.

Here, also the glacial-historical reconstructions have to be stated, which Kalvoda (1979a, b) was the first to

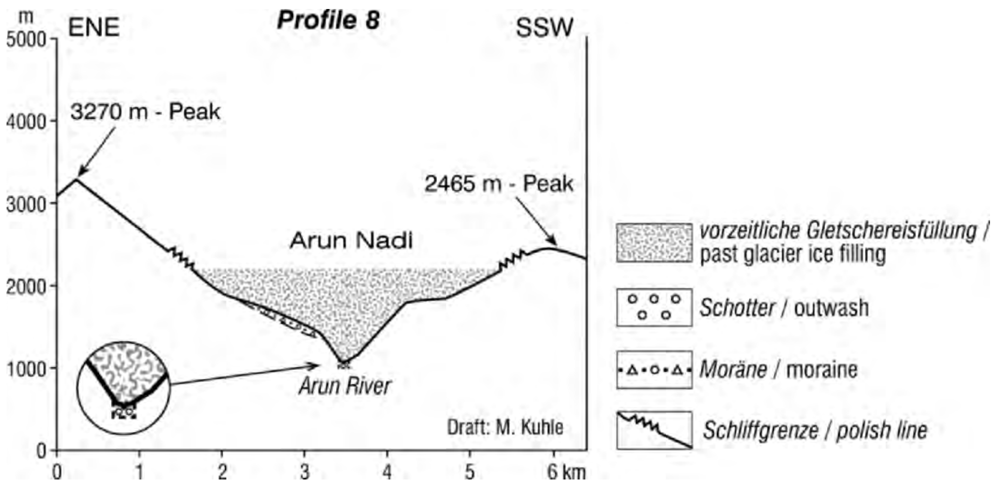


Figure 15. (Profile 8) Cross-section (not exaggerated) across the Arun Nadi main valley, looking down from the 3270 m-high spur-summit in the orographic left valley flank as far as the 2465 m-peak or spur-summit on top of the right valley flank with its minimum glacier ice filling reconstructed for the last glacial period (ca. 60–18 Ka). Two interlocked valley cross-profiles are concerned: an upper profile with a very wide bottom and steeply rising slopes (the orographic left one is especially steep), which, accordingly, shows the character of a trough valley profile, and a V-shaped cross-profile set into the trough bottom 300–700 m deep (cf. Photos 27, 30, 41). The trough bottom of the upper cross-profile has developed on a pre-glacial, i.e. pre-Pleistocene, Tertiary old surface level. It has been syngenetically cut through subglacial meltwater erosion during high glacial periods and through fluvial linear erosion during the ice-free episodes in interglacial periods, i.e. during the Pleistocene, so that the lower V-shaped valley profile has come into being. Locality: Figure 4.

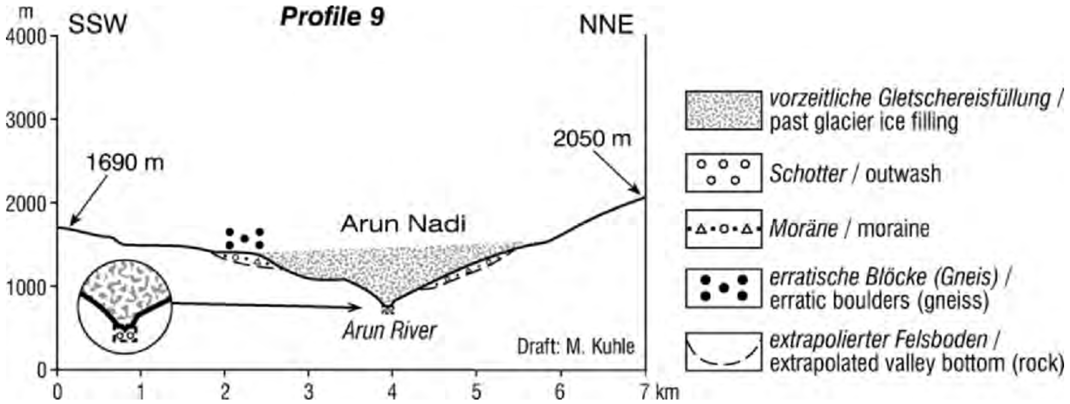


Figure 16. (Profile 9) Cross-section (not exaggerated) across the Arun Nadi main valley, looking down from the 1690 m-point on the spur, 1.3 km SSW of the Num settlement in the orographic left valley flank as far as the 2050 m-point near to the Bakle hamlet on the right valley flank with its minimum glacier ice filling reconstructed for the last glacial period (ca. 60–18 Ka = Stage 0; Table 1) (see also Photo 46). Here too (cf. Figure 15), two interlocked valley cross-profiles are obvious: an upper one with a very wide bottom, showing several characteristics of a trough valley profile, and a V-shaped cross-profile, set into the bottom of this wide trough-profile ca. 300–400 m-deep. The valley bottom of the upper cross-profile has developed on a pre-glacial, i.e. pre-Pleistocene, Tertiary old surface level, which still approx. represents the current orographic left, ca. 500 m-wide valley terrace about 1100 m a.s.l. (between 3 and 3.5 km). It has been syngenetically cut here, ca. 2300–2600 m below the High Glacial ELA (snow-line), by subglacial meltwater erosion during the high glacial periods and by fluvial linear erosion during the ice-free interglacial periods, i.e. during the Pleistocene, so that the lower V-shaped cross-valley profile has come into being. Locality: Figure 4.

carry out in the upper Barun Nadi on both sides of the Barun glacier and in its forefield. However, Kalvoda's results, which do not concern the maximum past glaciation, cannot be discussed here with the appropriate accuracy, because my study is focused on the maximum High Glacial glaciation. In this respect a future paper is planned, which will be especially concentrated on the Holocene and historic glacier stages in the Central Himalaya and the Arun Nadi. The author has found many local confirmations of Kalvoda's investigations (ibid.) and comparable approaches to moraines. However, besides the observation of the maximum past ice filling of the valley, which Kalvoda did not consider, the author's renewed walking of the upper Arun Nadi has brought about a major difference as to the estimated age of the moraines. So, the author dates the striking, 100–120 m-high lateral moraine ledge on the orographic left side of the Barun glacier (Photo 1: VIII) as belonging to the historical Glacier Stage VIII (cf. Table 1) and thus as being only ca. 300–400 years old. Kalvoda (1992: 80–81, Plate VI/1) however, classifies it as belonging to the Holocene. This difference in dating, from which conclusions can also be drawn with regard to the age of the older, i.e. younger generations of moraine ledges above and below, has led to the author's compressed age model in contrast to Kalvoda's extended one.

2.1.1. Insertion concerning the reconstruction of the Late Glacial, neoglacial and historical morainic- and glacial landscape in the upper Barun Nadi

Due to its classification according to the common relative age scheme of Himalaya glaciers (Kuhle, 1982), the attached moraine of Stage X is considered as belonging to the glacier advance of the Little Ice Age from ca. 1820–1900 (cf. Table 1). By its corresponding level on a cross-profile of the Barun valley it can be diagnosed in many places on both valley sides (Photos 1–3, 5, 6: X). Its geomorphologically fresh character confirms this age dating. The tongue basin of the Barun glacier pertinent to Stage X, is filled with a lake, interrupted by the front moraine of Stage IX (advance in 1920; see Table 1) (Photo 7).

According to their geomorphological state of preservation, the lateral moraine ledges attached to the valley flanks along the upper Barun Nadi can generally be classified as belonging to three groups, which clearly differ: (1) the historical moraines of Stages XI–VII (Photos 1–3 and 5–12); (2) the neoglacial moraines of Stages ′VII–V (Photos 1–3, 6–10, 13, 14) and (3) the Late Glacial moraines, here only represented by the moraines of Stage IV [Photos 7–10 and 15 of Stages IV–I (Table 1; Figure 3)]. The lateral moraines of Stages III–I and those of the High Glacial maximum glaciation during the last glacial period (Stage 0 = Würm = last High Glacial maximum; Table 1) have no longer been developed in this valley section. The causative factor is that the glacier surface lay far above the corresponding snow-line and only ground moraines have been deposited, but no lateral moraines. Only 20 km down-valley ground moraines of Stage III can be distinguished (Photo 19; Figure 11 above No. 46). The nearly complete sequence of lateral moraine remnants up to their lower end and bending into a terminal- or front moraine is preserved between the end of the current Barun- and Lower Barun glacier from the historical Stage X up to the neoglacial Stage V as far down as ca. 4000 m (Photos 8–10; 12–14; Figures 3 and 11). Further down-valley no terminal moraines are to be diagnosed. The natural cause of this is the younger glaciofluvial and fluvial erosion by the Barun river in the narrow receptacle of the Barun Nadi.

The glaciofluvial modification of even the youngest terminal moraines, which geomorphologically are still unambiguously preserved, is proved by sample 4.12.94, taken from the terminal moraine of Stage X (Photo 7, X;

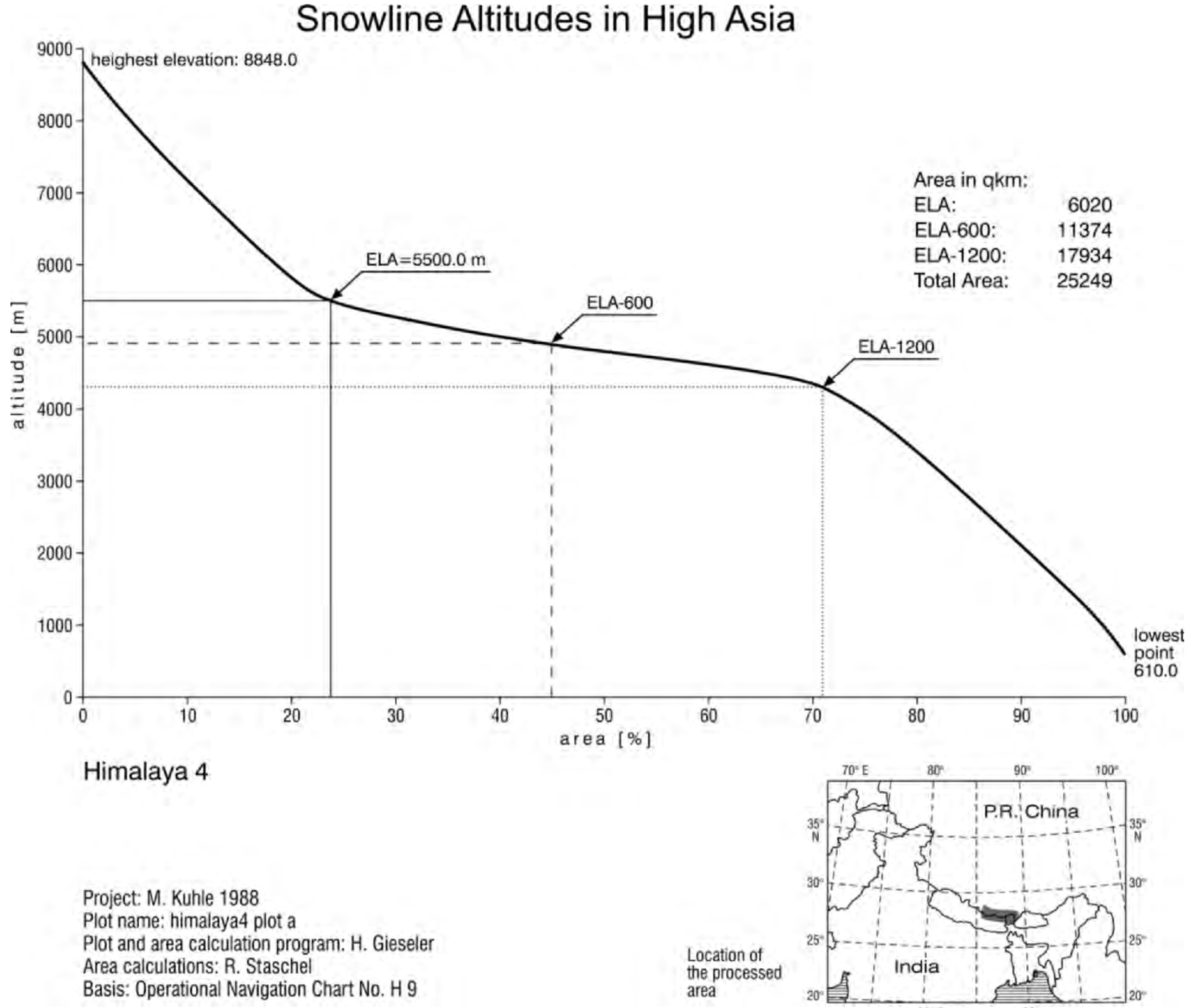


Figure 17. Contemporary High Glacial (Würm Age, last glacial period, last High Glacial maximum, Stage 0; see Table 1) and late Late Glacial snow-line altitudes (ELAs) in the investigation area (Figure 2 No. 1; Figures 4 and 11). The highest point of the current and past glacier feeding areas is the 8848 m-high Mt. Everest. The contemporary climatic snow-line runs at 5500 m a.s.l. The Late Glacial decrease of the ELA during Sirkung Stage IV (cf. Table 1) has been noted down with at least −600 m and the High Glacial one of the last glacial period, i.e. the Würmian Ice Age or Stage 0 (cf. Table 1), with −1200 m. As for the altitude-dependent parts of the surface of the test area in this valley landform of the Himalaya-S-slope the increase in glacier feeding areas at corresponding ELA-depressions is shown. At the same time the factor concerning the elevation of the ice surface, which additionally and by feedback reinforces the glacier development, has not been taken into account. Nevertheless, the increase in the glacier feeding area from currently 6020 km^2 via 11,374 km^2 during the late glacial period and 17,934 km^2 during the high glacial period is so significant that inclusive of the ablation area the entire investigation area (25240 km^2) must have been glaciated during the High Glacial. In the high mountain valley landscape concerned the ratio of the surface of the glacier feeding- to the ablation area is ca. 2:1. This corresponds to an AAR (accumulation area ratio) of 0.66. Cf. Figure 18.

locality: Figure 3). During the 200 years between ca. 1800 and 2000, which at most have been available, the seepage of glacier meltwater was able fluvially to polish not quite 30% of the quartz grains (Figure 6, No. 8). Somewhat more than 30% even grew dull through the constantly blowing glacier wind.

Much more unambiguously glacigenic, however, is the matrix of the ground moraine terrace of the 13,000 years older Stage IV (sample 3.12.94/1; locality: Figure 3; Photo 9). This is shown by more than 50% glacially crushed quartz grains (Figure 6, No. 7). But here, too, a fluvial modification becomes obvious: (1) (morphoscopically) by not quite 30% polished quartz grains and (2) (granulometrically) by the small clay portion of only 3% (Figure 5). The bimodal course of the curve characteristic of moraines is still preserved, but the insignificant sorting coefficient (So) of 2.63 likewise shows the secondary fluvial modification. However, the substantial thickness of this accumulation, in the matrix of which erratic boulders are embedded, as well as its great height of 500 m above the valley bottom of the Barun Nadi (Figure 10 Pro 4; Photos 8–10, IV), unequivocally evidences its morainic character.

During historical times up to the present day the glacier tongue of the 6825 m-peak S-glacier (Photo 9 below No. 23) has been adjusted to the moraine terrace

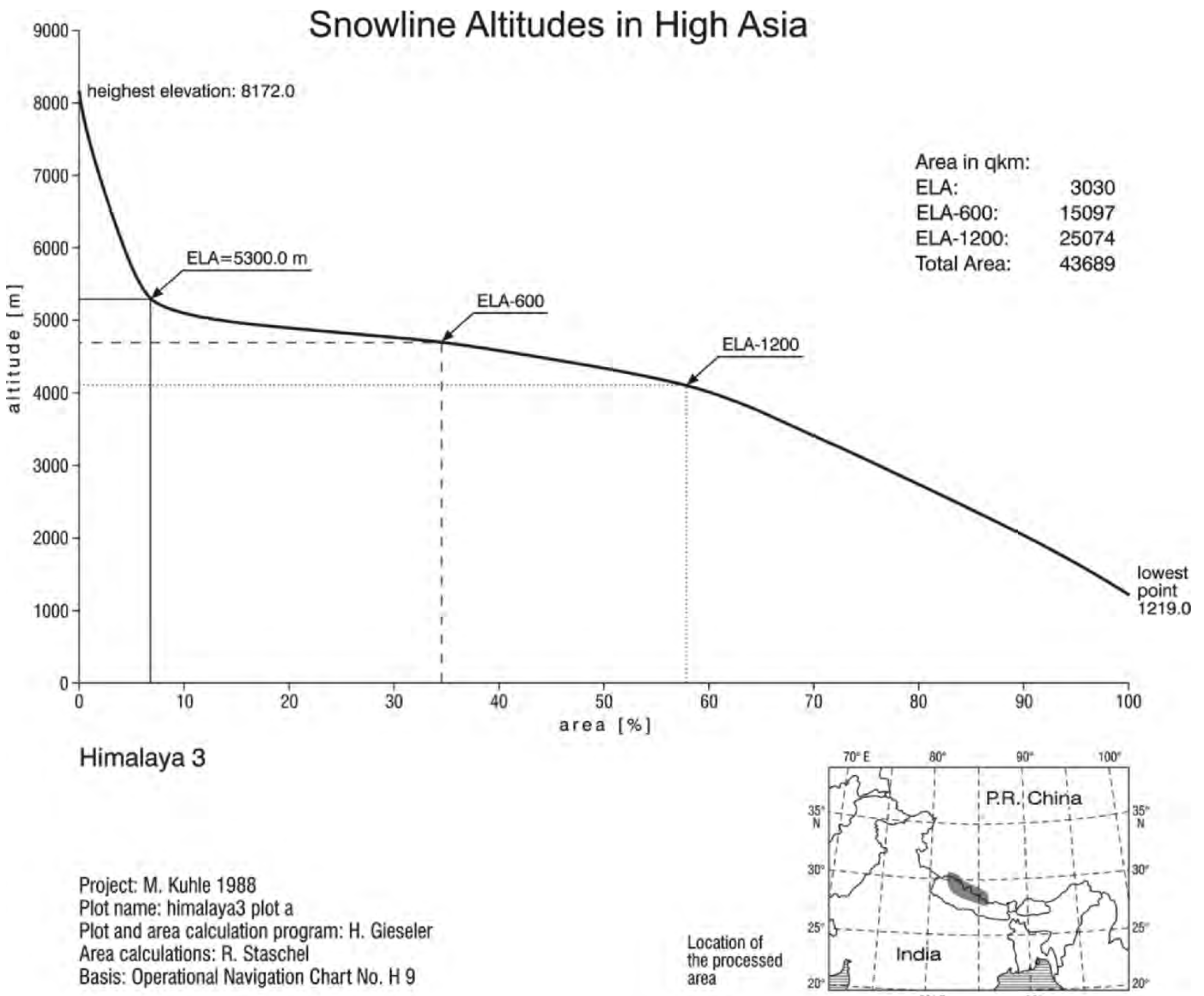


Figure 18. Here, the increase in the glacier feeding area is indicated in the same way as in Figure 17 (see text of Figure 17). Himalaya 3 (Figure 1 No. 2; Figure 2 No. 4) is a test area for comparison with Himalaya 4 (Figure 17), ca. 350 km W from the research area treated in this paper. The highest point of the current and past glacier feeding areas is the 8172 m-high Dhaulagiri. The correspondence of this likewise extended glacier cover to that of the area of Mt. Everest concerned (Himalaya 4; Figure 17) proves that this is no local specific feature, but a High Glacial glaciation of the ice stream network representative for the entire Himalayan arc.

of the Late Glacial Stage IV (Photo 9 VII, IX, X on the very right; Figure 10) and, accordingly, has contributed to its development into a pedestal moraine by its significantly greater extension during this stage. This large Late Glacial pedestal moraine terrace in the middle of the upper Barun Nadi (Figure 3 near viewpoints 8 and 9) has also been built-up at the same time by the Barun glacier tongue, because the glacier tongues, today separated, have coalesced. This is inevitably deducible from the corresponding ELA-depression of ca. 700 m. Thus, during that time the Barun Glacier tongue flowed 400–500 m higher. Accumulations of pedestal moraines below the ice such as this are typical of Late Glacial Himalaya glaciers (Kuhle, 1983a: 125–128). The reason for this is that the submoraine masses under the ice, accumulated during the high glacial period with an increasing snow-line, are no longer transported away. The position of the Late Glacial ice becomes higher, because the submoraine becomes thicker. During the High Glacial (Stage 0; Table 1) the at least 200–300 m-thick masses of the pedestal moraine, which during the Late Glacial increased and in the meantime thawed and became devoid of ice, have been occupied by the ice of the Barun glacier and the 6825 m-peak S-glacier. The pedestal moraine cannot have existed in the High Glacial, because the intensity of the ground scouring of the much thicker glacier, dependent on the high pressure, has prevented its accumulation. At that time the valley chamber discussed here, lay under a ca. 1400 m-thick ice (Figure 10), so that it was a marked area of glacial erosion. During the further, still more intensive glacier shrinkage, the tongue of the Barun main valley glacier, which had become very narrow after the Late Glacial, has cut up to 300–500 m deep below the surface level of the pedestal moraine terrace (Photo 10, IV below No. 23; Photo 8 cf. IV with V and VIII; Figure 3 cf. on the left of viewpoint 8 IV with VIII). This erosive deepening during the Holocene glacier shrinkage was

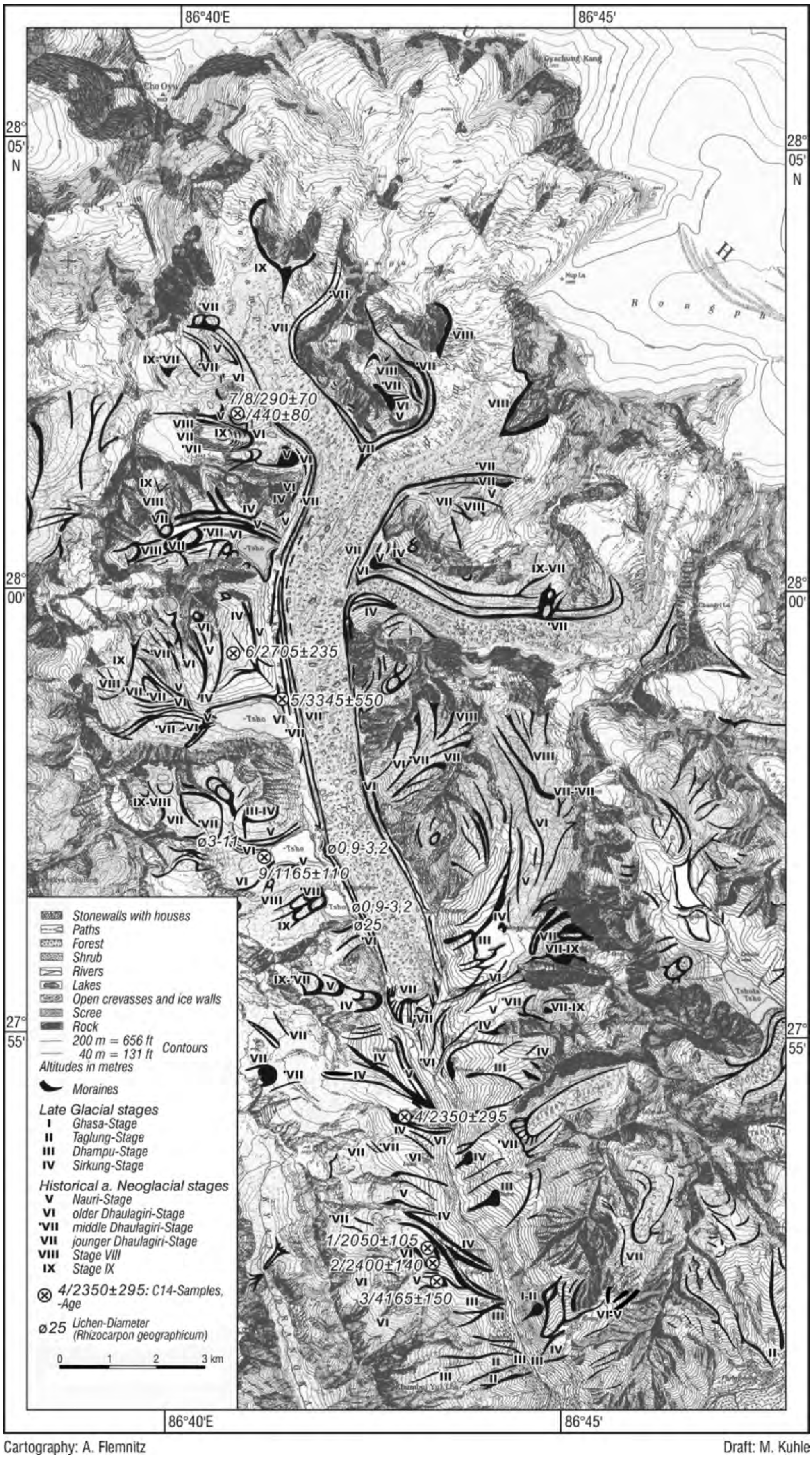


Figure 19. Late Glacial-, Neoglacial- and Historical glacier stages in the south slope of Cho Oyu with the Ngozumpa glacier system and the Ngozumpa Drangka. Reconstruction of the glacier stages. M. Kuhle (cf. Tables 1 and 2; Figure 3); topographic map E. Schneider.

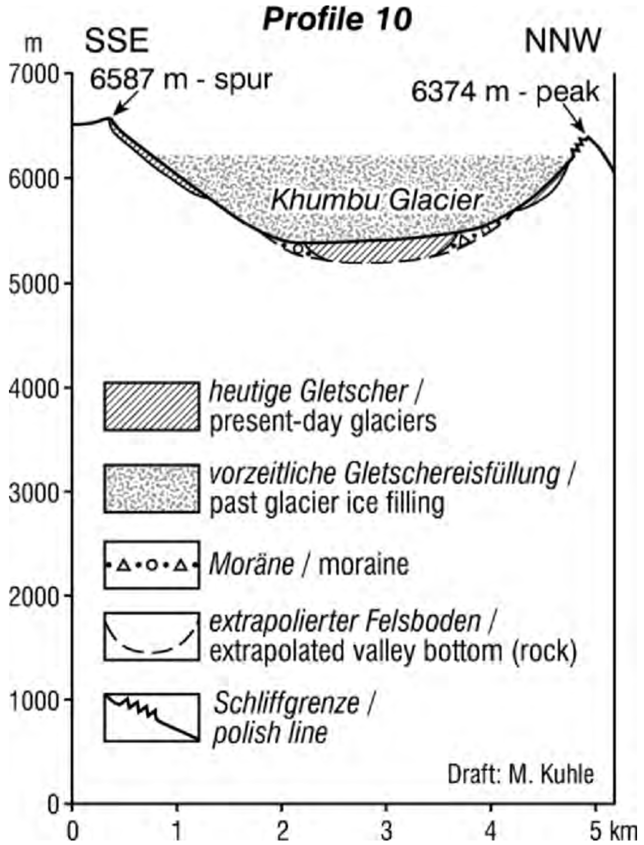


Figure 20. (Profile 10) Cross-section (not exaggerated) across the Khumbu valley looking down from the 6587 m-spur to the 6374 m-peak with its minimum glacier ice-filling reconstructed for the last glacial period (ca. 60–18 Ka = Stage 0; Table 1) (see Photos 53–57). It concerns a profile of a classic trough valley which by its orographic right polish line points to a past ice thickness of somewhat above 1000 m. The orographic left polish line has been covered and probably also reshaped by current flank glaciation. The Ice Age glacier surface was situated more than 2000 m above the related High Glacial ELA. Locality: Figure 3.

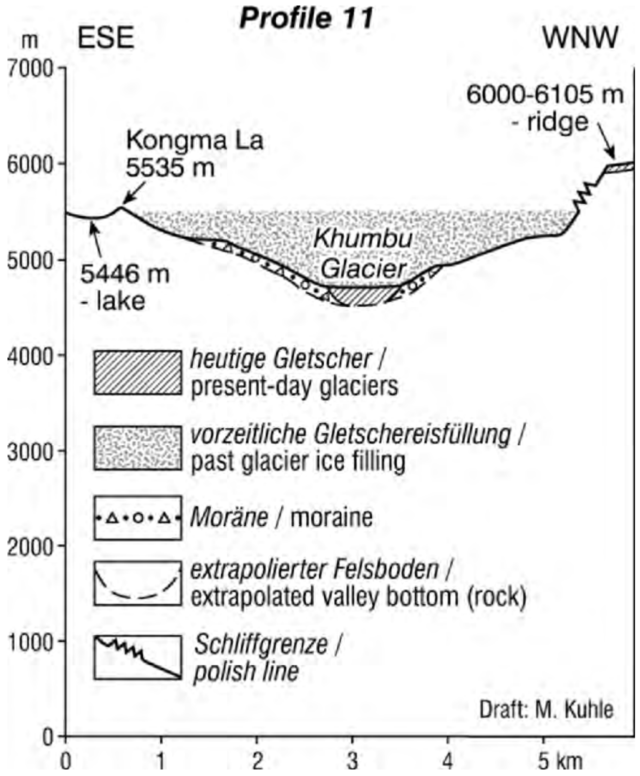


Figure 21. (Profile 11) Cross-section (not exaggerated) across the Khumbu valley looking down from the Kongma La to the 6000–6105 m-ridge with its minimum glacier ice filling reconstructed for the last glacial period (ca. 60–18 Ka = Stage 0; Table 1) (see Photos 61 and 63). Below 5200 m a classic trough valley profile is concerned. According to the orographic right polish line a past ice thickness of ca. 1000 m can be suggested. On the orographic left valley slope a ground moraine overlay covers the glacigenic polish flank up to 5250 m a.s.l. The Ice Age glacier surface lay nearly 2000 m above the simultaneous High Glacial ELA. The current Khumbu glacier has eroded the High- to Late Glacial ground moraine. Locality: Figure 3.

due to a progressive subglacial meltwater erosion, owing to the concentration of meltwater in only one subglacial talweg, linked with the shrinkage of ice.

The geomorphological chronology of the neoglacial (Stages V–′VII) and historical (Stages VII–XI) end- and lateral-moraine sequence is obligatory. The complete sequence is shown in Figure 3 and Photos 1–11. For comparison with the older moraines, four representative samples of historical moraines have been chosen. They describe the fine material matrix of Stages VII and X in lateral- and end-moraines (localities: Figures 3: 29.11.94/1/2 and 2.12.94/1/2). The morphoscopic quartz grain analyses show 57–71% of glacially crushed grains and less than 25% of fluvially polished (lustrous) grains. At most 18% of the quartz grains contained are eolianly treated (dull).

2.1.2. Geomorphological indicators as to late Late Glacial snow-line altitudes, i.e. snow-line depressions, and the chronology of the deglaciation of the Barun Nadi as well as the current lower limit of permafrost

A cirque with a flat, moraine-filled bottom and a steep back slope is situated in a W-exposition in the root region (proximal region) of the podest moraine of the Late Glacial Stage IV referred to above (Photo 7 ●; Figure 3 above viewpoint 8). A block glacier, which is still active today, i.e. an unambiguous indicator of permafrost, flows together with the material of the past moraine of the cirque glacier down to 4900 m a.s.l. (Photo 7▽; Figure 3 on the left above viewpoint 8). Accordingly, the permafrost limit lies below ca. 5000 m a.s.l. (cf. Kuhle 1978a; 1985c). At the level of the cirque floor about 5400 m, that is to say at ca. half the height of the corresponding past cirque glacier, the snow-line of this cirque glacier was situated. This glacier and the cirque can only have been developed after the Late Glacial melting-down of the Barun glacier surface below the level of the pedestal moraine of Stage IV (2.1.1.) about 5400 m a.s.l. The current orographic snow-line lies about 5900 m a.s.l., so that a snow-line depression of 500 m can be calculated. This snow-line depression is less than 700 m, which value has been determined for the somewhat older Late Glacial Stage IV (Sirkung-Stage; cf. Table 1) in the Central Himalaya (Kuhle, 1982: 150–168). Owing to this, the geomorphologically documented chronology of the ELA-depressions of 500 m and more (ca. 700) metres, in

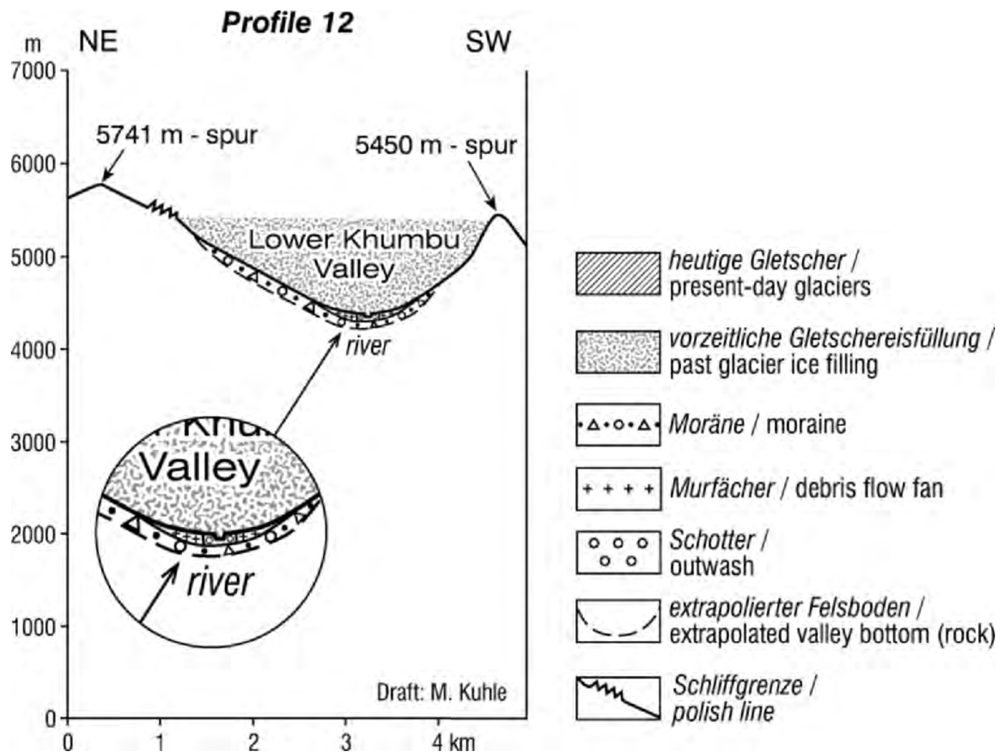


Figure 22. (Profile 12) Cross-section (not exaggerated) seen down-valley from the orographic left side across the lower Khumbu Drangka with the 5741 m-spur to the 5450 m-spur with its glacier ice filling reconstructed for the last glacial period (ca. 60–18 Ka = Stage 0; Table 1) (see Photos 64 and 66 from No. 40 to the right margin; 78 left third of the panorama). Below 5500 m an asymmetric trough valley profile is involved. According to the orographic left polish line a maximum past ice thickness of 1200 m can be assumed. On the orographic left valley slope a ground moraine cover up to ca. 5200 m a.s.l. upward masks the glacigenic polish flank. The Ice Age glacier surface lay approximately 1800 m above the simultaneous High Glacial ELA. The current Khumbu river is set into glacier mouth gravel floors of the Neoglacial to Historical (No. −1 to −6; Table 1) Khumbu glacier. The gravel floor is interlocked with debris flow fans. Locality: Figure 3.

comparison with the already investigated mountain-massifs of the Central Himalaya, points to the chronological classification of the cirque glacier as belonging to the ending late Late Glacial. The large pedestal moraine in the Barun Nadi (2.1.1.) has to be classified as being of the somewhat older late Late Glacial Stage IV. Due to absolute moraine datings (14C), which the author has carried out in the immediately W-adjacent Khumbu Himalaya (Kuhle, 1986g, 1987b), he has classified the same ELA-depressions as belonging to ages older than 13,500–13,000 YBP for Stage IV and somewhat (probably several centuries) younger for an ELA-depression of only 500 m (Table 1).

Summarizing Sections 2.1.1. and 2.1.2 it has to be stressed, that the late glacial coverage of the valley bottoms and the sections near to them by debris of pedestal moraines, which has taken place in many Himalaya valleys from the High Glacial Stage 0 onwards (last glacial period), i.e. since the deglaciation, can be evidenced here, too (Photos 8 and 9). Afterwards a subglacial fluvial cutting into these ground moraines took place, combined with their partial evacuation. Then the neoglacial (Holocene) and comparatively minor but thick historical moraines and flat glaciofluvial gravel fields (sanders) (Figure 10; Photos 7 and 10) have been inserted into these valley cross-profiles, developed toward the ending Late Glacial. A renewed burying of the valley bottoms also through lateral- and dumped-moraines, accompanied by the historical glacier shrinkage, currently takes place in the higher valley chambers (Photos 1–6; Figure 7 and 8).

2.1.3. Continuation of the reconstruction of the maximum Last Glacial Barun glacier and its trim-line from the valley heads of the Barun- and Lower Barun glacier valley up to the confluence of these two valley source branches between the Shershon- (Photos 9 and 10) and the Mera alpine pasture (Photo 12) (Figure 11 between Nos. 37 and 43)

Obviously, even the late Late Glacial ice level of Stage IV lay clearly above 5400 m a.s.l., i.e. the level of the pedestal moraine overflowed by this glacier stage (Section 2.1.1). This is evidenced by round-polished metamorphite ridges (Photo 7 ∩ on the right) covered by ground moraine (■ small on the right).

Ground moraine remnants situated very high up the valley flanks above the moraine levels of Stage IV testify to older, higher glacier trim-lines. They are sporadically preserved in the valley chambers above Shershon (Photo 4 ■ white; 6 ■ black and white on the right above; 7 ■ white, small; 11 ■ black on the left above). The highest past glacier trim-lines, which, accordingly, are classified as High Glacial (last glacial period, Würmian, Stage 0; see Table 1) (Photos 1–11: – – –; ****, ___, ...), can be diagnosed by geomorphologically preserved upper limits

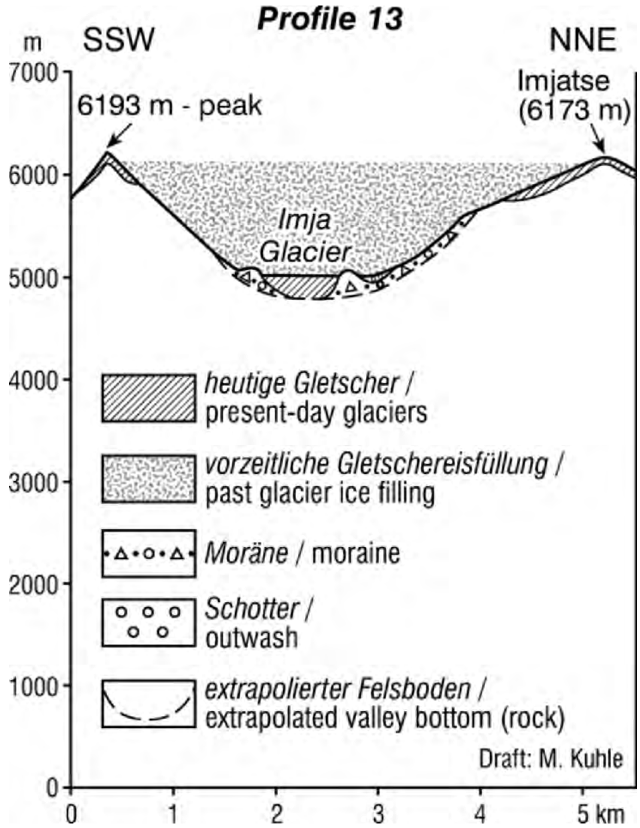


Figure 23. (Profile 13) Cross-section (not exaggerated) across the upper Imja Drangka (Khola) seen from the left side down-valley with the 6193 m-peak, that is the E-satellite of the 6238 m-peak (Figure 3 No. 58), to Imjatse with its glacier ice filling reconstructed for the last glacial period (ca. 60–18 Ka = Stage 0; Table 1) (see Photo 69 showing the cross-section up-valley). Up to an altitude of 5600 m a classic, slightly asymmetric trough valley profile is concerned. On the orographic right valley slope a ground moraine cover mantles the glacigenic polish flank up to ca. 5650 m a.s.l. On both valley flanks the past upper limits of abrasion are covered, i.e. reshaped by current flank glaciations, i.e. hanging glaciers. According to the shape of the cross-profile and the adjacent abrasion limits a maximum past ice thickness of 1300 m can be suggested. The Ice Age glacier surface lay approximately 2400 m above the simultaneous High Glacial ELA. The current Imja glacier has cut its bed into the Late Glacial (Stages I–IV; see Table 1) ground moraine pedestal. On the orographic right side a glaciofluvial lateral sander (outwash, gravel field: No. −3 to −7; Table 1) has been discharged into the lateral valley. Locality: Figure 3.

of polishing and abrasion on the rock slopes of the valley flanks through rock roundings, which toward above break-off linearly (Photos 1–11: ∩; Figure 3 on the left below and directly below No. 3; above and on the right of No. 39; on the right of No. 31; between No. 31 and 12; on the right of No. 42), by scoured truncated spurs and glacigenic triangle-shaped slopes (Photo 9▲; Figure 3 on the right of Nos. 29, 13, 30; from left to right below No. 3; between Nos. 12, 44 and 31; on the right of No. 42). In places the upper limit of wall foot pedestals – so far they are not dependent on the changing of rock resistance – is also a hard indicator of the highest trim-line. Wall foot pedestals, which occur at many places in the formerly glaciated Himalaya, are rounded rock flattenings, on the upper margins of which the valley flank steepens like a wall (Kuhle, 1982: 53; 1983a: 132–134). Here, in an upward direction, the cleft-controlled back shifting of the wall sets in, forced by subaerial processes like frost weathering, rock fall and wall glaciation with denudation by avalanches (Photos 6, 7 above −−− black; 8–10 above −−− on the right below No. 3; 9 above ____ on the left below Nos. 31, 37). This kind of development of a steep wall, which significantly sets in inan upward direction, is especially pronounced, because during the entire Pleistocene it has never been interrupted by an Ice Age glacier filling of the valleys up to its level. Owing to this, it is a special indicator of the highest past glacier trim-line.

At other flank localities the upper past polish line is verifiable at places, where wall ravines become abruptly narrower from above to below (Photo 11 cf. wall ravine on the left below No. 44 above and below of ...), that is below the polish line, where their development has started after the lowering of the glacier level during the Late Glacial deglaciation.

The altitudes of the glacier surfaces suggested in correspondence with the reconstructed past glacier trim-lines reach 6200–6300 m a.s.l., i.e. a maximum of 6450 m a.s.l. (Figure 7) in the source area of the Barun Nadi (Photos 1, 2, 8, 9 −−−, **** and ___). Accordingly, the transfluence passes at 6070–6275 m leading into the N-adjacent Kangchung Nadi (Khola) or Karma Chu (Figure 3 between Nos. 10 and 3; Figure 4) have been overflowed by ca. 230- to 30-m thick ice masses. The author's investigations in 1989, carried out on the other side of the transfluence passes, in the Karma Chu, have led to the same result (Kuhle, 1991a: 204–210; 225–229). There it is said about the Last Glacial Karma glacier: The Karma glacier "communicated with the S-Tibetan ice stream network, which was linked to the Kharta (Kadar) valley in the N. The ice had a considerable influx from the flanks of the high peaks mentioned above. At the same time, however, it was limited by the direct overflow of ice into the Himalayan south-slope. The Barun valley (ibid. Figure 43, No. 60) drained this ice overflow steeply down to the S, thus keeping the ice thickness there on the low side. The 6107 (or 6070) m-high transfluence E of the Pethangtse (ibid. Photos 104, No. 0⌒; 102 No. 0⌒) was overflowed as well as the 6177 (or 6130) m-high ridge W of Pethangtse (ibid. Photo 105⌒ right of No. 0), though both these ice transfluences are likely to have had thicknesses of at most 100–150 m" (ibid.: 210). The ice transfluence across the 6220-m high pass between Cho Polu (No. 29) and Shar Tse (Peak 38) (No. 10) from or into the W-adjacent Imja Khola had a thickness of just 100 m (Photo 1 −−−), as also that across the southern 6190 m-transfluence pass between Cho Polu and Baruntse (No. 13) (corresponding ice level see Photo 2 ****) (Figure 3 between Nos. 10 and 13). Three further ca. 6100 m-high transfluence passes, connected to the Barun Nadi on the orographic right side, which have mediated to the W-adjacent Lower Barun glacier branch, have been overflowed by an at most 30–100 m-thick ice (Figure 3 between Nos. 30 and 41; related ice level see Photos 4

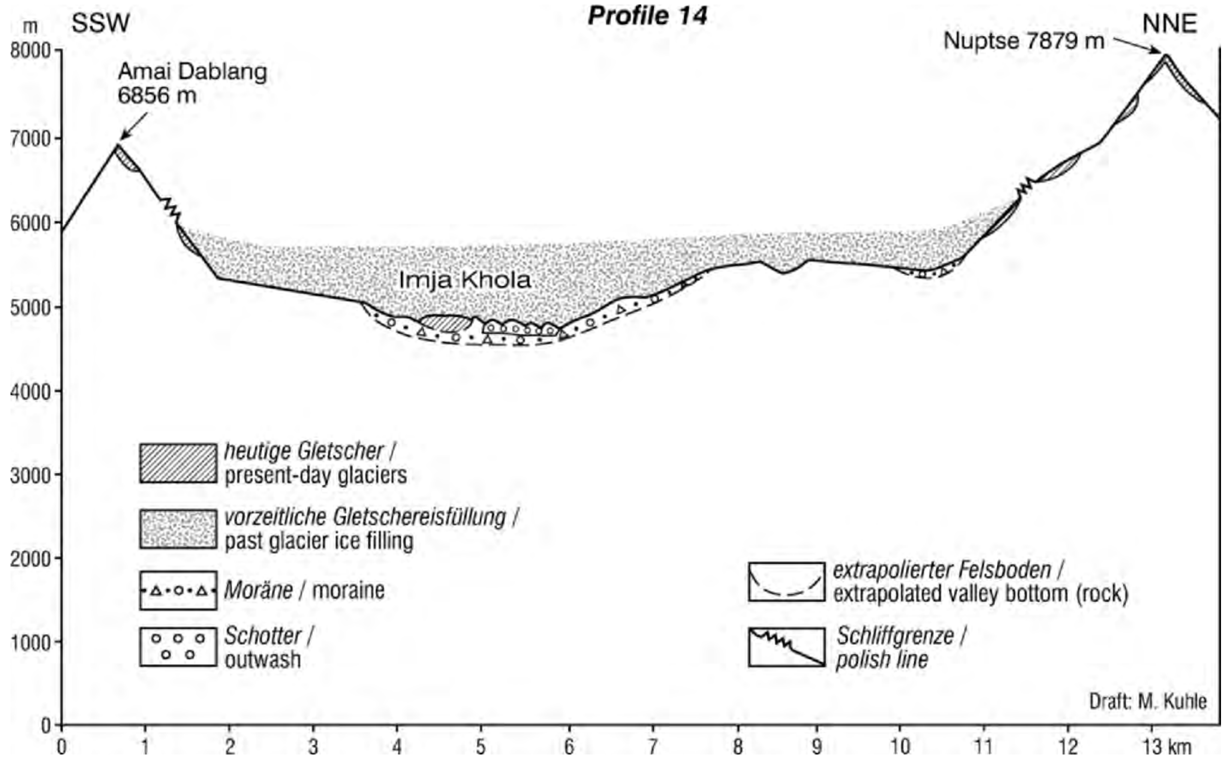


Figure 24. (Profile 14) Cross-section (not exaggerated) seen down-valley from the left across the middle Imja Khola (Drangka) with Amai Dablang (Figure 3 No. 20) to Nuptse (No. 8) with its glacier ice filling reconstructed for the last glacial period (ca. 60–18 Ka = Stage 0; Table 1) (see Photo 74 between Nos. 20 and 8). On the orographic left side an upper abrasion limit is preserved at not quite 6000 m and on the orographic right at 6100–6200 m. Due to the feeding by avalanches from the steep walls and the connected development of avalanche cones on the glacier surface the Imja glacier had a concave, i.e. marginally increasing, surface. So, at the same time its surface has inclined from NNE to SSW, because its feeding from the 1000-m-higher Nuptse-wall was stronger than that from the wall of Amai Dablang. On the orographic right valley slope a ground moraine overlay covers the bedrock up to ca. 5400 m a.s.l. According to the abrasion limits a maximum past ice thickness of ca. 1200 m can be suggested. The Ice Age glacier surface lay 2000 m above the simultaneous High Glacial ELA. The actual Imja glacier has cut its bed into the Late Glacial ground moraine pedestal. On the orographic right side a glaciofluvial lateral sander (outwash, gravel field: No. −3 to −8; Table 1) has been sedimentated in the lateral valley and accumulated on the ground moraine. Locality: Figure 3.

and 5 ____; Figure 8). In the direction of the approximately 15 km-wide valley chamber above the Shershon alpine pasture the altitude of the highest past glacier trim-line decreases to ca. 6000 m a.s.l. (Figure 10 left third of the profile; Photo 9 ____ below Nos. 23 and 43). This is due to the ca. 5770 m-high transfluence pass across which the upper ca. 230 m of the Barun glacier ice flowed steeply down into an orographic right side valley of the E-neighbouring, ca. 4000 m lower Arun Nadi (Figure 11 between Nos. 23 and 28; Photo 9).

The level of the Ice Age Lower Barun glacier reached – similarly to that of the upper Barun glacier – an altitude of 6400 m. Up to the confluence with the Chamlang glacier branch (Figure 3) it lost ca. 200 m in height (Photo 11 ...); then the level ran nearly horizontally over ca. 1.5 km up to the valley exit (Figure 9; Photos 8, 9, 10: −−−, i.e. ____ below No. 12). In the area of the connected junction, i.e. confluence step, down to the main valley, where an ice fall is presently situated (Photo 11), the Ice Age glacier trim-line of the Lower Barun glacier decreased to ca. 5900 m a.s.l. and thus to the joint level with the Barun main glacier (Figure 10; Photos 8 and 9:____ on the left below No. 31). The level in the source basin of the Lower Barun glacier is controlled by the ice overflow of the 6135 m-high West Col transfluence pass (Figure 3 below No. 30), so that the ice surface is lower than it otherwise would have been accumulated. Thus, at the ice level of ca. 6400 m a.s.l. (see above), the thickness of the overflowing glacier ice, which discharged into the Hunku Drangka (Khola) (height of the valley bottom 5200 m), was ca. 270 m. The three further transfluence passes, which had a joint ice level with the upper Barun glacier branch, have already been mentioned. As for the ice level in the confluence area of the two source branches of the Barun valley (Figure 10 right half of the profile), the past ice transfluence between the Barun Khola and Irkhuwa Khola, the Iswa La (Figure 3 and 11 No. 47; Photos 9 and 10 No. 47), is important. Here, the highest trim-line runs from ca. 5900 m (see above) down to 5850–5800 m a.s.l. along the N-flank of the Iswa Peak (or Peak 6) (Photo 9 ____ on the left below No. 37), so that in relation to that 5340 m-high pass a 510–560 m-high ice overflow into the neighbouring valley could have occurred. However, the High Glacial glacier level of the Irkhuwa (Isuwa) Khola with its height of 5300 m has held against it (Photo 24), so that a steep and at the same time very fast and thus mass-effective discharge cannot have taken place from the Barun- into the Irkhuwa Khola.

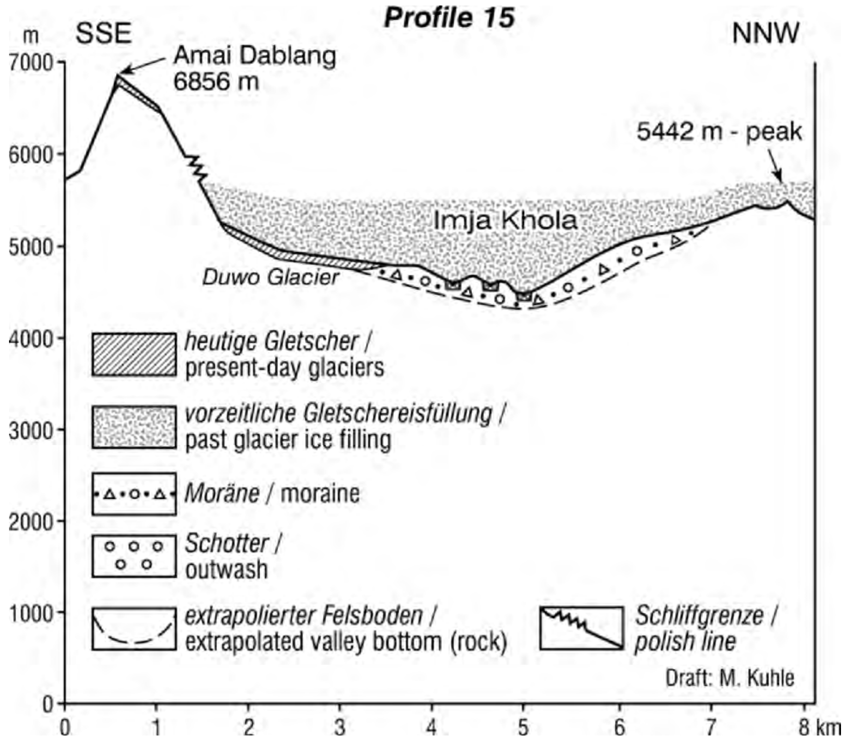


Figure 25. (Profile 15) Cross-section (not exaggerated) seen from the orographic left side down-valley across the lower Imja Khola (Drangka) with Amai Dablang (Figure 3 No. 20) to the 5442 m-peak with its glacial ice filling reconstructed for the last glacial period (ca. 10–18 Ka = Stage 0; Table 1) (see Photo 68 between No. 20 and ∩ black on the right below No. 53; Photo 76 between No. 20 and ☗ on the right below No. 53). On the orographic left side an upper abrasion limit runs at 5650 m; on the orographic right the rock ridges are glacigenically abraded and rounded. Due to the avalanche feeding from the steep walls and the connected development of avalanche cones on the glacier surface, the Imja glacier has had a concave, marginally increasing surface on the orographic left side. On the orographic right side, too, its surface has been heightened by the supply of ice avalanches from the 2200 m-high Nuptse-wall. At the orographic right valley slope a Late Glacial (Stage I–III or IV, Table 1) remnant of a ground moraine pedestal covers the abraded rocks up to ca. 5350 m a.s.l. According to the abrasion limit a past maximum ice thickness of ca. 1200 m can be suggested. The Ice Age glacier surface lay ca. 1700–1800 m above the simultaneous High Glacial ELA. The current Duwo glacier is adjusted to the Late Glacial ground moraine pedestal. Glaciofluvial gravel bands have been accumulated in the postglacial fluvial incisions of ground moraine. Locality: Figure 3.

In comparison with all transfluence passes, the most substantial loss in ice masses has been caused by the transfluence pass toward the E (Figure 11 between Nos. 23 and 28; Photo 9 ⌒), down the steep slope into the Arun Nadi (see above), because – due to the relief – no abutment could develop there. Despite that, the over-flowing ice was 230 m-thick. This is evidenced by the polished rock head (☗ on the left below No. 28) and can be explained by the insignificant viscosity of very cold ice a good 2000 m above the snow-line.

In the confluence area of the two source branches of the Barun Nadi (Photos 10 and 11), the upper and the lower Barun Nadi, the sequence of the decreasing heights of the glacier levels from the High Glacial confluence of the two glacier surfaces (____, −−−, ...) reaching up to 1300 m above the rock bottom of the valleys, up to the lateral- and end moraines of the two thin glacier tongues, which during the neoglacial (′VII) to historical time (VII–X; cf. Table 1) were separated, and finally up to the current glacier margins, can be completely followed (Figure 3 between Nos. 23, 31 and 47). The ground moraine areas of the interlocking past ice margins, which become younger and younger, are partly covered by gravel fields (sander) of the corresponding younger glacier mouth gravel floors (e.g. Photo 10 □ −4; Figure 3 No. −4). In this confluence area the transition from the High- to Late Glacial features (Stage 0–III; see Table 1) marked by glacial erosion- or denudation forms as e.g. flank polishings (Photos 10 and 11: ∩), to the late Late Glacial accumulation forms, i.e. moraines (Stages IV–X) and gravel fields on the same valley cross-profiles is also well recognizable by small-scale ground moraine remnants on the polished rocks on the slopes (Photo 11 ■). In the valley cross-profiles further down, the moraines are becoming older and older, because the valley chambers down from the Mera alpine pasture are currently no longer glaciated (see below Section 2.1.4). Therefore, in the downward direction the past glacigenic store of forms is increasingly better preserved, because the number of glacier advances and their destructive work wanes.

The reconstruction of the ice levels of the upper valley chambers of the Barun Nadi with regard to their maximum ice thicknesses can be summarized into four exemplary data: in the Barun glacier valley the ice thicknesses amounted to ca. 1200 m (Figures 7 and 8) during the Last Ice Age, in the Lower Barun glacier valley to ca. 1150 m (Figure 9) and in the confluence area of the two source branches of the Barun valley to ca. 1300 m (Figure 10).

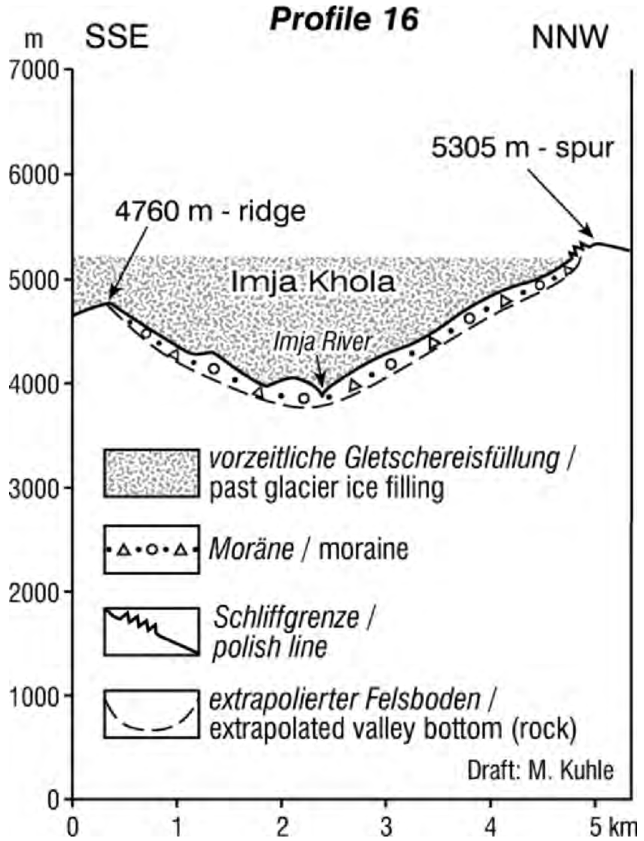


Figure 26. (Profile 16) Cross-section (not exaggerated) seen from the left side down-valley across the lower Imja Khola (Drangka) with the 4760 m-ridge to the 5305 m-spur with its glacier ice filling reconstructed for the last glacial period (ca. 60–18 Ka = Stage 0; Table 1) (see Photo 83 from behind ◥ below No. 36 up to the right margin). On the orographic right side is an upper abrasion limit at 5250 m; on the orographic left the rock ridges have been glacigenically rounded and abraded, i.e. they have been overflowed. The entire valley cross-profile is covered with ground moraine. According to the abrasion limit a maximum past ice thickness of ca. 1450 m can be inferred up to the rock ground of the valley bottom. The Ice Age glacier surface lay ca. 1500 m above the simultaneous High Glacial ELA. The present-day Imja river is cut into the ground moraine. Locality: Figure 3.

2.1.4. Reconstruction of the maximum Last Glacial Barun glacier and its trim-line in the valley chamber between the Mera Kharka (Photo 12, Figure 4) and Yangri Kharka (Photo 17, Figure 4; Figure 11 on the left below No. 45) alpine pastures with references as to the younger glacier history

The last stage during which the Upper and Lower Barun glacier have joined was the neoglacial Stage V (Table 1). They flowed together with a thickness of over 100 m near the Shershon alpine pasture. This is evidenced by ca. 190 m-high lateral moraines of this stage on the orographic right side in the upper Barun Nadi (Figure 3, Photo 8: V). During Stage VI the two glacier tongues were perhaps even just in ice contact. In any case, the tongue of the Lower Barun glacier still reaches far beyond the confluence area, i.e. nearly down to the Mera Kharka alpine pasture (Figure 3, Sedua) (Photos 9 and 10: □ on the right of X; Photo 12, X on the left). During the oldest neoglacial Stage V the joint glacier tongue, i.e. the tongue of the Barun main glacier, flowed down to ca. 4000 m a.s.l. past the Mera Kharka alpine pasture. This is proved by ca. 100 m-high, end-moraine-like lateral moraine ramps with relatively flat (17–27°-inclined) outer slopes (Photos 13 and 14: V; Figure 11 V on the left below No. 45). On these moraine slopes at the level of the timberline rhododendron copse already grows in the climax stage. This merely proves that these moraines are older than the oldest historical Stages VIII or VII and, accordingly, belong to the neoglacial period (Holocene) (cf. Table 1). The classification as belonging to the oldest stage of the neoglacial period (Holocene) (Stage V) has been relatively dated by seven younger ice margin positions, evidenced up to the current glacier tongue up-valley (cf. Sections 2.1.1, 2.1.2 and 2.1.3).

Down the Barun Nadi no further neoglacial and Late Glacial lowest terminal positions of glacier tongues have been preserved by remnants of end moraines, i.e. lateral moraines close to end moraines. The lowest remnant of ground moraine, which, due to its pedestal moraine (Figure 11 on the left below No. 45) can unambiguously be classified, is situated above the Yangri Kharka valley chamber between 3750 and 3900 m a.s.l. It belongs to Stage IV (Photos 15, IV).

Today up to 4 km-long glaciers still flow down from the S-exposed walls and slopes of the Chamlan Himal toward the Mera Kharka alpine pasture. The largest one is the Yaupa (Peak 28) S-glacier, fed by the ca. 6645 or 6112 m-high Peak 43, the ca. 6750 or 6432 m-high Yaupa-peak (Photo 12 No. 28), the 6166 m-high Yaupa-middle peak and the 6422 m-high Yaupa E-peak. At the end of the 1994 'budget-year' its tongue end reached down to 4590 m (above XI), so that a current orographic snow-line (ELA) about 5300 m a.s.l. can be established (orogr. ELA = medium height of the crest fringe of the glacier feeding area minus lowest height of the glacier tongue end divided by 2 plus lowest height of the glacier tongue end, i.e., orogr. $ELA = 6000 - 4600/2 = 700$; $700 + 4600 = 5300$).

Since Stages IV–V, after the Barun main glacier had retreated from the orographic left flank of the Barun Nadi, the Yaupa-S-glacier had enough room to push a pedestal moraine into the main valley (Figure 11 on the left below No. 43; Photo 12 ■ below and on the right of No. 28) and to create an alluvial debris- and debris flow fan (△). In the meantime the centre of the pedestal moraine, i.e. the ground moraine pedestal upon which the glacier advanced during a neoglacial stage (Stages VI–'VII), has been excavated by the historical advances and modified by the attachment of lateral- and end-moraines. X (below No. 28) marks the attached end moraine ramp of the Little Ice Age. Despite an increase of the snow-line by 10–20 m (cf. Table 1, XI), the tongue of the Yaupa-S-glacier, which due to these attachments and abutments by moraine grew smaller and smaller, reached down just as far or even somewhat further (Photo 12, XI) during the stage about 1920–1950.

Much older, i.e. Late Glacial, ground moraine remnants are preserved in an immediately contiguous

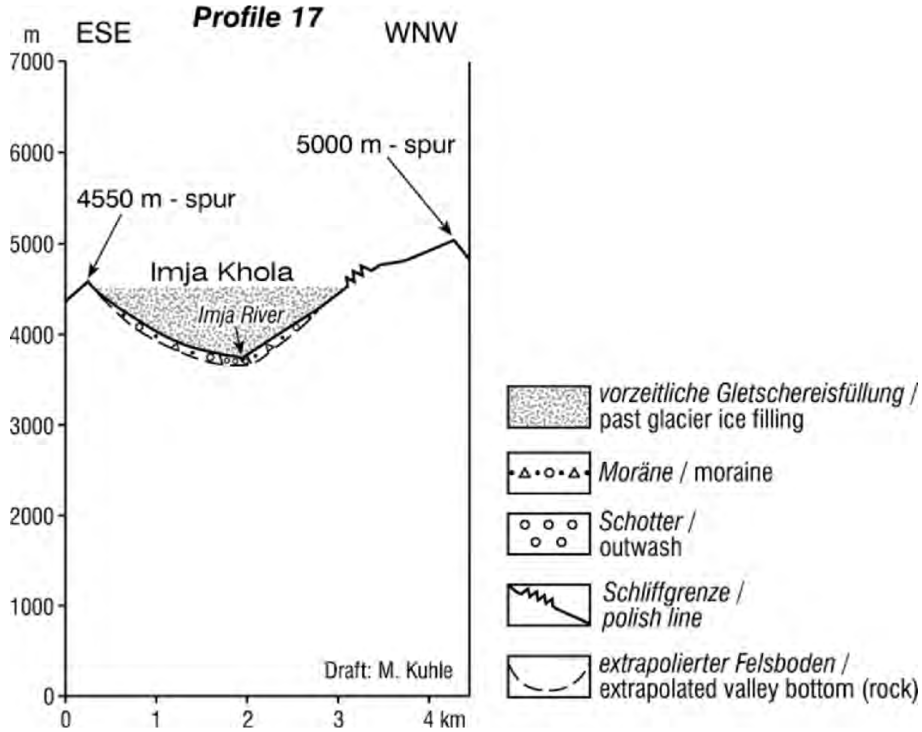


Figure 27. (Profile 17) Cross-section (not exaggerated) seen from the left side down-valley across the lower Imja Khola (Drangka) with the 4550 m-spur to the 5000 m-spur with its glacier ice filling reconstructed for the last glacial period (ca. 60–18 Ka = Stage 0; Table 1) (see Photo 83 from the second .... on the left below No. 60 up to .... on the right below No. 60). On the orographic right side an abrasion limit runs at 4500 m; the ground moraine cover on the orographic left reaches up-slope up to this altitude. The valley cross-profile has been concavely abraded by the flank polishing of the glacier forming a trough valley. According to the upper limit of abrasion and ground moraines, a maximum past ice thickness of ca. 900 m has to be inferred up to the rock ground of the valley bottom. The Ice Age glacier surface lay ca. 800 m above the simultaneous High Glacial ELA. The current Imja river is cut into the ground moraine. Locality: Figure 3.

spur position up to ca. 5000 m a.s.l. (■ on the left below No. 43; Figure 11 on the left of No. 43). However, in this valley chamber the glacigenically worn-down forms (Figure 11 on the left below up to below No. 43) reach even higher up, 800 m at a maximum (Photo 12☗), but the Late Glacial (Stages IV–I) abrasion forms and flank polishings can no longer be clearly separated from the High Glacial (Stage 0) ones, at least not in all places. Correspondingly, the Ice Age glacier trim-line (––– on the left) is verifiable at 5800 m and, above high-hanging side valleys, even at 5900 m (––– on the right).

With regard to the form analysis of the massive-crystalline rocks such as the outcropping gneisses here, one has to bear in mind that – due to their comparatively substantial masses – the rock crumblings, which have taken place since the deglaciation, have brought about significant reshapings of the glacigenically rounded wall forms, so that the roundings are no longer preserved generally, but only sporadically. This can also be observed indirectly by the fresh angular particles of the debris masses below the walls (▲; Photo 14 △). However, not all of the crumblings are angular-cubic (Photo 15 ◇). They also occur in plate-like forms as surface-concordant exfoliations (Photo 13 ▼). The latter might be mixed up with glacigenic smoothings, but a mistake like this can be excluded with the help of rounded rock edges enclosing the pre-glacially or subglacially broken out rock faces. On the other hand, especially unambiguously formed postglacial crumblings, which have taken place after the deglaciation, render the geomorphological evidence of a former glacial abrasion as objectivization of a Holocene to current – but not glacigenic – reshaping possible. Here, smooth round curves (Photo 13 ∩ white; 14 ∩ white, left half) are sometimes cut off, i.e. bended or broken and interrupted by break-offs in size up to that of a tower block (⇩ on the left).

In some places the reshaping of High Glacial polishings through Late Glacial polishings, resulting from a change of the direction of ice flow, is verifiable. So, for instance, the Barun glacier with its important ice thickness during the High Glacial (Stage 0, Table 1), has polished back the 'riegel'-like rock pillars (Photo 12 second and third☗ from the right; 13 the two☗ from the left; 15 the two black ∩ below No. 45). In the Late Glacial (Stages I–IV) they have been polished and sharpened at right-angles to it by the hanging glaciers of the orographic left hanging valleys and the cirque terrace down from the Chamlan Himal (Photo 13 →). Similar conditions occurred in the orographic right flank, where the rock pillar (Photo 13 ∩ white), polished by the Arun parent glacier into a bulging form, has been sharpened into a glacial horn by Late Glacial hanging glaciers (seen from a top-view perspective) (Photo 14 ∩ white, left half; Figure 11 on the right below No. 37).

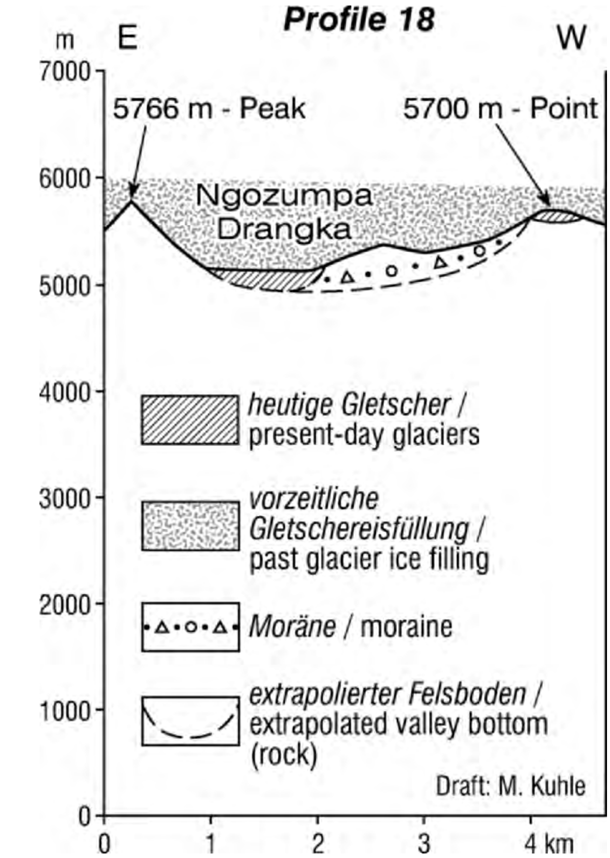


Figure 28. (Profile 18) Cross-section (not exaggerated) across the upper Ngozumpa Drangka seen down-valley, with the current Lungsampa valley glacier branch, looking from the left with the 5766 m-peak, a S-satellite of the 6066 m-peak (Figure 3 No. 67), to the 5700 m-point in the Labtshan side valley with its glacier ice filling reconstructed for the last glacial period (Würmian: ca. 60–18 Ka = - Stage 0; Table 1) (see Photo 116 from No. 67 up to the right margin; 119 from No. 67 to 36 and Photo 117 from No. 36 up to the right margin). The flank- and ground polishing of the glacier has abraded the valley cross-profile concavely and trough-like. Due to the upper limits of the ground moraines and the complete rounding of the 5700 m-point, a maximum past ice thickness down to the rock bottom of the valley of ca. 1000 m can be suggested. The Ice Age glacier surface lay 2000–2300 m above the simultaneous High Glacial ELA. At least in part, the current Lungsampa glacier (western substream of the Ngozumpa glacier) has eroded itself into the 400 m-thick moraine pedestal still preserved on the orographic right side. Locality: Figure 3.

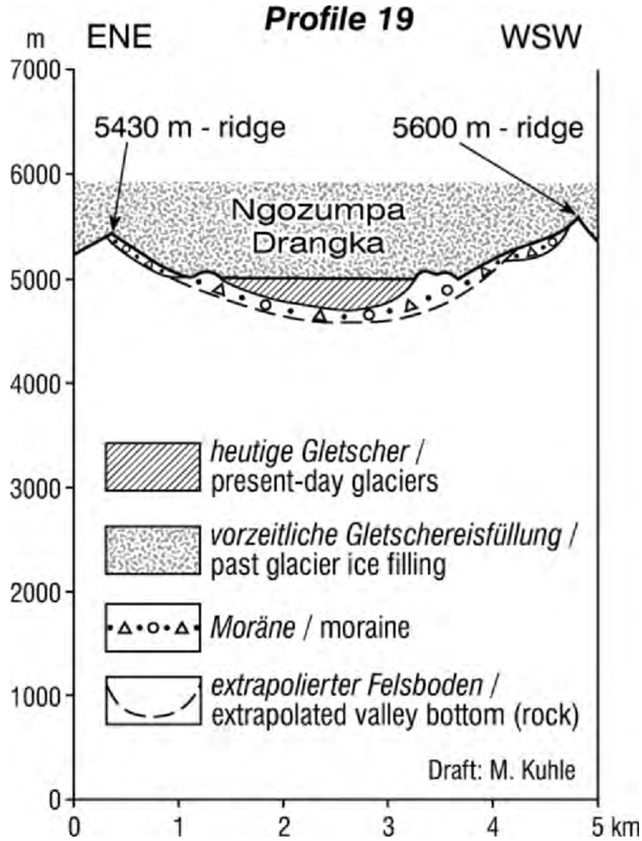


Figure 29. (Profile 19) Cross-section (not exaggerated) seen down-valley across the middle Ngozumpa Drangka with the current Ngozumpa parent glacier, looking from the left with the 5430 m-ridge, in the area of Gyuba Tshomoche, to the 5600 m-ridge in the Gyazumpa side valley with its glacier filling reconstructed for the last glacial period (Würmian: ca. 60–18 Ka = Stage 0; Table 1) (see Photo 119 from below No. 55 to the right margin; Photo 128 on the left below No. 71). The valley cross-profile has been trough-like concavely abraded by the Ice Age glacier. Due to the upper limit of the preserved ground moraine cover and the polish line observed in the neighbourhood of the cross-profile, the ice level can be verified at ca. 5900 m. The maximum past ice thickness down to the rock bottom of the valley amounted to 1300–1400 m. The Ice Age glacier surface lay ca. 2000–2200 m above the simultaneous High Glacial ELA. The current Ngozumpa glacier has partly eroded itself into a marginally preserved 200–400 m-thick ground moraine pedestal; also the current valley glacier still indicates characteristics of a dam- (pedestal-) glacier. Locality: Figure 3.

Besides the high-lying moraine remnant on the orographic left above Mera Kharka (Photo 12 ■ on the left below No. 43), which has already been mentioned, two further early Late Glacial to High Glacial (Stages III–0, Table 1) deposits of ground moraines are to be observed as far down as Yangri Kharka (Figure 11 on the left below Nos. 43 and 45): one on the bulging protrusion of the orographic right glacial horn at 480–560 m (at 4480–4560 m a.s.l.) above the valley bottom (Photo 14 ■ white above) and the other on the orographic left side of the concave trough valley flank as far as the upper half of the slope (Photo 15 the two ■ below - - - 0). At the same time this valley flank section shows a glacigenic triangle-shaped face. Additionally, on the orographic right side down the valley, in the geomorphological shadow of the glacial horn (Photo 14 ■ on the left), ground moraine remnants, reshaped by a slight burying and fluvial undercutting, tower above the valley bottom, which has been reworked from the neoglacial period up to the present (Stages V–XII, Table 1). Similar mantlings of ground moraine are preserved 4–5 km down-valley on the orographic left above and down-valley from Yangri Kharka (Photo 15 ■ on the right; Figure 11 below No. 45).

The entire valley section discussed here shows trough valley cross-profiles (Figure 11 below Nos. 43 and 45). The valley bottom has been heaped up box-like by pedestal moraines and/or glaciofluvial gravel covers and mudflow fans (Photos 12–15). The largest alluvial

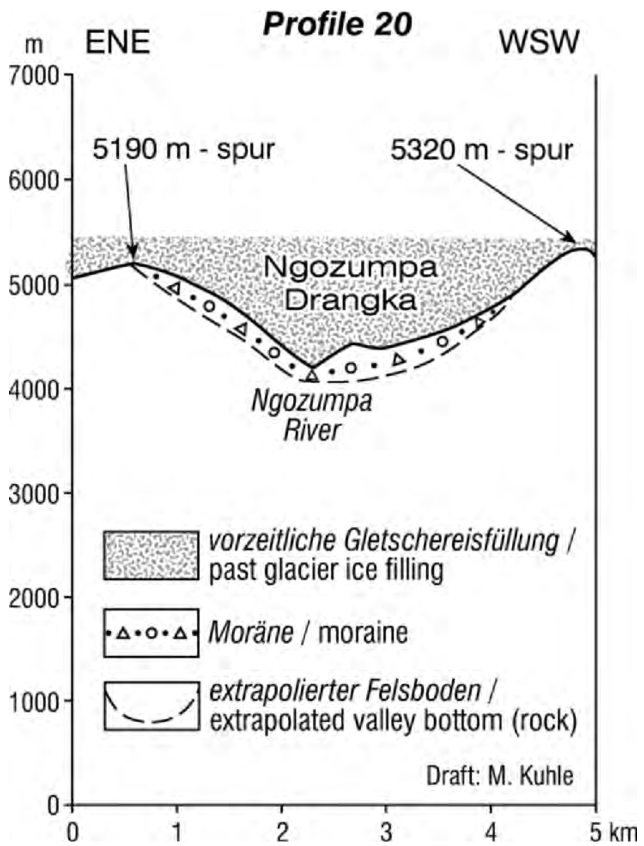


Figure 30. (Profile 20) Cross-section (not exaggerated) seen down-valley across the middle Ngozumpa Drangka, down the current Ngozumpa valley glacier, looking from left with the 5190 m-spur W of Taboche (Figure 3 No. 40) to the 5320 m-spur in the Luza side valley with its glacier filling reconstructed for the last glacial period (Würmian: ca. 60–18 Ka = Stage 0; Table 1) (Photo 138 shows the middle section of the cross-profile close to the talweg; 139 the orographic right two/thirds of the cross-profile seen up-valley). The valley cross-profile has been trough-like- concavely polished by the Ice Age glacier. Due to the upper limit of the preserved ground moraine cover and that of abrasion, verifiable in the vicinity of the cross-profile, the ice level can be suggested at ca. 5500 m a.s.l. The maximum past ice thickness down to the rock ground of the valley amounted to 1350–1400 m. The Ice Age glacier surface lay ca. 1600–1700 m above the simultaneous High Glacial ELA. The Late Glacial Ngozumpa glacier has left behind a 250–400 m-thick ground moraine pedestal. During the neoglacial period the Ngozumpa river has already cut it subglacially into a V-shape. Since the complete deglaciation, this cutting has taken place subaerially. Locality: Figure 3.

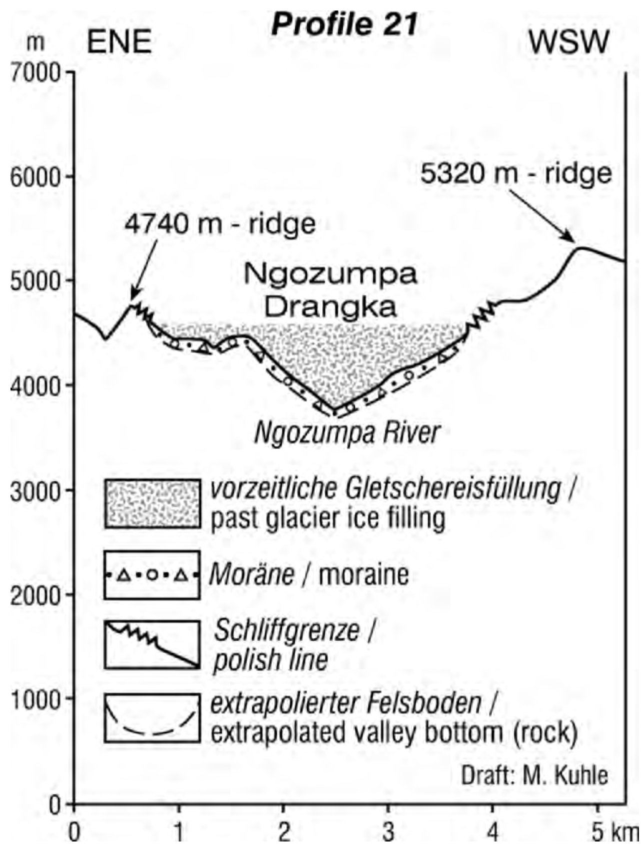


Figure 31. (Profile 21) Cross-section (not exaggerated) seen down-valley across the lower Ngozumpa Drangka looking from the left side with the 4740 m-ridge, SW of Taboche (Figure 3 No. 40), to the 5320 m-ridge NE of the Khumbui Yul Lha (No. 74) with its glacier ice filling reconstructed for the last glacial period (Würmian: ca. 60–18 Ka = Stage 0; Table 1) (see Photo 145 the completely visible valley cross-profile line situated next; 148 from the right below No. 74 up to the right margin). The valley cross-profile has been slightly concavely polished out by the Ice Age glacier, so that a trough-like V-shaped valley has developed. Due to the upper limit of glacigenic abrasion and that of the preserved ground moraine cover, which here reaches up to the upper limit of abrasion, a glacier trim-line running at 4500 m a.s.l. can be verified. The maximum past ice thickness down to the rock ground of the valley amounted to 900 m. The Ice Age glacier surface lay ca. 700–800 m above the simultaneous High Glacial ELA. Locality: Figure 3.

debris- and mudflow fans, which mostly occur in a combined, i.e. polygenetic form, are situated in the confluence area of high valleys, which were still glaciated from the neoglacial period up to the present (Photos 12–14: △ large or ▽ large; Figure 11 below Nos. 43 and 45). Exemplary for this are the two hanging troughs which join the valley chamber of Yangri Kharka nearly parallel and very close to each other from the orographic right side (Photo 15). They show a 6164 m-high catchment area (or 6185 m, ENE-flank of Peak 7, S-satellite of Iswa Peak No. 37) (Photo 15 ▢ and below – – – on the left) and are separated by a 'riegel' (on the right of ▢). Their respective confluence steps between 4300 and 4000 m are in part glaciofluvially cut (△ large) showing ca. 200–280 m-high roundings formed like roches moutonnées (∩ white below – – – on the left and centre; Figure 11 on the right below No. 37).

On the orographic right side opposite the Yangri Kharka alpine pasture (Photo 15 →; see Figure 4; Figure 11 far below No. 45) well preserved glacier striations are to be observed in the outcropping gneiss rock (Photos 16 and 17). These striations 150 m above the current talweg in the gravel- and ground moraine material needed for their development a Barun glacier thickness of at least 200–250 m, provided that the then ice stream lay approximately on the rock ground of the valley. However, if it should have flowed on a ground moraine pedestal – and this can be assumed because of its late Late Glacial age – a less thick ice of e.g. only 100 m would have been enough to let the glacier polishing reach the level of striations. The youngest possible age to classify the striations is Stage IV, because in comparison with the current glaciation which with the

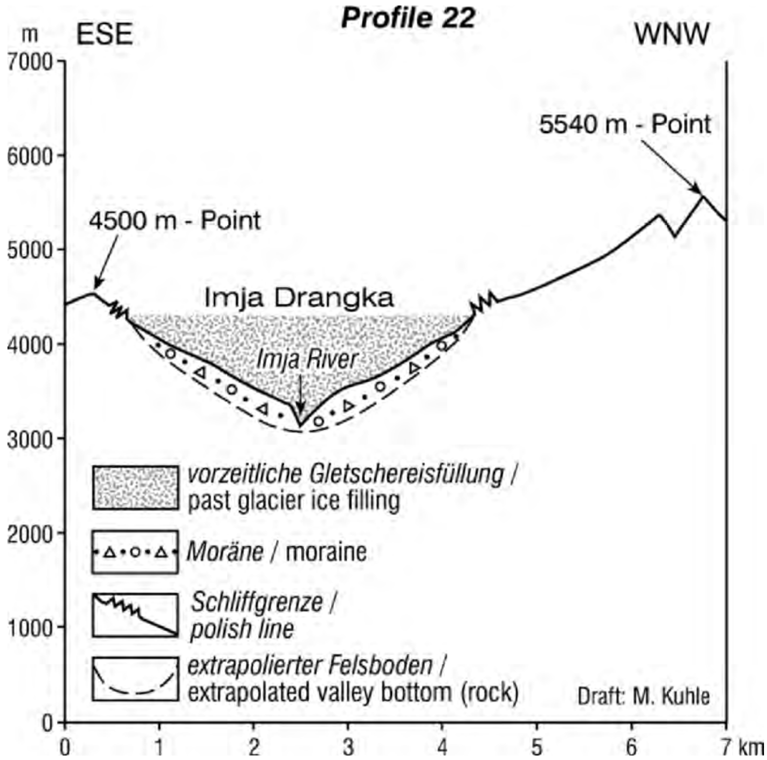


Figure 32. (Profile 22) Cross-section (not exaggerated) seen down-valley across the lower Imja Drangka from the left with the 4500 m-point on the Tramserku (Figure 3 No. 36) NW-crest to the 5540 m-point on the SW-crest of the Khumbui Yul Lha (No. 74). Its glacier filling has been reconstructed for the last glacial period (Würmian: ca. 60–18 Ka = Stage 0; Table 1) (Photo 157 left half; 151). The Ice Age glacier has polished out the valley cross-profile, so that a trough-shape has been developed. The very thick ground moraine on the valley bottom has formed a ground moraine pedestal on which the Late Glacial (Stages I–II) Imja parent glacier has discharged on a heightened level. According to the upper limit of glacigenic abrasion and the upper limit of the ground moraine cover preserved – here nearly reaching up to the upper limit of abrasion – the glacier trim-line has run at 4300 m a.s.l. The maximum past ice thickness down to the rock ground of the valley bottom amounted to 1250 m. The Ice Age glacier surface lay ca. 600 m above the synchronous High Glacial ELA. Locality: Figure 3.

tongue end of the Barun glacier reaches down to ca. 4600 m a.s.l. (Figure 3 lower corner on the right), an ELA-depression of more than 550 m would have been necessary in order to supply and preserve here, at a 3500 m-high valley ground, an up to 200 or 250 m-thick valley glacier. In the adjacent areas of the Himalaya S-slope the snow-line depression of the late Late Glacial Stage IV amounts to ca. 700 m. The next-younger, then already neoglacial (Holocene) Stage V shows a depression of only 300 m, so that the corresponding length of the glacier cannot have reached up to here and the age classification (Stage IV) is probable (cf. Table 1). In terms of geomorphology the ground moraine pedestal of Stage IV, preserved only 2.5 km up-valley, also pleads for this (Photo 15, IV; see Figure 4; Figure 11 far below No. 43).

Summing up, the High Glacial (Stage 0; Table 1) Barun glacier level of the 6–7 km-long valley section discussed here, can be described as follows: the glacier trim-line runs in a steady slope from 5800 m above the end of the current Lower Barun glacier (Photo 12 – – – on the left; 18 – – – below No. 37) down to a level of ca. 5100 m a.s.l. near Yangri Kharka (Photo 15 – – – 0; 18 – – – above). Accordingly, the ice thickness at the upper beginning of this valley section was 1200–1400 m and at its lower end 1400–1600 m, depending on the underlying thickness of ground moraine.

2.1.5. Reconstruction of the maximum Last Ice Age Barun glacier and its trim-line between the Yangri Kharka alpine pasture (Photo 18 and Figure 12, Figure 4; Figure 11 above No. 46) and the confluence into the Arun main glacier (Photo 22 and Figure 13, Figure 4; Figure 11 on the left of No. 48)

This valley section is divided in two parts. The upper, ca. 12 km-long section slopes relatively flatly from 3550 down to 2710 m a.s.l. (Photo 20 below ☗), that is 840 m, whilst the lower one falls away nearly twice as steeply from 2720 m down to the Arun Nadi talweg near the Barun Bajar locality (Photo 27) at 1110 m a.s.l., that is 1600 m, over a distance of also 12 km. At a comparable current rate of water run-off in the talweg this difference has an increased effect on the subglacial and postglacial linear erosion. By comparison of the two cross-profiles (Figures 12 and 13) the striking distinction of the two valley sections becomes obvious: the upper section shows a smoothly formed V-shaped valley furnished glacigenically and tending towards a narrow trough form (Photo 19 ⊍); the lower valley section, however, has the form of a gorge with steep flanks (Photo 20 below ∨). As a result of this difference, in the upper section a mantling with moraine can be diagnosed, preserved from the debris-covered talweg (ground moraine and moraine washed out into a gravel cover, i.e. moraine separated from the fine matrix) up to 800 or

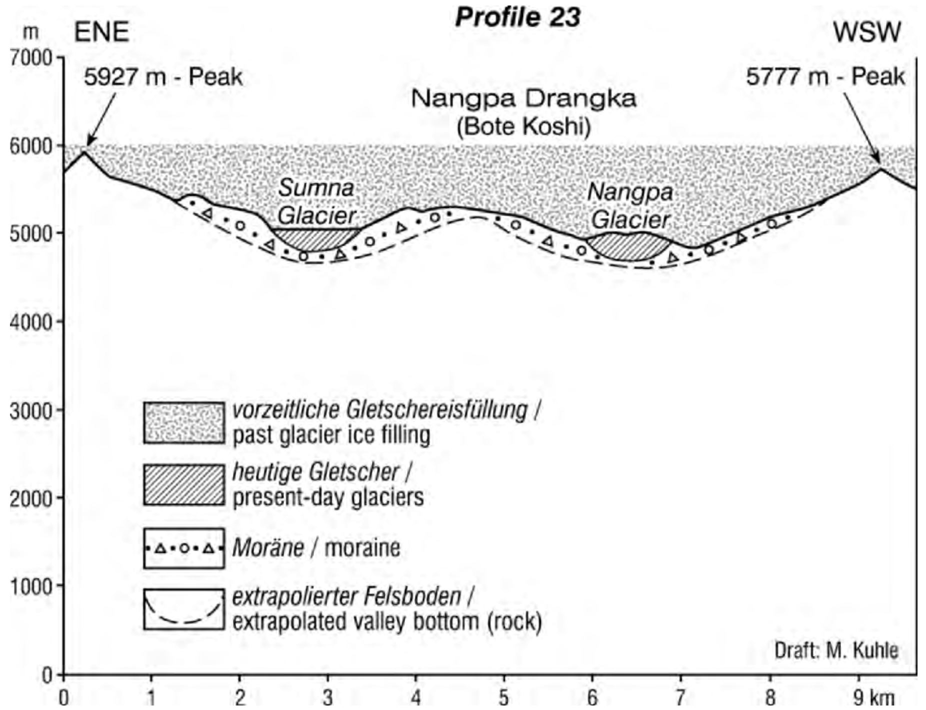


Figure 33. (Profile 23) Cross-section (not exaggerated) seen down-valley across the upper Sumna- and Nangpa Drangka (valleys) in the upper catchment area of the Bote Koshi, looking from left with the 5927 m-peak (Figure 3 and Photo 162 No. 71) to the 5777 m-peak at the eastern end of the 6907 m-peak ESE-crest (Figure 3 and Photo 162 No. 77). The actual Sumna- and Nangpa glaciers have pressed themselves into the Late Glacial (Stage IV) ground moraine pedestal (Photo 162). Probably the ground moraine of this pedestal is up to 400 m-thick. The glacier filling of this cross-profile has been reconstructed for the last glacial period (Würmian: ca. 60–18 Ka = Stage 0; Table 1) (Photo 162 .... below No. 71 and on the left below No. 77). The Ice Age glacier has polished out the valley cross-profiles into a trough-shape. In accordance with the glacigenic abrasion roundings on the valley flanks up- and down-valley of the cross-profile and also with the upper limit of the preserved cover of ground moraine reaching up to ca. 5400 m, the glacier trim-line ought to have run here about 6000 m a.s.l. The maximum past ice thickness down to the rock ground of the valley bottom amounted to approx. 1400 m. The Ice Age glacier surface lay ca. 2200–2300 m above the synchronous High Glacial ELA. Locality: Figure 3.

even 900 m up the flanks (Photos 18–20; Figure 4; Figure 11 far above No. 46). The lower valley section, however, is a gorge- to ravine stretch from which the loose rock has not only been transported away, but even the bedrock has been eroded. Accordingly, in the upper of the two sections of the Barun valley the two-part development of the relief is to be observed, typical of medium altitudes in mountain valleys which were glaciated during the Ice Age: from the High Glacial glacier abrasion of the bedrock (Figure 12 Pro. 5 dotted line; Photo 18–20: ☗ and ∩) to the post-high-glacially increased compaction of the debris in the valley receptacles by Late Glacial covers of ground moraine and -pedestals (Photos 18–20:■; Figure 12) as well as Late Glacial and postglacial gravel floors (Photos 18–20: □ and ○; Figure 12), slides, debris flow activities and crumblings, i.e. erosion (Photo 18 △). The present process is the interglacial re-establishment of the Tertiary V-shaped valley relief developed before the Ice Age era. This re-establishment takes place in the upper valley section (Figure 12), still within the decametres-thick ground moraines on the valley bottom (Photo 18). The substantial thickness of the moraine material points to a ground moraine pedestal of Stage IV continuing from up-valley (Photo 15, IV) down to this valley section. At the appropriate ELA-depression of ca. 700 m during the Sirkung Stage (Table 1, IV) the corresponding glacier might have reached down to ca. 3300–3200 m a.s.l. This is the valley area down from Profile 5 (Figure 4; Photo 20 near ■), ca. 6–7 km down from Yangri Kharka. A potential end moraine marking the exact past ice margin, could not be preserved in this narrow valley section (Photo 20), because it would have been washed out. The existence of moraine material in this probably late Late Glacial ice margin position (IV) is evidenced by sample 8.12.94 (Figure 4), taken on the orographic right side (Photo 20 on the right of ■) at 3220 m a.s.l., 20 m above the current talweg. It contains 67.4% glacially crushed quartz grains (Figure 6, No. 11). Because far-travelled boulders are contained, weathering *in situ*, i.e. freshly weathered quartz grains, can be ruled out.

In the same area of the Barun valley glaciofluvial gravel terraces set in (Photos 19 and 20: □ 1). Due to their abrupt start they are the only firm indicators of the immediately up-valley glacier terminus of Stage IV. These localities are situated about 3300 m a.s.l., 1200 m below the current tongue end of the Barun glacier (4600 m). This corresponds to an ELA-depression about 650 m and approximately coincides with Stage IV (cf. Table 1). Among the glaciofluvial gravels is ground moraine material which, accordingly, has to be classified as being from the next-older Stage III (Photo 19). The meltwater of Stage IV has truncated the older ground

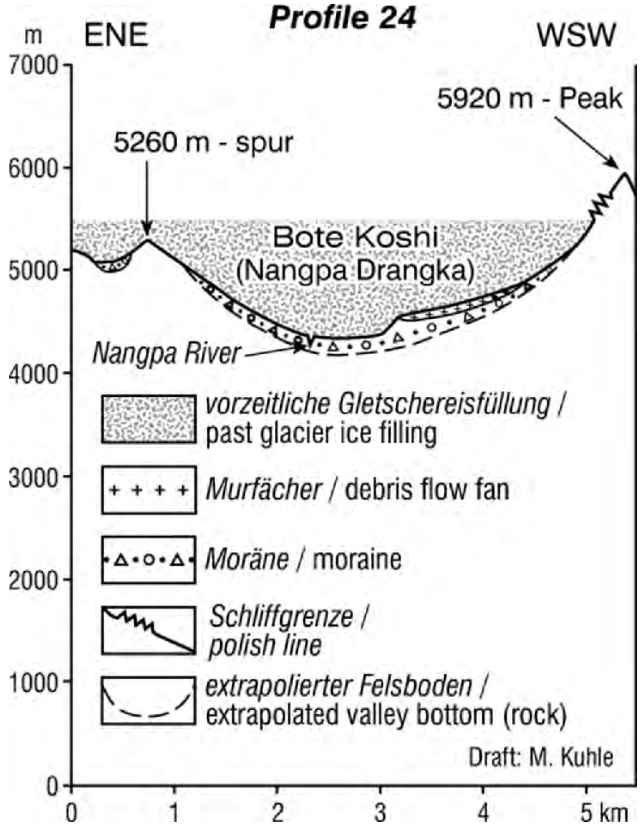


Figure 34. (Profile 24) Cross-section (not exaggerated) seen down-valley across the upper Bote Koshi, i.e. Nangpa Drangka 5260 m-spur in the SW-crest of the 5941 m-peak (Figure 3 and Photos 169 and 173 No. 72; Photo 169 left margin) to the 5920 m-peak in the NE-crest of the 5967 m-peak (Figure 3 and Photo 169 No. 89). A Holocene debris flow fan has been deposited on the remnant of a ca. 200 m-thick Late Glacial (Stages III–IV) ground moraine pedestal. The glacier filling of this cross-profile has been reconstructed for the last glacial period (Würmian: ca. 60–18 Ka = Stage 0; Table 1) (Photo 169 .... on the right of No. 89 and on the right of the left margin of the panorama). The Ice Age glacier has polished out the valley cross-profile to the form of a trough. In accordance with the upper limit of the ground moraine cover preserved here up to ca. 5250 m and the glacigenic abrasions on the valley flanks up to an abrasion limit at 5450–5500 m a.s.l., the glacier trim-line ought to have run at 5500 m a.s.l. The maximum past ice thickness down to the rock ground of the valley bottom amounted to approx. 1300 m. The Ice Age glacier surface lay ca. 1700–1800 m above the synchronous High Glacial ELA. Locality: Figure 3.

moraine and laid down its gravel field (sander) No. 1 on the truncated face in the area of the glacier mouth and glacier forefield.

By means of the transition from Profiles 5 to 6 (Figures 12 and 13; cf. Figures 4 and 11 far above No. 46 and on the left of No. 48) and Photos 19 (▢) to 20 (∨) the modification of the valley form from further above, that is a trough-shaped valley (Figures 7–10; cf. Figure 11 far below No. 43), via a narrow trough form and a glacigenic, still relatively wide V-shaped valley (Pro. 5) into the form of a gorge (Pro. 6) has been approached (see above). At the same time it has been referred to the growing steepness of the valley and the resulting increase in transportational agents of the Barun river as an explanation. The narrow form of the valley fits the increasing fluvial erosion as well as the tractive forces which increased in accordance with the steepness of the past Barun glacier, amplifying the ground scouring against the flank polishing down to the inflow into the very low-lying Arun main valley glacier. However, the flank polishing was also still effective up to the Barun confluence gorge. This is evidenced by abrasion forms and truncated spurs (Photo 20 ∩,▲); Figure 11 far on the right above No. 46).

A further process leading to the development of V-shaped valleys and gorges is the subglacial meltwater discharge beneath the valley glacier. In geomorphological terms this discharge must have been especially effective, because it was strongly accelerated by high hydrostatic pressure. The high speed of water discharge resulting from this, has led to cavitation corrasion, which even without large boulders and erosional weapons is erosionally very effective. The cause of this was the cross-profile of the ice tunnel which due to the glacier flow was very narrow. In addition, a more than 1000 m-high inter-communicating water pillar pressed into the intraglacial meltwater pipes in the ice (glacier mills), into which the water penetrated from the surface of the valley glacier and discharged. These glacier mills and ice pipes have been created along the vertical glacier crevasses through which the meltwater, developed on the glacier surface, infiltrated into the glacier body. Accordingly, the position of the glacier surface below the snow-line was the condition for the lasting effect of subglacial meltwater erosion in the respective downward valley section.

In Profile 5 (Figure 12) the glacier surface was situated above the ELA from the High Glacial into the Late Glacial (Stage 0 to Stage III or II; Table 1). In Profile 6 (Figure 13) the ice surface lay ca. 800–900 m below the snow-line even in the High Glacial. On the 12 km-long stretch between these two valleys (cf. Figure 4) the snow-line must have cut the surface of the Barun glacier, i.e. remained under it, during the High Glacial and during the Late Glacial the Barun Nadi still further up. Owing to this, the increasing subglacial meltwater erosion has, with growing intensity, incised the Barun gorge into the ground of the simultaneously glaciated valley (see Figure 13; Photo 20 in the background). During the High Glacial the glacier snow-line (ELA) ran at ca. 3500 m a.s.l., so that the forced amount of meltwater must have started where the Barun glacier level remained below 3500 m. This was the case somewhat down-valley of the viewpoint in Photo 20 (Figure 4); in the background of this photo the High Glacial ice level has already dropped to 2800 m a.s.l., 700 m below the ELA (Photo 20 – – –). The highest glacier level (– – – on the left) shown in Photo 19 ran about 3400 m, that is only just below the High Glacial level of the snow-line discussed here.

The subglacial meltwater erosion, i.e. the subglacial development of gorges and ravines prepares the ground polishing by the glacier bottom. It thus intensifies the glacial erosion. The two upper edges of the fluvial erosion rill provide additional points of attack and resistance for the glacier's detersion- and detraction

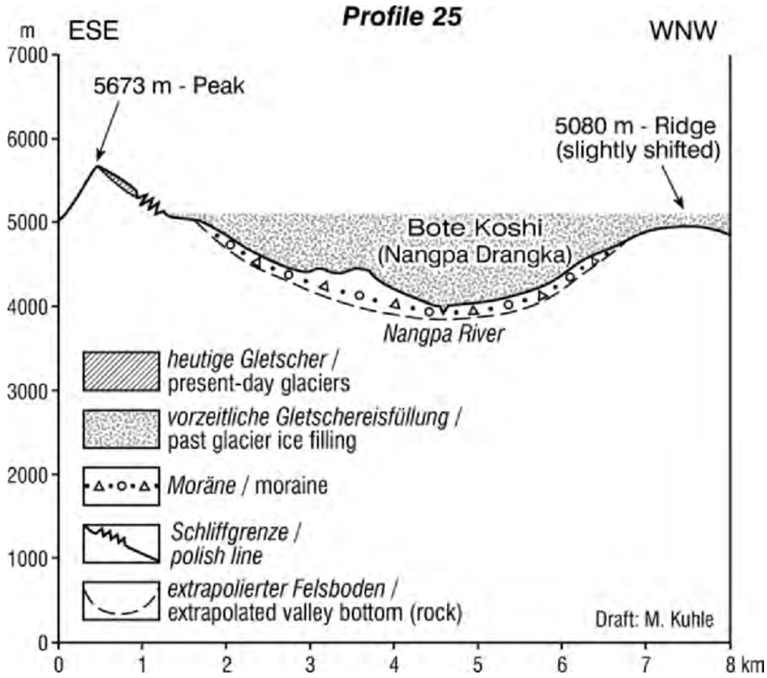


Figure 35. (Profile 25) Cross-section (not exaggerated) seen down-valley across the Bote Koshi from the 5673 m-peak somewhat N of Kabsale (Figure 3, Photos 178, 189 and 183 No. 92) to the 5080 m-ridge (Photo 178 left margin, 179) in the SE-crest of the 5967 m-peak (Figure 3 No. 89). The Ice Age glacier has polished out the valley cross-profile and has formed a trough. As far as up the slopes the trough bottom is covered by ground moraine. Its accumulation, which up to 4500 m is several hundred metres thick, concerns remnants of a Late Glacial (Stage IV) basement of a pedestal moraine. The maximum glacier filling of this cross-profile has been reconstructed for the last glacial period (Würmian: ca. 60–18 Ka = Stage 0; Table 1) (Photo 189 .... on the left of No. 89 and on the left below No. 92). According to the upper limit of the ground moraine cover preserved, reaching up to ca. 5000 m, and also according to the glacigenic abrasions on the valley flanks up to an abrasion limit about 5100 m a.s.l., the glacier trim-line ought to have run at 5100 m a.s.l. (Photo 183 .... on the right below No. 104 and on the left below No. 92). The maximum past ice thickness down to the rock ground of the valley bottom amounted to ca. 1250 m. In this profile the Ice Age glacier surface lay ca. 1300–1500 m above the synchronous High Glacial ELA. Locality: Figure 3.

work so that, according to the fluvial deepening and its own broadening effect, it follows the talweg with its deepened glacier bed (Louis, 1968: 255; Kuhle, 1976: 178).

Due to its thickness in the High Glacial the Barun parent glacier (Figures 12 and 13) has also polished round and abraded the valley flanks in the confluence area of the side- and hanging valleys (Figure 11 far above No. 46; Photo 22 ᗜ; 23 ∪) up to more than 800–1200 m above the Barun talweg (Photos 21 and 22:▲). The tributary glaciers were adjusted to the surface of the main glacier, on to which they flowed down. In the Late Glacial, however, when it moved upwards (see above) the proportion of reshaping of the valley flanks by subglacial meltwater has increased. For instance, in the steep hanging valley leading down from the Tutu La (pass) (Figure 11 above No. 46; Figure 4 viewpoint 22) to the N into the Barun valley, gullies have been developed (Photo 21∨), eroded by the down-slope meltwater and then partly filled with ground moraine (○). Unambiguously subglacial indicators of meltwater are the flushing rills related to potholes (↓; Figures 11 above No. 46) which only due to the canalizing of the water by the ice could develop on convex abrasion roundings. In the late Late Glacial (Stage IV), when the Barun glacier had completely left this valley area, the terminus of the hanging glacier in correspondence with the increase of the snow-line by ca. 600 m and its comparably very insignificant catchment area of at most 4830 m (Photo 23) had also moved upwards near to the Tutu La, and that pothole locality was devoid of ice.

In the High Glacial (Stage 0), however, the glacier of the Tutu La N-valley flowed on to the Barun glacier, because its level ran below that of the Tutu La (4075 or 4188 m a.s.l.) and the snow-line lay about 3300–3600 m a.s.l. (see below). The latter led to the filling-up of the rock bowl between Tutu La and Keke La (Photo 23; Figure 11 above No. 46) up to a level of 4270 m (–––), so that the Tutu La (∩ black, on the right below –––) has been overflowed by an at least 200 m-thick ice during the High Glacial. This transfluence is also evidenced by ground moraine on the lee-side (N) of the pass (Photo 22 ■).

The bottom of this over-deepened, currently non-glaciated rock bowl of the Kalo Pokhari Lake lies at an altitude of 4000 m. It has to be approached as a glacigenic polishing depression between the two passes polished out with a relatively important ice filling above the snow-line (Stages 0–III; Table 1) as well as at and below the level of the snow-line (Stage IV) (Photo 23 ∩). Probably this is a glacial landform which has already been polished out during earlier

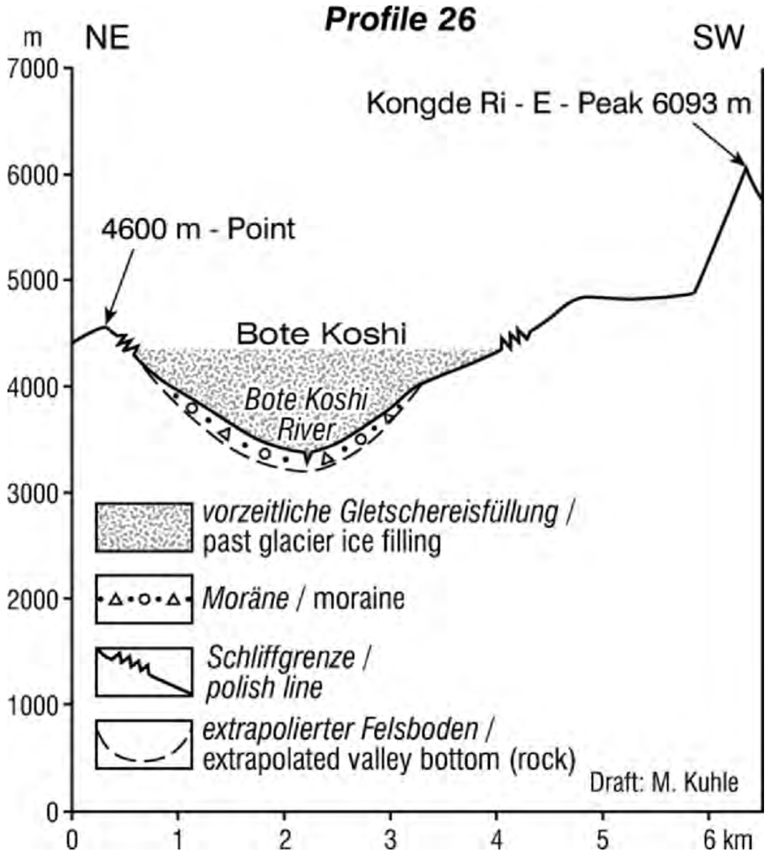


Figure 36. (Profile 26) Cross-section (not exaggerated) seen down-valley across the lower Bote Koshi or Nangpo Tsangpo from the 4600 m-point (Photo 180 left margin) in the SSE-crest of Kabsale (Figure 3 and Photo 183 No. 92) to the E-peak of Kongde Ri (Photos 183 and 193 on the left of No. 60). The Ice Age glacier has polished the valley cross-profile into a trough-shape. The outcropping rock is covered by ca. 150 m-thick ground moraine, the thickness of which decreases down to the talweg. The maximum glacier filling of this cross-profile has been reconstructed for the last glacial period (Würmian: ca. 60–18 Ka = Stage 0; Table 1). In accordance with the upper limit of the ground moraine cover preserved reaching up to ca. 4100 m, and the glacigenic abrasions which occur on the trough flanks up to an abrasion limit about 4350–4400 m a.s.l., the glacier trim-line ought to have run at 4400 m a.s.l. (Photo 183 and 193 (....) below No. 27 and on the left below No. 60). The maximum past ice thickness down to the rock ground of the valley bottom amounted to ca. 1200 m. The Ice Age glacier surface in this profile lay ca. 600–800 m above the synchronous High Glacial ELA. Locality: Figure 3.

Pleistocene glacial periods (Riß Glaciation = pre-last High Glacial maximum), i.e. polyglacially, and over-deepened.

During the oldest neoglacial Stage V, i.e. at a snow-line depression of ca. 300 m (Table 1), the uppermost section of the cirque (o on the right) below the 4830 m-summit was still glaciated. Due to the insignificant relief span compared with the High Himalayas, this landscape between Barun Nadi in the N and Irkhuwa (Isuwa) Khola in the S to SW is and was a typical E-Alpine glacial landform marked by the repeated change between a completely glacial forming during the Ice Age and a completely subaerial forming and roughening erosion during interglacial periods (▽) (Figure 11 above No. 46).

On the opposite orographical left valley side of the Barun Nadi a good 5 km-long trough-shaped hanging valley joins from the N (Photo 23 ∪ 22 ▽; Figure 11 far above No. 46 and on the right below No. 45). A 5492 m-high mountain belongs to its catchment area. It consists of three small summits and is occupied by cirque glaciers (○ on the left). A ca. 4800 m-high glacigenic transfluence area (⌒) mediates to its western parallel valley. From the confluence areas of these two past tributary glaciers down the main valley into the Barun parent glacier an unequivocal polish line, i.e. glacier trim-line (– – –) at 3800 m a.s.l. is preserved above a round-polished, truncated spur (▲). However, this is probably not the level of Stage 0 (Table 1) but that of a Late Glacial glacier of Stages I–III. What argues against a High Glacial level is, that the Barun glacier would only have been 640 m-thick here and, accordingly, its ice thickness would increase up-valley (Figure 12 Pro. 5) as well as down-valley (Figure 13 Pro. 6). This is impossible, because the thickness of a valley glacier as a rule is thickest in the area of the course of the snow-line and decreases up- and down-valley. Situated about 3800 m a.s.l., the cross-profile of the Barun Nadi discussed here, lies still up-valley of the High Glacial snow-line (Stage 0) about 3300–3600 m a.s.l. However, a distortion of this law valid for steady valley inclines has to be conceded because of the extreme increase of the gradient of the Barun Nadi in a down-valley direction. Owing to this, the most important ice thickness has shifted up-valley to a good 1200 m above the snow-line up to Profile 5 (Figure 12). Here, the ice surface lay about 4700–4800 m a.s.l., so that a maximum of 1600 m ice thickness has been reached.

sample No. / *Proben-nummer*	Date / *Datum*	counted quartz grains of the medium sand / *ausgezählte Quarzkörner der Mittelsand-fraktion*	Freshly weathered/ glacially crushed / *frisch verwittert/ glazigen gebrochen* [%]	lustrous (fluvially polished) / *fluvial poliert* [%]	dull (aeolian) / *äolisch mattiert* [%]	remarks / *Anmerkungen*
1	09.03.03/1	186	96,8	3,2	0,0	homogeneous sample / *homogene Probe*
2	09.03.03/2	282	95,7	4,3	0,0	large part of grains only slightly rounded, small portion well-rounded / *häufig nur angerundete Körner, wenige gut gerundete*
3	09.03.03/3	352	96,3	3,7	0,0	- / -
4	09.03.03/4	198	99,5	0,5	0,0	homogeneous sample, high portion of mica, small portion of quartz / *homogene Probe, viel Glimmer, wenig Quarz*
5	09.03.03/5	661	61,1	38,9	0,0	high portion of mica, many grains only slightly rounded / *viel Glimmer, viele nur schwach gerundete Körner*
6	09.03.03/6	149	95,3	4,7	0,0	relatively small portion of quartz / *relativ wenig Quarz*
7	09.03.03/7	175	96,6	3,4	0,0	very high portion of feldspar and mica, small portion of quartz / *sehr viel Feldspat und Glimmer, wenig Quarz*
8	11.03.03/1	997	90,9	9,0	0,1	large portion of fluvially treated grains crushed again, relatively high portion of quartz / *viele fluvial beanspruchte Körner wieder gebrochen, relativ viel Quarz*
9	11.03.03/2	509	96,3	3,7	0,0	large portion of feldspar and quartz, relatively small portion of mica, fluvial grains mainly slightly rounded / *viel Feldspat und Quarz, verhältnismäßig wenig Glimmer, fluviale Körner überwiegend leicht angerundet*
10	11.03.03/3	491	86,4	13,6	0,0	very high portion of quartz, often with oxide crust / *sehr viel Quarz, häufig mit Oxidkrusten belegt*
11	11.03.03/4	123	70,7	29,3	0,0	relatively small portion of quartz, often with iron-oxide crust / *relativ wenig Quarz, häufig mit Eisenoxidkrusten belegt*
12	11.03.03/5	266	83,5	16,5	0,0	large portion of feldspar, slightly rounded grains, partly crushed again / *viel Feldspat, schwach gerundete Körner teilweise wieder gebrochen*
13	13.03.03/1	446	94,6	5,4	0,0	- / -
14	13.03.03/2	503	89,7	10,1	0,2	- / -
15	14.03.03/1	775	67,1	32,9	0,0	large portion of quartz / *viel Quarz*
16	15.03.03/1	903	58,4	41,6	0,0	relatively large portion of quartz, many of the fluvially treated grains show edges / *relativ viel Quarz, viele fluvial beanspruchte Körner weisen Ecken und Kanten auf*
17	16.03.03/1	388	53,6	46,4	0,0	high portion of only slightly rounded grains / *viele nur leicht angerundete Körner*
18	17.03.03/1	977	81,4	18,5	0,1	mainly quartz, few sharp edges / *überwiegend Quarz, wenige scharfe Kanten*

Figure 37. Morphometric quartz grain analysis of 47 representative samples from the Khumbu Himalaya with the Bote Koshi and Dudh Koshi Nadi (cf. Figure 3). Sampling: M. Kuhle

19	17.03.03/2	378	76,2	23,8	0,0	fluvial grains, slightly rounded and well-rounded / *fluviale Körner teilweise nur leicht angerundet, aber auch gut gerundete dabei*
20	18.03.03/1	413	87,7	12,1	0,2	large portion of mica / *viel Glimmer*
21	18.03.03/2	544	87,3	12,7	0,0	- / -
22	18.03.03/3	184	91,3	18,7	0,0	- / -
23	19.03.03/1	257	98,8	1,2	0,0	very high portion of mica (esp. muskovite, but also biotite) / *sehr viel Glimmer (v.a. Muskovit, aber auch Biotit)*
24	20.03.03/1	298	96,0	4,0	0,0	large portion of quartz and muskovite / *viel Quarz und Muskovit*
25	21.03.03/1	316	79,7	20,3	0,0	relatively small portion of quartz / *relativ wenig Quarz*
26	22.03.03/1	292	84,6	15,4	0,0	fluvially treated grains, partly crushed again; fluvial grains mainly with rounded edges / *fluvial beanspruchte Körner teilweise wieder gebrochen, fluviale Körner überwiegend kantengerundet*
27	22.03.03/2	337	86,1	13,9	0,0	- / -
28	23.03.03/1	140	50,0	50,0	0,0	difficult sample because of incomplete solubility of organic compounds; grains stick together / *schwierige Probe, da organische Verbindungen nur unvollständig gelöst, Körner verklebt*
29	23.03.03/2	356	50,8	49,2	0,0	- / -
30	24.03.03/1	312	88,8	11,2	0,0	fluvial grains only slightly rounded, freshly-weathered grains with sharp edges / *fluviale Körner nur schwach gerundet, frisch verwitterte weisen scharfe Kanten auf*
31	26.03.03/1	599	95,3	4,7	0,0	relatively large portion of quartz, fluvial grains well- rounded / *relativ viel Quarz, fluviale Körner gut gerundet*
32	27.03.03/1	647	93,2	6,8	0,0	several fluvially treated grains, afterwards crushed again / *einige fluvial beanspruchte Körner nachträglich wieder gebrochen*
33	29.03.03/1	210	96,2	3,8	0,0	- / -
34	30.03.03/1	1219	97,6	2,4	0,0	homogeneous sample, very large portion of quartz / *homogene, Probe, sehr viel Quarz*
35	31.03.03/1	295	86,4	13,6	0,0	fluvial grains only slightly rounded / *fluviale Körner nur leicht angerundet*
36	31.03.03/2	372	96,2	3,8	0,0	homogeneous sample, relatively high portion of quartz / *homogene Probe, relativ viel Quarz*
37	01.04.03/1	285	82,1	17,9	0,0	relatively large portion of quartz, fluvial grains partly crushed again, often only slightly rounded / *verhältnismäßig viel Quarz, fluviale Körner teilweise wieder gebrochen, häufig auch nur angerundet*
38	01.04.03/2	857	95,3	4,6	0,1	- / -
39	02.04.03/1	968	93,3	6,7	0,0	- / -
40	03.04.03/1	381	95,8	4,2	0,0	relatively small portion of quartz, fluvial grains partly crushed again / *relativ wenig Quarz, fluviale Körner teilweise wieder gebrochen*

Figure 37. Continued.

41	04.04.03/1	251	88,8	11,2	0,0	relatively small portion of quartz / *relativ wenig Quarz*
42	05.04.03/1	325	92,6	7,4	0,0	fluvially treated grains partly crushed again; then often only newly fluvially rounded/ *fluvial beanspruchte Körner teilweise wieder gebrochen, häufig dann nur erneut fluvial angerundet*
43	05.04.03/2	263	95,8	4,2	0,0	large portion of muskovite / *viel Muskovit*
44	06.04.03/1	811	82,1	17,9	0,0	large portion of quartz, few sharp-edged grains / *sehr viel Quarz, wenige scharf gebrochene Körner*
45	06.04.03/2	277	93,5	6,5	0,0	- / -
46	07.04.03/1	266	90,6	9,4	0,0	- / -
47	08.04.03/1	273	93,0	7,0	0,0	large portion of quartz / *viel Quarz*

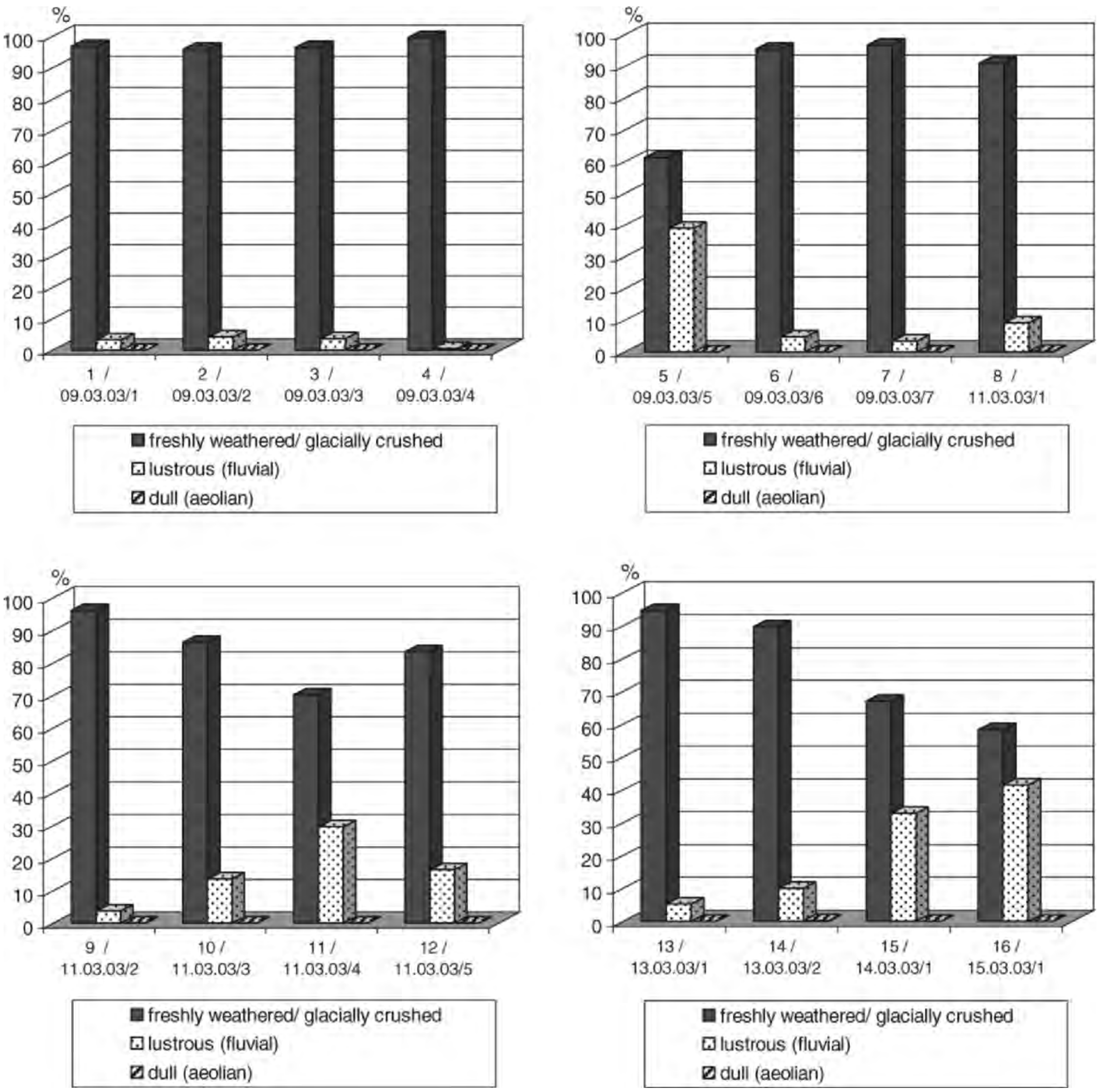


Figure 37. Continued.

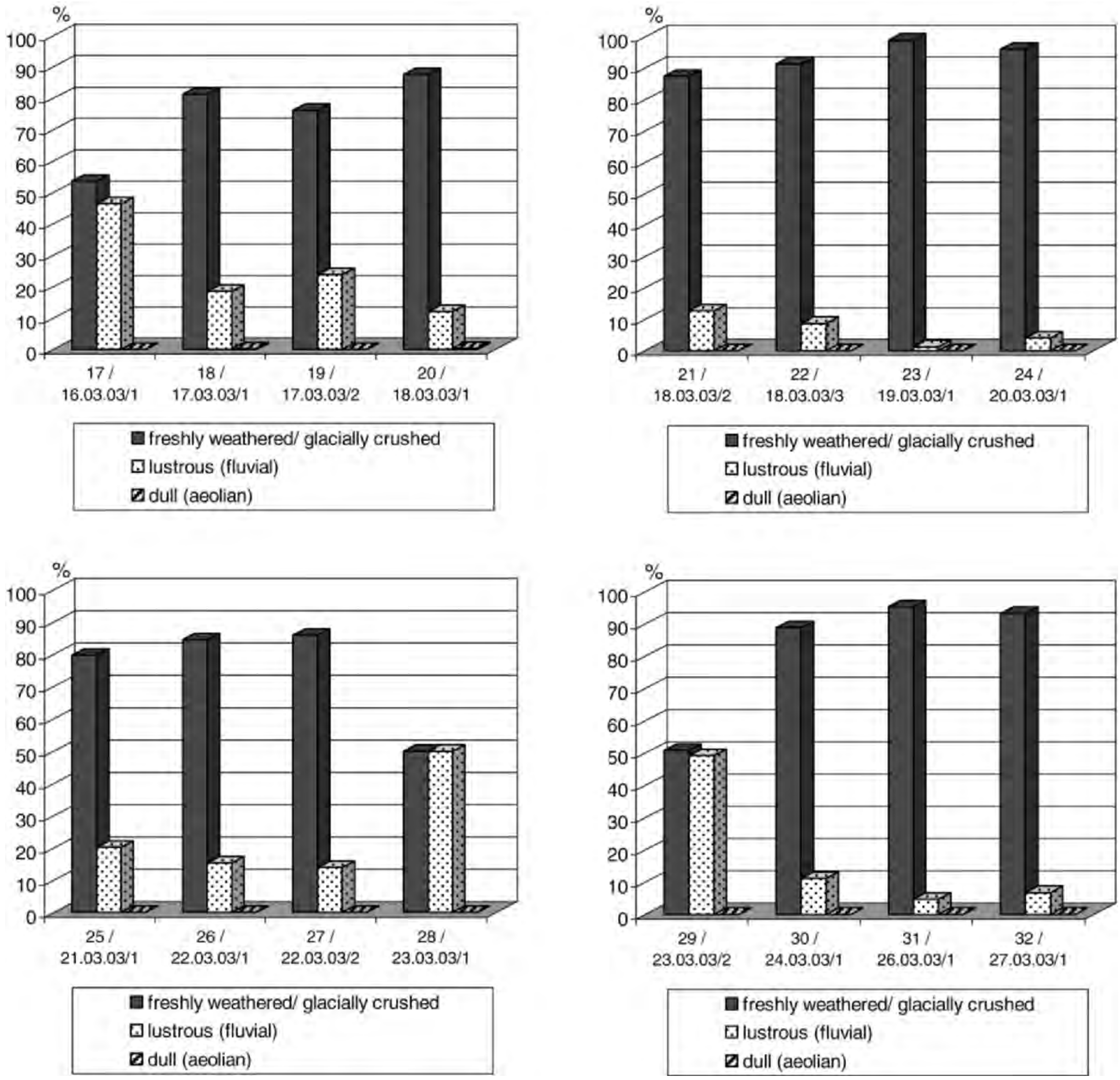


Figure 37. Continued.

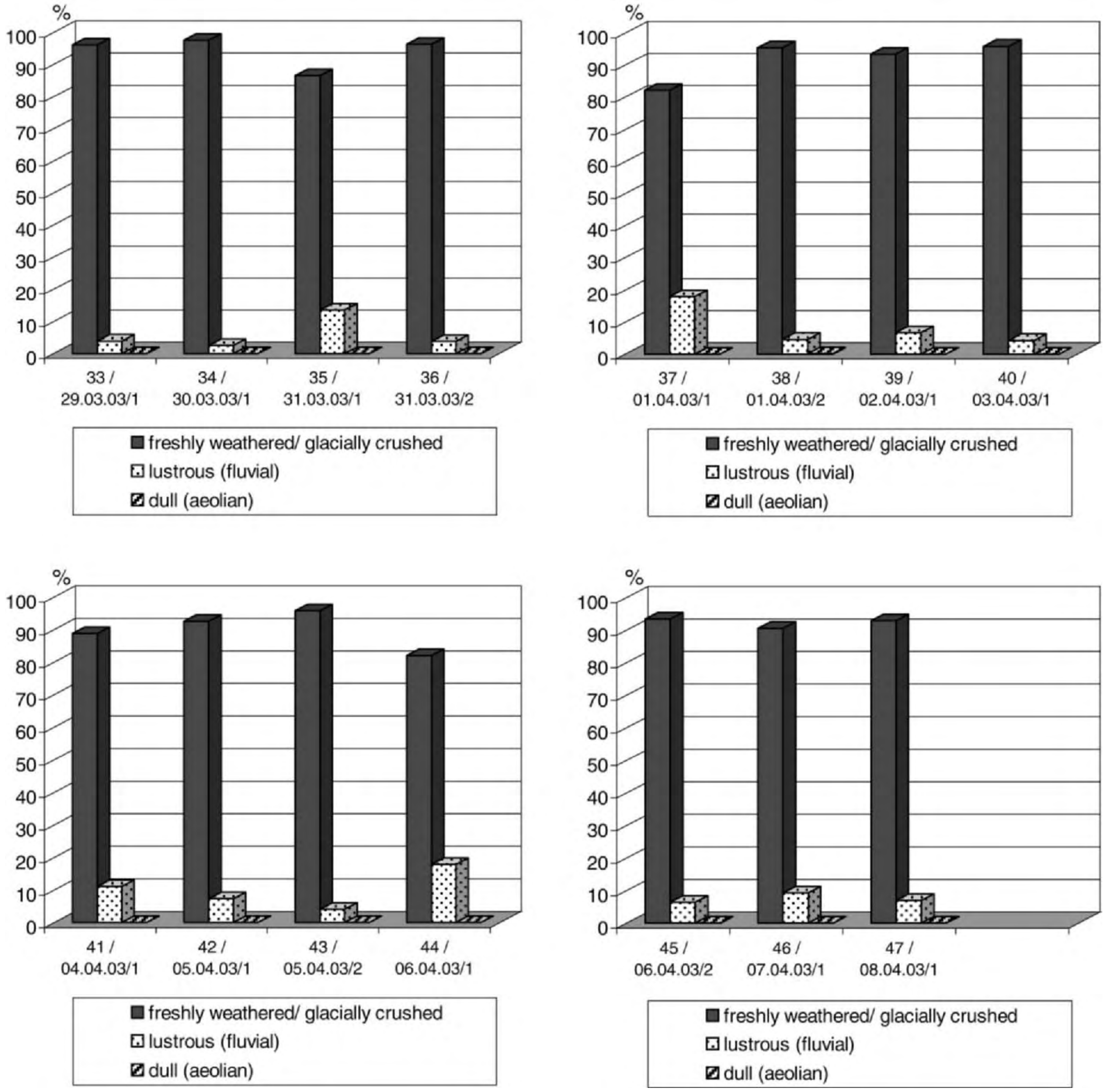


Figure 37. Continued.

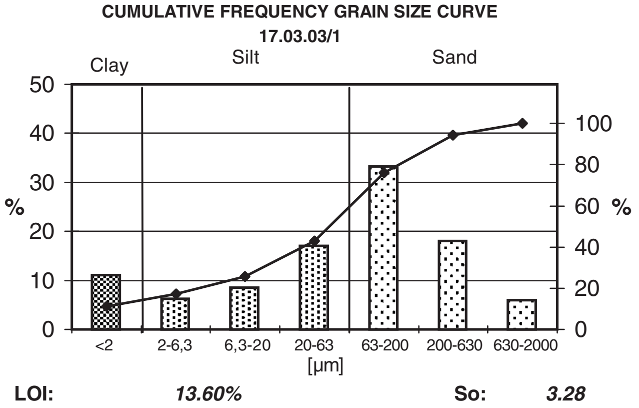


Figure 38. (Grain size diagram 17.03.03/1) At 4850 m a.s.l. on the orographic right flank of the lower Khumbu Drangka westward opposite the junction with the Imja Khola, matrix of ground moraine (Photos 78–80, foreground) taken from a depth of 0.3, 700 m above the current valley bottom with the Pheriche settlement. This ground moraine has been sedimentated during Stages 0–II (Table 1). The primary maximum is relatively coarse-grained, i.e. it lies with 33% in the fine sand; the secondary maximum with ca. 12% clay determines the bimodal course of the cumulative curve, which is typical of moraine matrix; the rather high content of clay itself is also typical of moraine. Sorting coefficient calculated according to Engelhardt (1973, p. 133) So = 3.28 (So = $\sqrt{Q3/Q1}$); the loss of ignition (LOI) is 13.60%. Locality: Figure 3: 17.03.03/1, Photo 66 ■ large white, below No. 40; see also Figure 37. Sample No. 18. Sampling: M. Kuhle.

In this area the High Glacial snow-line altitude of 3300–3600 m a.s.l. during the last glacial period has been established by the author by means of 14 cirques for the SE-, S- and SW-exposition (Figure 11 on the right of No. 46; Photo 26). Additionally, currently non-glaciated higher cirques have been mapped, lying with their bases between 3800 (Photo 22 ○ on the right) and 4400–4600 m a.s.l. (Photo 23 ○ on the right; Figure 11 above No. 46 and below No. 45). In correspondence to the rising snow-line (Table 1) they have been glaciated for the last time from the early up to the late Late Glacial (Stages I–IV) or even during the neoglacial period.

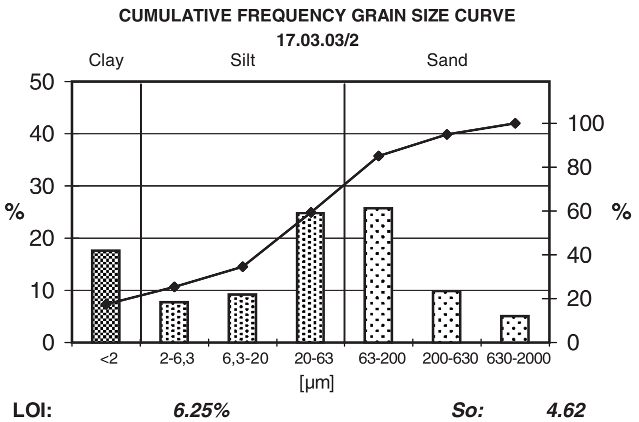


Figure 39. (Grain size diagram 17.03.03/2) At 4630 m a.s.l. on the orographic right flank of the lower Khumbu Drangka westward opposite the junction with the Imja Khola, ground moraine matrix taken from a depth of 1 m, 480 m above the current valley bottom with the Pheriche settlement. This ground moraine has been sedimentated during Stages 0–III (Table 1). The primary maximum occurs twice, with 25 and 26% (together 51%) in the fine sand and the coarse silt. The secondary maximum with ca. 18% clay determines the bimodal course of the cumulative curve, which is typical of moraine matrix; the very high portion of clay itself is also already typical of ground moraine. Sorting coefficient calculated according to Engelhardt (1973, p. 133) So = 4.62 (So = $\sqrt{Q3/Q1}$), the loss of ignition (LOI) amounts to 6.25%. Locality: Figure 3: 17.03.03/2; Photo 66 between and V on the left below No. 40; see also Figure 37. Sample No. 19. Sampling: M. Kuhle.

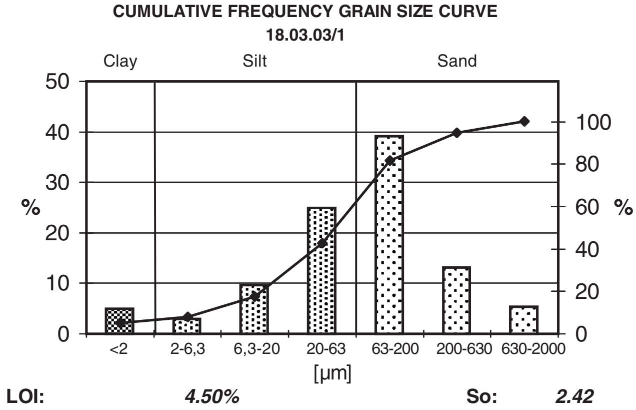


Figure 40. (Grain size diagram 18.03.03/1) At 4230 m a.s.l. on the orographic right flank of the lower Imja Drangka in the confluence area of the Imja Khola, end moraine matrix taken from a depth of 0.3 m ca. 100 m above the current talweg near the Dingpoche settlement. This outermost, oldest end moraine dam, which from the end moraine dam of the Nauri Stage (V) near Pheriche is the fourth and thus eastern-most one, has been sedimentated during the Late Glacial Sirkung Stage (= Stage IV; see Table 1). The primary maximum is relatively coarse-grained and lies with ca. 39% in the fine sand; the secondary maximum with ca. 5% clay determines the bimodal course of the cumulative curve which is typical of moraine matrix. Also the marked content of clay itself is already typical of moraine. Sorting coefficient calculated according to Engelhardt (1973, p. 133) So = 2.42 (So = $\sqrt{Q3/Q1}$), the loss of ignition (LOI) amounts to 4.5%. Locality: Figure 3: 18.03.03/1; Photo 78 □ on the right of IV; see also Figure 37. Sample No. 20. Sampling: M. Kuhle.

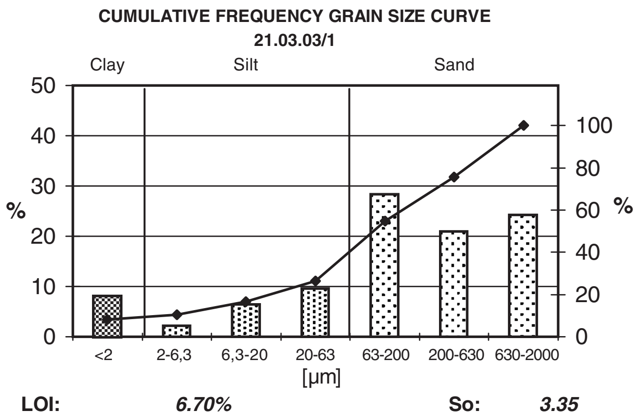


Figure 41. (Grain size diagram 21.03.03/1) At 500 m a.s.l. on the orographic right side of the Imja Drangka from the culmination of the front moraine of Stage X (Table 1) of the Lhotse Nup glacier in the area of the junction with the Imja Khola, end moraine matrix taken from a depth of 0.3 m. The primary maximum is relatively coarse-grained and lies with ca. 28% in the fine sand; the secondary maximum is with ca. 25% in the coarse sand and the third maximum with ca. 8% clay determines the trimodal course of the cumulative curve which is typical of moraine matrix. Also the marked portion of clay itself is already typical of moraine. Sorting coefficient calculated according to Engelhardt (1973, p. 133) So = 3.35 (So = $\sqrt{Q3/Q1}$), the loss of ignition (LOI) amounts to 6.70%. Locality: Photo 76 ■ X; Figure 3: 21.03.03/1; see also Figure 37. Sample No. 25. Sampling: M. Kuhle.

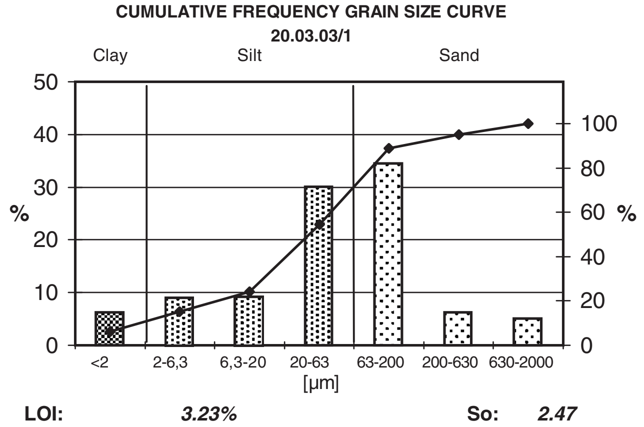


Figure 42. (Grain size diagram 20.03.03./1) At 5050 m a.s.l. on the orographic left side of the Imja Drangka from the culmination of the lateral- to front moraine of Stage VI–′VII (older or middle Dhaulagiri Stage; Table 1) of the Lhotse glacier in the confluence area with the Imja glacier, matrix of end moraine taken from a depth of 0.4 m. The maximum is relatively coarse-grained and lies with ca. 34% in the fine sand. In addition, the matrix contains ca. 6.5% clay. The clay content, which is rather low here, is typical of moraine. As to the undoubted moraine material, the sorting coefficient calculated according to Engelhardt (1973, p. 133) So = 2.47 (So = $\sqrt{Q3/Q1}$), too, is not very clearly marked. The loss of ignition (LOI) amounts to 3.23%. Locality: Photo 70 ↓; Figure 3: 20.03.03/1; see also Figure 37. Sample No. 24. Sampling: M. Kuhle.

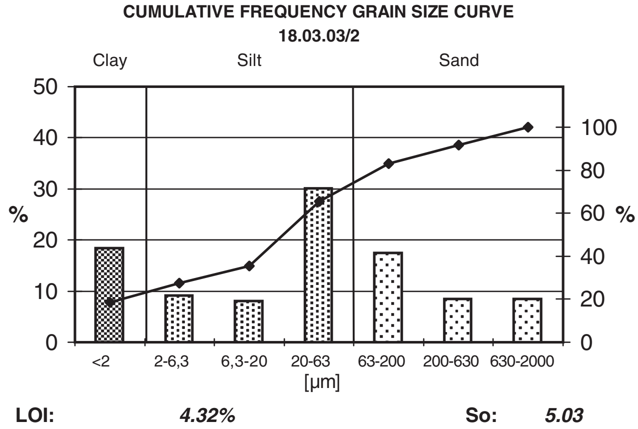


Figure 44. (Grain size diagram 18.03.03/2) At 4660 m on the orographic left side of the Imja Drangka valley exit in the confluence area with the Khumbu Drangka. Ground moraine matrix taken from a depth of 0.4 m from a pedestal- (ground-) moraine slope of the Dhampu Stage (Late Glacial Stage III, Table 1) developed by the incision of the Imja river since deglaciation. The primary maximum lies with 30% in the coarse silt, the secondary peak with ca. 18% in the clay. The bimodal course of the cumulative curve of the fine material matrix and also the important clay portion are typical of moraine. Sorting coefficient calculated according to Engelhardt (1973, p. 133) So = 5.03 (So = $\sqrt{Q3/Q1}$); the loss of ignition (LOI) amounts to 4.32%. Locality: Photo 77 next to III; Photo 75 III in the foreground; Photo 76 III; Figure 3: 18.03.03/2; see also Figure 37. Sample No. 21. Sampling: M. Kuhle.

The Barun Nadi cross-profile of the Barun gorge (Figure 13), still filled by an 800 m-thick glacier, is situated only 5 km away from the confluence with the prior main valley, the Arun Nadi (Figure 4). Just from these circumstances one can draw the conclusion that the Ice Age Barun glacier has reached the Arun Nadi. The ice thickness of 800 m – despite the very steep incline (see above) of ca. 730 m per 5 km (from 1840 to 1110 m a.s.l.) – evidenced by upper limits of abrasion (Figure 11 on the left of No. 48) and reaching up to the junction with the main valley near Barun Bajar, points to an Arun valley glacier serving as an abutment for the Barun glacier (see below Section 2.4). On the other hand, the narrow V-shaped form of the subglacial meltwater gorge (see above) (Figure 13) developed

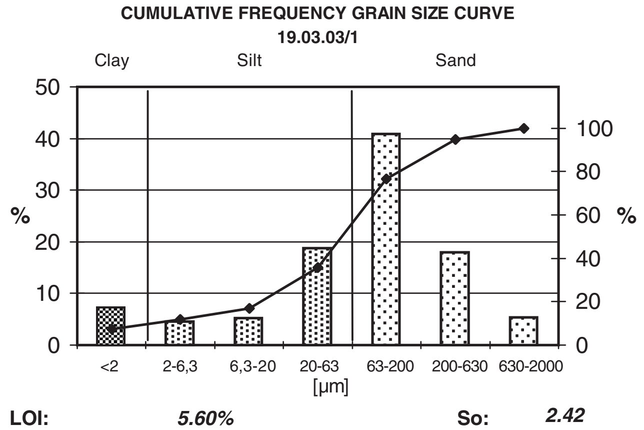


Figure 43. (Grain size diagram 19.03.03/1) At 5000 m a.s.l. on the orographic left side of the Imja Drangka from the culmination of the lateral- and end moraine of Stage VII (younger Dhaulagiri Stage; Table 1) of the Lhotse glacier in the area of the lower glacier tongue end, 2 km E of the Chhukhung alpine pasture. End moraine matrix taken from a depth of 0.4 m. The primary maximum is with 41% very clear in the relatively coarse-grained material, in the fine sand; the secondary peak with ca. 7% is in the clay. The bimodal course of the cumulative curve of the fine material matrix and also the important clay portion are typical of moraine. Sorting coefficient calculated according to Engelhardt (1973, p. 133) So = 5.6 (So = $\sqrt{Q3/Q1}$); the loss of ignition (LOI) amounts to 2.4%. Locality: Photo 74 ⇓, Figure 3: 19.03.03/1; see also Figure 37. Sample No. 23. Sampling: M. Kuhle.

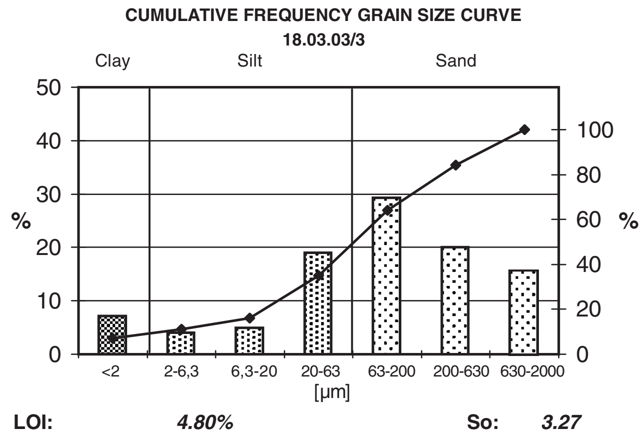


Figure 45. (Grain size diagram 18.03.03/3) At 4570 m a.s.l. on the orographic right side of the Imja Drangka, close to the valley exit in the confluence area with the Khumbu Drangka, ground moraine matrix taken from a depth of 0.4 m from a High- to Late Glacial (Stages 0–IV; Table 1) cover of ground moraine on the valley slope. The primary maximum of 29% is in the fine sand in a relatively coarse-grained material; the secondary peak is with ca. 7% in the clay. The bimodal course of the cumulative curve of the fine material matrix is typical of moraine matrix and also the important clay portion. Sorting coefficient calculated according to Engelhardt (1973, p. 133) So = 3.27 (So = $\sqrt{Q3/Q1}$); the loss of ignition (LOI) amounts to 4.8%. Locality: Photos 75 and 77 ■ on the very left; Figure 3: 18.03.03/3; see also Figure 37. Sample No. 22. Sampling M. Kuhle.

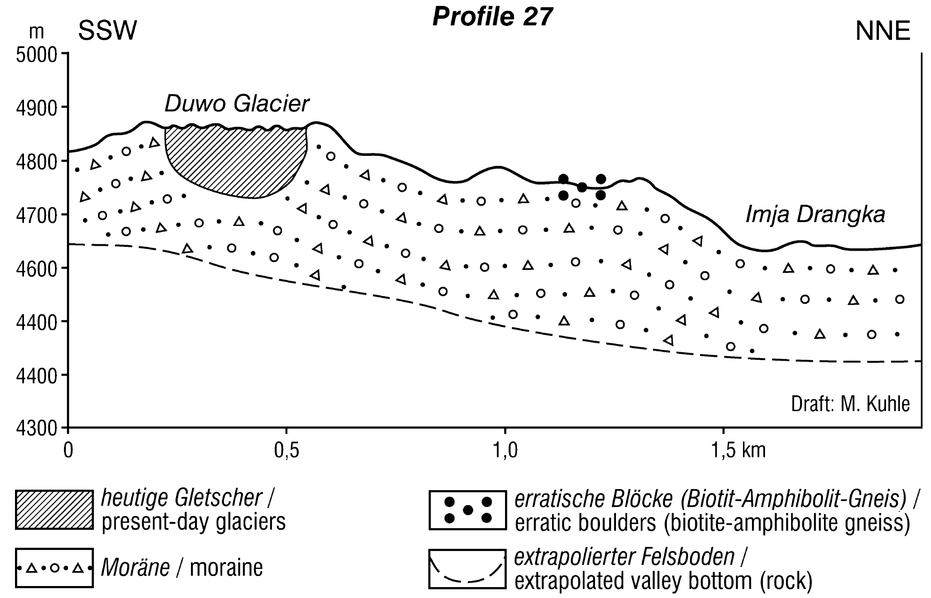


Figure 46. (Profile 27) Cross-section (flattened) N of Amai Dablang across the current Duwo glacier and the remnant of the ground moraine pedestal of the late Late Glacial (Sirkung Stage IV; Table 1) with erratic boulders, especially with a biotite-amphibolite-gneiss boulder. Tourmaline granite crops out in the immediate postglacial glacier catchment area, in the Amai Dablang flank. The erratic boulder must have been transported here from the valley head of the Imja Khola situated 12–20 km away, where biotite-amphibolite-gneiss outcrops in the Lhotse-S-wall (Figure 3 below Nos. 2–10) as well as in the area of Amphu Labtsa (on the right below No. 58) (Nepal Geological Map 1985: Sheet No. 72I-B). Locality: Figure 3 next to IV above No. 20, on the right above the Duwo glacier; Photo 70 above IV white; Photo 72 below □ below No. 36; Photo 76 below □ on the left of IV; Photo 77 on the left of III below ▽; Photo 78 between ■ and ■ below No. 3).

below the snow-line, must have heightened the friction, so that it held back the ice discharge.

In the case that the Barun glacier had come to an end in the confluence area or even before it, the glacier surface would have dropped over a distance of only 5 km from a height of 2700–2800 m (Figure 13) to 1110 m, i.e. by approximately 1650 m. A longitudinal profile of a valley glacier tongue such as this can be ruled out because it is too steep to be realistic.

Summing up, it has been shown that: the trim-line of the High Glacial Barun Nadi glacier has sloped from ca. 5100 m a.s.l. near Yangri Kharka (Photo 15

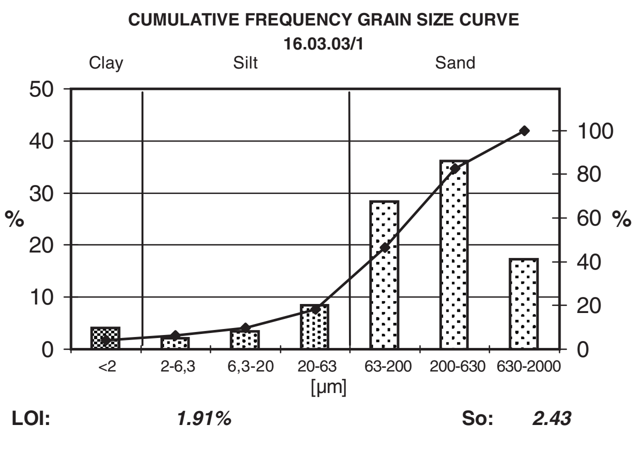


Figure 47. (Grain size diagram 16.03.03/1) At 4400 m a.s.l. on the orographic right side of the Imja Drangka N above the Pangpoche settlement, matrix of ground moraine from a High- to Late Glacial (Stages 0–III; Table 1) ground moraine cover on the valley slope, taken from a depth of 0.4 m. The primary maximum with 36% has been developed in the relatively very coarse-grained material, in the medium sand; the secondary peak with ca. 4.5% is in the clay. The bimodal course of the cumulative curve of the fine material matrix is typical of moraine and also the clay portion. Sorting coefficient calculated according to Engelhardt (1973, p. 133) So = 2.43 (So = $\sqrt{Q3/Q1}$); the loss of ignition (LOI) amounts to 1.91%. Locality: Photo 83 ■ on the right margin; Photo 87 ■ on the right, foreground; Figure 3: 16.03.03/1; see also Figure 37. Sample No. 17. Sampling: M. Kuhle.

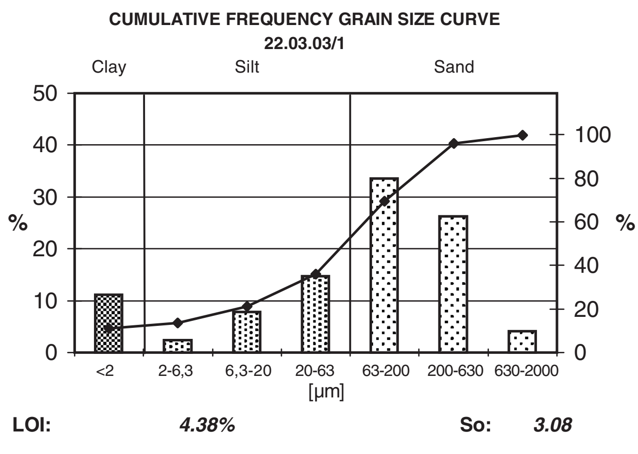


Figure 48. (Grain size diagram 22.03.03/1) At 4065 m a.s.l. on the orographic right side of the Imja Drangka westward down-valley of the Pangpoche settlement, ground moraine matrix taken from a depth of 0.6 m from a High- to Late Glacial (Stages 0–III; Table 1) ground moraine cover on the valley slope. The primary maximum is with 34% in the relatively coarse-grained material, in the fine sand; the secondary peak is with 12% in the clay. The bimodal course of the cumulative curve of the fine material matrix is typical of moraine and also the relatively high clay portion. Sorting coefficient calculated according to Engelhardt (1973, p. 133) So = 3.08 (So = $\sqrt{Q3/Q1}$), the loss of ignition (LOI) amounts to 4.38%. Locality: Photo 89 ■ on the left of the stick; Figure 3: 22.03.03/1; see also Figure 37. Sample No. 26. Sampling: M. Kuhle.

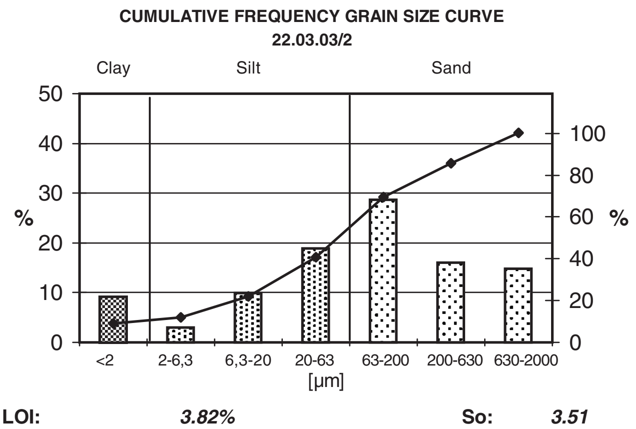


Figure 49. (Grain size diagram 22.03.03/2) At 4200 m a.s.l. on the orographic right side of the Imja Drangka 2 km westward down-valley of the Pangpoche settlement, ground moraine matrix from a High- to Late Glacial (Stages 0–II or III) ground moraine cover on the valley slope taken from 1 m below the surface. The primary maximum is with 28.5% in the relatively coarse-grained material, in the fine sand; the secondary peak with ca. 9.5% is in the clay. The bimodal course of the cumulative curve of the fine material matrix is typical of moraine; sorting coefficient calculated according to Engelhardt (1973, p. 133) So = 3.51 (So = $\sqrt{Q3/Q1}$), the loss of ignition (LOI) amounts to 3.82%. Locality: Photo 94 ↓; Figure 3: 22.03.03/2; see also Figure 37. Sample No. 27. Sampling: M. Kuhle.

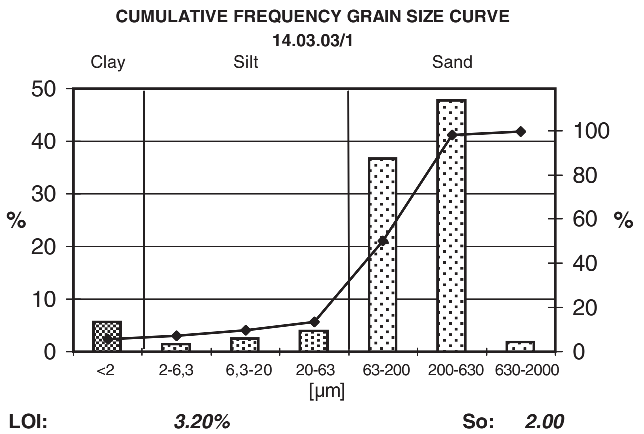


Figure 51. (Grain size diagram 14.03.03/1) At 4000 m a.s.l. on the orographic left side of the Imja Drangka SE above the Tengpoche monastery, matrix from a High- to Late Glacial (Stages 0–III; Table 1) ground moraine cover on the valley slope taken from an exposure 5 m below the surface of the moraine slope. The primary maximum is with 47% in the relatively very coarse-grained material, in the medium sand; the secondary peak is with ca. 5.5% in the clay. The bimodal course of the cumulative curve of the fine material matrix is typical of moraine and also the marked portion of clay; sorting coefficient according to Engelhardt (1973, p. 133) So = 2.00 (So = $\sqrt{Q3/Q1}$), the loss of ignition (LOI) amounts to 3.20%. Locality: Photo 95 ↓; Photo 96 ■; Figure 3: 14.03.03/1; see also Figure 37. Sample No. 15. Sampling: M. Kuhle.

––– 0; 18 ––– on the left) via 4600–4700 m a.s.l. 9 km down-valley at Profile 5 (Figure 12) to 2800–2700 m at Profile 6 (Figure 13) (Photos 18–20: –––). Suggesting that during the High Glacial (Stage 0) a ground moraine veil with a thickness of only a few metres has covered the bedrock of the valley ground, ice thicknesses can be reconstructed from 1600 m at the maximum (Pro. 5) up to ca. 800 m (Pro. 6) 5 km up-valley from the inflow into the Arun Nadi (cf. Figure 4). The cause of this important decrease in ice thickness (cf. Photo 19 –––) is the steep and thus accelerating glacier discharge into the low-lying Arun valley. The glacier thickness of 800 m, which is nevertheless significant, can be explained by the abutment of the Arun Nadi main valley glacier (Section 2.4). Due to the increasing valley incline toward the junction with the Arun Nadi, the most important ice thickness, normally situated where the ice surface cuts the ELA, has been shifted up-valley as far as up to Profile 5 (Figure 12). Here, the glacier surface lies ca. 1200 m above the snow-line. During the last glacial period the snow-line in the area of the lower Barun Nadi lay between 3300–3600 m a.s.l.

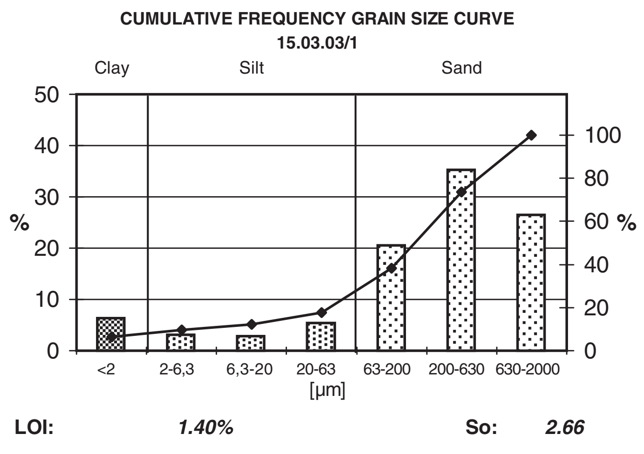


Figure 50. (Grain size diagram 15.03.03/1) At 3915 m a.s.l. on the orographic left side of the Imja Drangka, 2 km SW of the Pangpoche settlement, matrix of ground moraine from a High- to Late Glacial (Stages 0–IV; Table 1) cover of ground moraine on the valley bottom, 65 m above the Imja river, taken from an exposure from 3 m below the surface. The primary maximum is with 36% in relatively very coarse-grained material, in the medium sand; the secondary peak is with ca. 6.5% in the clay. The bimodal course of the cumulative curve of the fine material matrix is typical of moraine as is also the significant portion of clay; sorting coefficient calculated according to Engelhardt (1973, p. 133) So =2.66 (So = $\sqrt{Q3/Q1}$), the loss of ignition (LOI) amounts to 1.40%. Locality: Photo 91 ↓; Figure 3: 15.03.03/1; see also Figure 37. Sample No. 16. Sampling: M. Kuhle.

2.2. *The current and Ice Age Irkhuwa- or Isuwa glacier*

In the same way as the Barun Khola as an orographic right tributary valley is connected to the Arun Nadi, the Irkhuwa Khola joins the Arun Nadi – which has precedence over it – 15 km further to the SW (Figure 4). The current Irkhuwa (or Isuwa or Iswa) glacier reaches down to 4080 m a.s.l. (Photo 24 ■; Figure 11 half-left below No. 47). It is ca. 7.5 km-long and concentrates the ice of the Chamlang-SE-flank (Photos 24 and 25; Figure 3 on both sides of No. 12) in its ca. 4 km-long valley glacier tongue. In the course of its lowest kilometre the tongue is covered with surface moraine debris. Currently it is in the process of slow retreat. At the same time the striking inner slopes of the lateral moraines of Stage X (Table 1) overthrust 180–30 years before 1950, become more and more exposed (Figure 11 X half-left below No. 47). The orographic snow-line in the

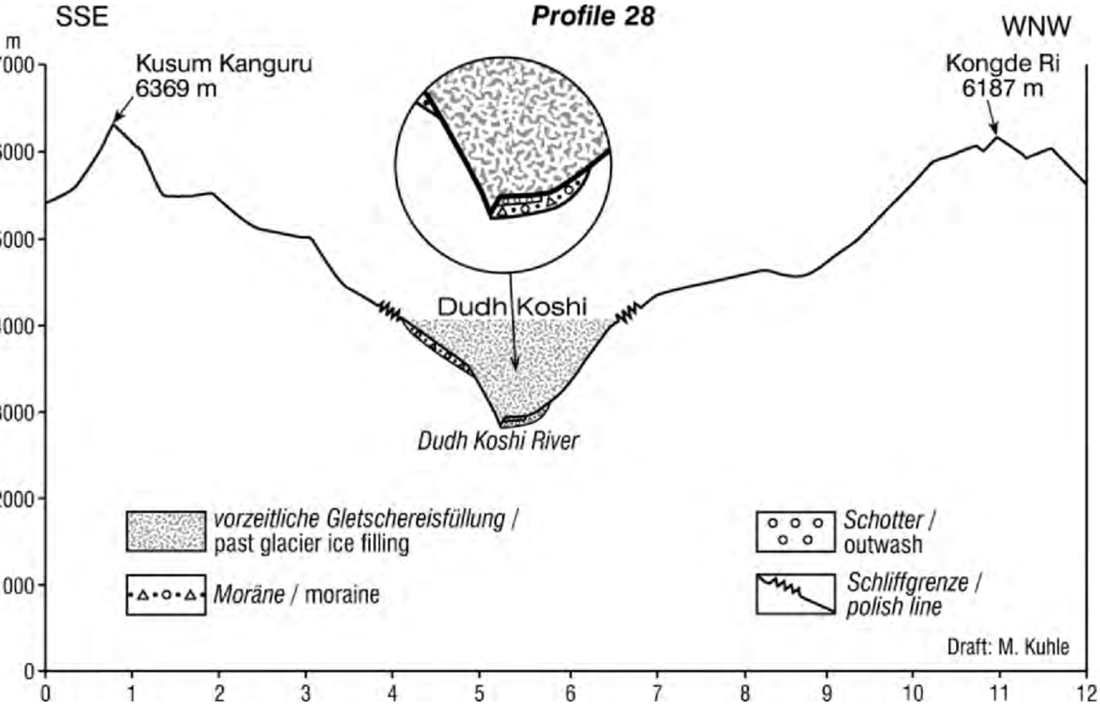


Figure 52. (Profile 28) Cross-section (not exaggerated) seen down-valley across the Dudh Koshi Nadi from the 6369 m-high Kusum Kanguru (Figure 11 and Photo 157: No. 73) to the 6187 m-high Kongde Ri (Figure 11 and Photo 157: No. 60; 227 and 222: ∪;). On this cross-profile the Ice Age glacier has polished out the orographic right flank of the valley into the form of a trough. On the orographic left side the bedrock is covered with a decametre-thick ground moraine up to the polish line. The maximum glacier filling of this cross-profile has been reconstructed for the last glacial period (Würmian: ca. 60–18 Ka = Stage 0; Table 1). In correspondence with the upper limit of the ground moraine cover preserved, reaching up to ca. 4000 m, and according to the glacigenic abrasions on both the valley flanks up to an abrasion limit about 4000 m a.s.l. (Photo 216 ∩ on the right below No. 36; 156 ∩, ⌒ (on the right below No. 73), the glacier trim-line must have run at 4000 m a.s.l. The valley floor shows a decametre-thick cover of Late Glacial ground moraine and glaciofluvial gravels lying over it, which have been – and still are – cut by the Dudh Koshi river. The maximum past ice thickness down to the rock ground of the valley floor was ca. 1300 m. In this profile the Ice Age glacier surface was situated ca. 200–400 m above the contemporaneous local High Würmian ELA. Locality: Figure 4.

SE-exposition of the Chamlang Himal-massif can be ascertained by means of the contemporary Irkhuwa glacier. The medium altitude of the crest fringe, i.e. catchment area lies at 7100 m a.s.l., the lowest ice margin, i.e. the end of the glacier tongue at ca. 4100 (4080) m, so that the ELA runs at half the altitude, i.e. at 5600 m (calculation of the ELA: 7100–4100 = 3000; 3000:2 = 1500; 1500 + 4100 = 5600).

The High Glacial Irkhuwa glacier and its approx. highest trim-line could be reconstructed with the help of several unambiguous indicators and evidences (Figure 11 between Nos. 47 and 46). So, for instance, the valley has a classically glacigenic trough form (Figure 14; Photos 24 and 25 ∪). Its bottom has been filled 100–200 m-thick with loose material up to 250 m above the talweg. This concerns the characteristic sedimentation of the subglacial deposit of ground moraine on the polished rock ground of the trough (Photo 25 ■ large) during the Late Glacial (Stages I–IV), via the postglacial glacier mouth gravel floors with their gravels in the glaciofluvial area of the talweg, up to debris flow fans and -cones interlocked with them (▽) and likewise cone-shaped masses of rock avalanches (Photos 24 and 25 ▼ black) from the deglaciation up to the present (Figure 14 enlarged section of the valley bottom). In many places the accumulations of debris flow are made up of moraine material from originally high-lying deposits of ground moraine in steep ravines of the valley flanks, dislocated downslope (Photo 25 ■ small, white). The rock avalanches come down from the trough slopes – steepened by the Ice Age flank polishing – in the form of crumblings. They also roughen the glacigenic smoothings and roundings (Photos 24 and 25 ∩) by the tracks of rock falls (Photo 24 ↓ on the right). In addition, the current polishing by avalanches during the winter reworks the ravines and gullies polished out by steep former hanging glaciers in the valley flanks (↓ on the left).

The ground moraine remnants most highly preserved are situated on orographic left flattenings of the valley flanks (Photo 24 ■ and 25 ■ black, small; Figure 11 No. 47) about 5300 m a.s.l., ca. 1000 m above the contemporary surface of the valley glacier tongue on this cross-profile of the Irkhuwa Khola. Here, a decametres-thick ground moraine core is concerned, buried by a minor thick cone of rock fall since deglaciation. The highest flank abrasions (Photos 24 and 25 ∩), which with increasing height are naturally preserved only at a small-scale or in a punctiform manner, give evidence of a polish line which falls away from 5800 m a.s.l. at the valley head (Photo 24 – – – above ■; 25 – – – ■ black, small) to 3900 m, 11 to 12 km down-valley (Photos 24 and 25 – – – near to the left margin). Profile 7 proves a trim-line about 4600 m a.s.l. situated in between 4–5 km

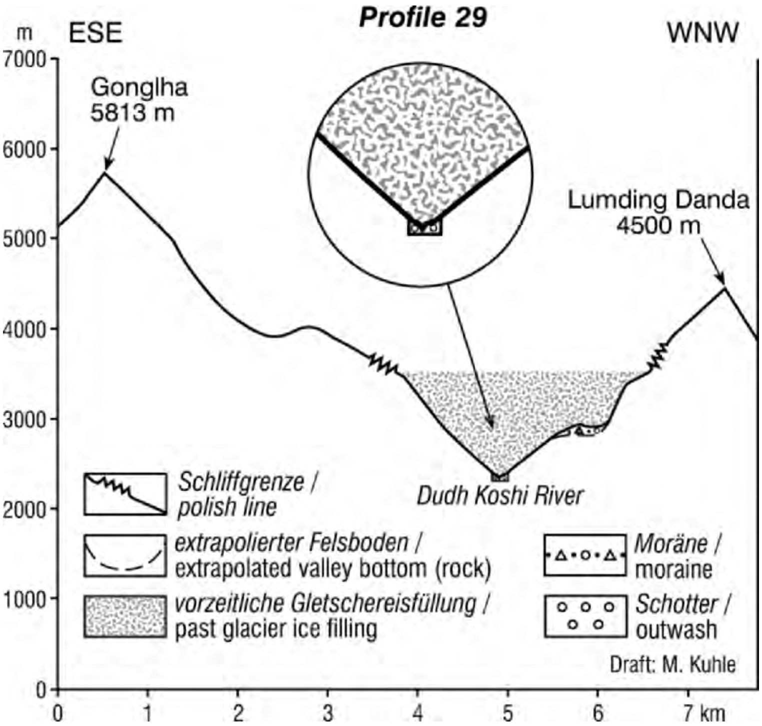


Figure 53. (Profile 29) Cross-section (not exaggerated) seen down-valley across the Dudh Koshi Nadi from the 5813 m-high Gonglha up to beyond the 4500 m-high mountain ridge of the Lumding Danda. On this cross-profile the valley has been slightly trough-like concavely polished out by the Ice Age glacier (Photos 218 and 228: ᑌ). On the orographic right side the rock is locally covered by a decametre-thick ground moraine. The maximum glacier filling of this cross-profile has been reconstructed for the last glacial period (Würmian: ca. 60–18 Ka = Stage 0; Table 1). According to the upper limit of the flank abrasions preserved, which reach up to ca. 3600 m (Photo 222 .... on the left and right; 157 _____ on the left below No. 60), the glacier trim-line must have run about 3600 m a.s.l. (Photo 231 _____ on both sides below No. 74). The valley floor is covered with glaciofluvial gravels. The maximum past ice thickness down to the rock ground amounted to ca. 1200 m. In this profile the Ice Age glacier surface was situated at approx. the contemporaneous local High Würmian level of the ELA up to ca. 200 m below. Locality: Figure 4.

down-valley from the valley head (Figure 14). Polished back mountain spurs, i.e. the uppermost tops of glacigenic triangle-shaped faces are preserved up to these abrasion limits (Figure 11 far below and half-right below No. 37, i.e. half-left above No. 46; Photos 24 and 25 ∩).

Seen in the general context of the Quaternary, polyglacial era, the orographic left trough valley flank has undergone a down-slope shaping by local hanging glaciers in every renewed early- and late glacial period of the different Ice Ages. These glaciers flowed down the ramp-like denudation terrace (rock terrace) from the SW-faces of the SE-continuation of the crest of the Iswa Peak (Photos 24 and 25 below No. 37). The great altitude of the walls above the ELA still leads to the feeding by avalanches from avalanche cone glaciers (●), which naturally are much smaller today. Those early- and late glacial hanging glaciers have abraded the left Irkhuwa valley flank down to the synchronous minor-thick main glacier (Photo 24 ▼ white; 25 ↓ full). Owing to this they have polished out three rock tongue basins lined up side by side (Photo 24 ▼ white). Between the rock tongue basins dividing crests have remained, which are in the process of development into ‘riegels’ (or ‘Torsäulen’). Here – though the slopes are steeper – similar glaciogeomorphological conditions exist as in the orographic left flank of the Barun Khola, in the area of the Chamlan Himal-SW-flank (see Section 2.1.4). Here, too, the more than 1000 m-thick Irkhuwa glacier reaching very high up in every high glacial period (– – –) (Figure 14), has polished the dividing crests and developing riegels again and again transverse to the direction of flow. At the same time it has rounded them and laid them lower. The decay of these rock heads due to early- to high- and then again late glacial changes of the glacigenic direction of abrasion, which has taken place for the last time during the last glacial period (Stage 0), has prepared for instance the Holocene (even historical), i.e. interglacial fresh rock fall in the left valley flank (Photo 24 ▽); ↓ on the right, ▼ black; 25 ▼).

Above the current snow-line (about 5600 m a.s.l.) polishing by avalanches takes place in the steep flanks, which has scoured out the wall gorges (Photos 24 and 25: ○). During the Pleistocene ice ages and the interglacial periods this has always taken place above the ELA.

The past maximum ice thickness has been reached in Profile 7 (Figure 14) in the Irkhuwa Khola and amounted to at least 1100 m (Figure 4). It continued at least 5–6 km down the valley (Photo 25 – – – left margin, foreground) as far as the glacier surface reached the vicinity of the snow-line (see below). At a constant valley incline the greatest ice thickness is there, where the ice surface cuts the snow-line and plunges beneath it. However, since below 2800 m a.s.l. the valley bottom becomes steeper and steeper – because as a hanging, gorge-shaped trough valley the Irkhuwa Khola is

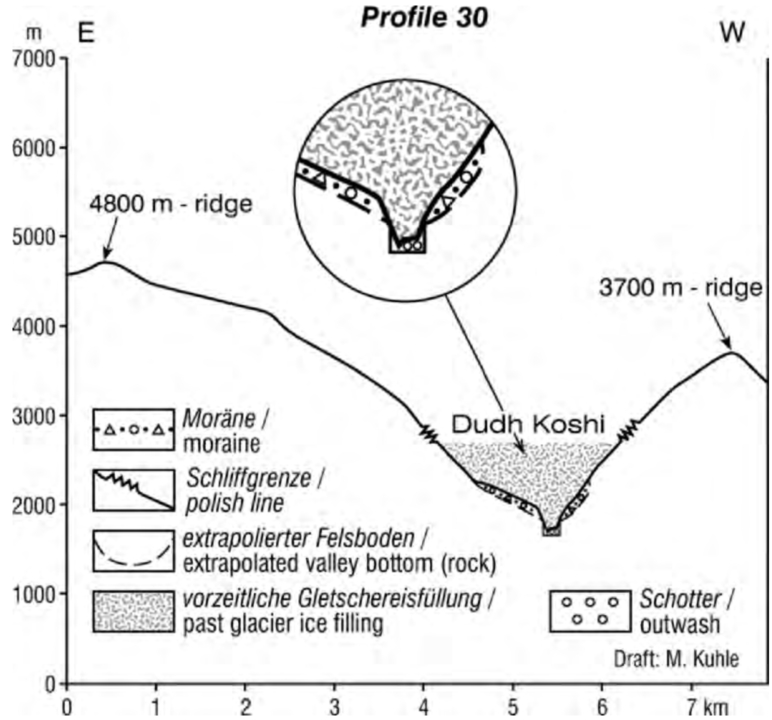


Figure 54. (Profile 30) Cross-section (not exaggerated) seen down-valley across the Dudh Koshi Nadi from the 4800 m-ridge up to beyond the 3700 m-ridge. On this cross-profile the valley has been slightly trough-like concavely polished out by the Ice Age glacier (Photo 230▲; 231▲ exactly below No. 16; 232 ▽). On the valley flanks the rock is covered with ground moraine, which in places is decametre-thick and reaches ca. 2350 m a.s.l. The maximum glacier filling of this cross-profile has been reconstructed for the last glacial period (Würmian: ca. 60–18 Ka = Stage 0; Table 1). According to the upper limit of the flank abrasions preserved up to ca. 2700 m (Photo 229⌒, ⌒), its glacier trim-line has run at approx. this altitude (Photo 230 ....). The valley floor shows the form of a subglacially developed glacial gorge with nearly vertical walls (see also Photo 232 ⇓) and a box-shaped cross-profile, through which the Dudh Koshi river drags away the boulders and gravels of flushed-out moraine. In this profile the past maximum ice thickness lay ca. 1000 m below the local High Würmian level of the ELA. Locality: Figure 4.

adjusted to the Arun main valley (Figure 11 below No. 52; Photos 49 and 50 ▽)–, in this special topographic case the greatest ice thickness occurred ca. 3–4 km up-valley of its surface height at the level of the ELA. Here, the Last Glacial snow-line ran about 3600 m. At the level of the snow-line the slightly concave surface profile of the glacier (Figure 14) has changed into a stretched and then, down-valley, slightly convex cross-profile.

Ca. 1–2 km down from the valley head, in the place where the Ice Age Irkhuwa glacier has crossed the Iswa La, this 5340 m-high transfluence pass (Figures 3, 4, 11 and Photo 24 No. 47) from the Arun Nadi, its level had dropped to ca. 5300 m and a ca. 510–560 m-thick inflow from the Barun glacier took place (cf. Section 2.1.3). Both the glaciers, the Barun- and the Irkhuwa glacier, merged into the same parent glacier, the Arun main glacier (Figure 4; 11). The Barun glacier reached the Arun glacier at 1100 m a.s.l., 37.5 km away from the Iswa transfluence pass, the Irkhuwa glacier at not quite 700 (684) m a.s.l. at nearly the same distance of 38 km (see Section 2.4). Accordingly, the latter has flowed down markedly more steeply. At nearly the same altitude of the snow-line at most 3600 m a.s.l., its ice must have flowed down much faster in that transfluence area, so that its level lay lower. This was the cause of the good 500 m difference between the levels.

Evidence of a High Glacial Irkhuwa glacier reaching the Arun main valley is provided by the development of a trough valley (Photo 50 ▽ black; Figure 11 on the left up to below No. 52) and an orographic left lateral moraine ledge (0 ■) at the valley exit (see Table 1 Stage 0). This is adjusted to the surface level of the Arun main valley glacier, proved by abrasion limits (Photo 49 ––– on the left and in the centre) (see Section 2.4). Due to the steepness of the valley incline the trough valley cross-profile is narrowed gorge-like. The result is a 'gorge-shaped trough', i.e. 'a trough-shaped gorge' typical of Himalaya cross-valleys (Kuhle, 1983a, 154/155) (Photo 50 ▽ black), the glacigenic characteristics of which become obvious by the trough flanks polished out concavely by the glacier. A second smaller trough-profile (▽ white) has been polished into this large cross-profile. Its tongue-basin-like narrowing with an exit in form of a gorge points to a Late Glacial ice margin position at 780 m a.s.l. This is classified as belonging to the oldest Late Glacial Stage I, the Ghasa Stage (Table 1), or a somewhat earlier stagnation of the glacier tongue during the re-melting of the High Glacial Irkhuwa glacier, the so-called pre-Ghasa stagnation. Two of these pre-Ghasa stagnations have already been evidenced as for the Dhaulagiri- and Annapurna Himalaya, 350 km further to the W (Kuhle, 1982: 80/81, 87, 91, 92, 98, 113, 153).

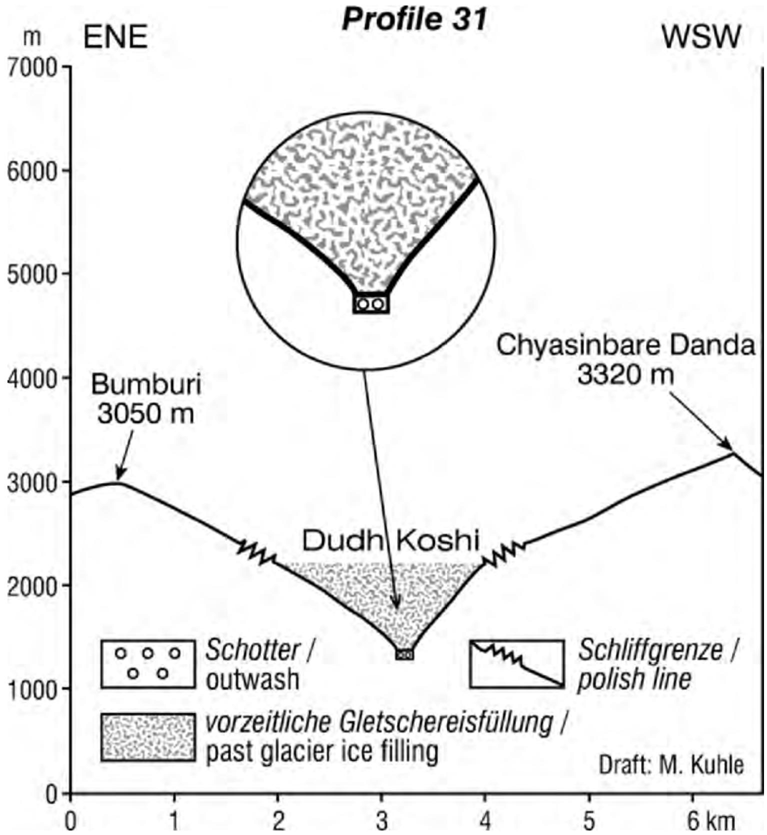


Figure 55. (Profile 31) Cross-section (not exaggerated) seen down-valley across the Dudh Koshi Nadi from the 3050 m-high Bumburi ridge up to the 3320 m-high Chyasinbare Danda. Here, the valley shows a V-shaped valley cross-profile, composed of stretched, glacigenically abraded flanks with small-scale roundings (see also Photo 233⊃,⌒). The rock of the valley flanks has been polished up to ca. 2250 m a.s.l. Accordingly, the upper limit of the maximum glacier filling of this cross-profile reconstructed for the last glacial period (Würmian: ca. 60–18 Ka = Stage 0; Table 1) has run at this altitude. The steepness of the rock slopes increases toward the valley floor. It shows the form of a subglacially developed glacial gorge with nearly vertical walls (see also Photo 232 ⇓). The Dudh Koshi river transports the boulders and gravels of flushed-out moraine across the rock ground of its box-shaped cross-profile. The maximum past ice thickness down to the rock ground of the valley amounted to ca. 850 m. In this profile the Würmian glacier surface lay ca. 1450 m below the local Würmian level of the ELA. Locality: Figure 4.

To sum up one may say that the current 7.5 km-long Irkhuwa glacier, which at the valley head flows down from the Chamlang-SE-flank (Photo 52 No. 12), reaches down to 4080 m. Its orographic snow-line runs at 5600 m.

The Last Glacial Irkhuwa glacier (Stage 0 = Last High Glacial maximum = last glacial period = Würm = Isotope Stages 4–2) has filled the entire 40 km-long valley (Photo 52 below No. 12) and joined the Arun parent glacier at ca. 700 m a.s.l. Over a distance of 5–6 km it has attained a thickness of at least 1100 m.

During the Late Glacial Ghasa Stage (I) or the pre-Ghasa stagnation the Irkhuwa glacier came to an end at 780 m a.s.l., immediately above the junction with the Arun Nadi. At a medium catchment area (crest fringe) of ca. 6500 m this glacier extension proves a corresponding orographic snow-line at 3640 m a.s.l. (calculation of the ELA: 6500−780 = 5720; 5720:2 = 2860; 2860 + 780 = 3640).

2.3. *The last glacial glaciation of the Kasuwa Khola*

The Kasuwa Khola runs between the Barun Khola in the N and the Irkhuwa Khola in the S as a smaller parallel valley down to the SSE (Figure 4; Photo 52 half-right below No. 3). It has a catchment area which consists of 14 cirques, hose cirques and short troughs, rising like an amphitheatre (Figure 11 on the right side above No. 46 up to the left side above No. 49; Photo 26 ○; Photo 46 and 47 *; Photo 52 the two left * on the right below No. 3), which via numerous steep small side valleys is connected to the talweg of the Kasuwa Khola. Short glacier tongues hung down from the cirques into these small valleys (Figure 11 half-left above No. 49). Due to the relief and the impenetrable woodland the lower sections of these side valleys are difficult to traverse. So far they have not been investigated in detail with regard to glacier traces. But this much is certain, that from these small valleys no glaciers have merged in this main valley floor to form a Kasuwa parent glacier. Owing to its comparably greatest height of the catchment area, the Kasuwa Khola itself has been flowed through by a ca. 6 km-long valley glacier. The height of the catchment area of the Kasuwa Khola reaches 4519, 4453 and – further to the E – 4447 m a.s.l. (Photo 26, summit on the very left).

2.5 i.e. 1.5 km E of the Tashigaon (Tasigau) and Robesa settlements a pedestal-like end moraine complex

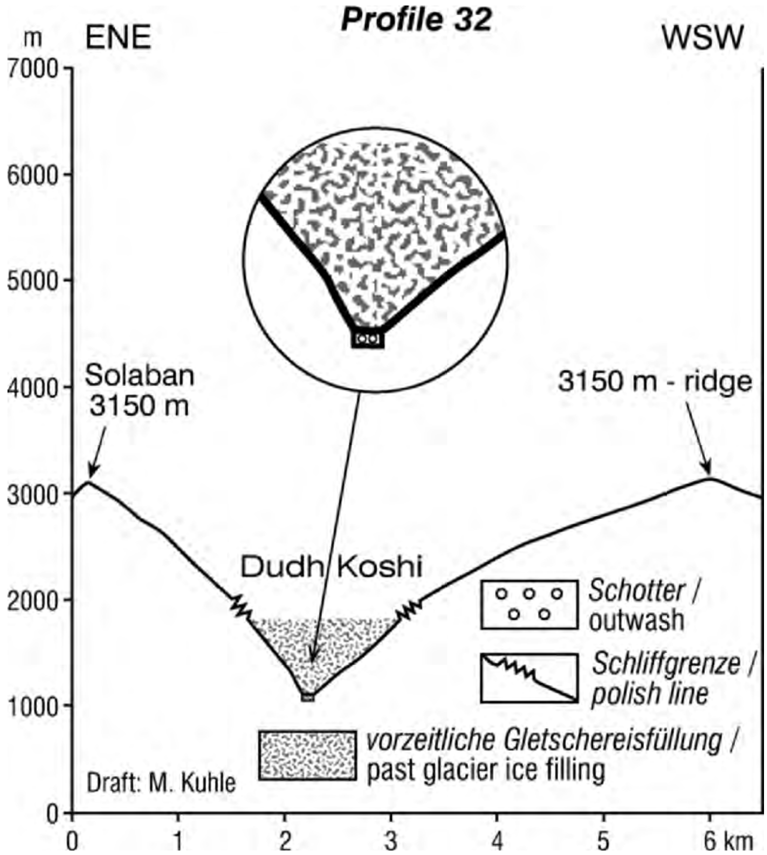


Figure 56. (Profile 32) Cross-section (not exaggerated) seen down-valley across the Dudh Koshi Nadi from the 3150 m-high Solaban ridge up to the 3150 m-ridge. Here, the valley shows a V-shaped valley cross-profile with nearly stretched, but glacigenically abraded flanks (see also Photo 233ↄ,⌒). The right flank is very slightly concave. The rock of the valley flanks has been abraded up to ca. 1800 m a.s.l. Accordingly, the maximum glacier filling of this cross-profile, reconstructed for the last glacial period (Würmian: ca. 60–18 Ka = Stage 0; Table 1), had its upper limit about 1800 m altitude. The steepness of the rock slopes slightly increases toward the talweg. Across the rock ground of its box-shaped cross-profile, the Dudh Koshi river transports gravels in the form of a transport body. The Würmian ice thickness down to the rock ground of the valley amounted to ca. 700 m. In this profile the Ice Age glacier surface was located ca. 1800–1900 m below the local Würmian level of the ELA. Locality: Figure 4.

can be observed. Pedestal-moraine-like, because there is no outer slope of the end moraine, but the accumulation passes with a flat culmination into the valley slopes. In the meantime the end moraine has been cut by the talweg, so that the slopes which have been secondarily developed, can be mistaken for inner slopes of moraines. It cannot be recognized if inner slopes of moraine – or even their beginnings – have existed here at all. The primary development of a moraine in the form of a pedestal- or pedestal terminal moraine seems to be probable because of the morphologic reasons mentioned. The preserved larger end moraine complex is situated on the orographic left side up-valley of the outer slope at the bend of the Kasuwa Khola (Figure 11 half-right below No. 46). The moraine contains granite boulders up to the size of a hut, either rounded or rounded at the edges. Several of these boulders can still be found ca. 1 km down-valley of the end moraine in the talweg. Probably these are moraine boulders flushed free, i.e. insignificantly displaced by high energy flow of the glacier meltwater or debris-flow activities in the talweg. Due to the minor extension of the catchment area and the only slight incline of the talweg, a long-distance transport of these huge boulders up to this position is improbable without glacier ice. Up-valley of the end moraine complex remnants of ground moraine are located (Figure 11 half-right below No. 46) containing gneiss- and granite boulders up to the size of a house. In places they cover truncated mountain spurs polished back glacigenically and triangular slopes (Figure 11 half-right below No. 46), which have developed between the inflows of small side valleys.

The lowest Ice Age ice margin position of the Kasuwa glacier, fixed by the pedestal end moraine described at 27°37′22″ N/87°17′ E (Figure 11 half-right below No. 46), was situated at ca. 1600 m a.s.l. and thus ca. 300 m above the talweg of the Kasuwa river, in the meantime cut into the loose rock of the pedestal moraine.

At a height of the catchment area of 4450 m a.s.l. and a lowest ice margin position about 1600 m an orographic snow-line in a SE-exposition can be calculated for the Ice Age (Stage 0 = last glacial period = Würm) Kasuwa glacier at 3025 m a.s.l. (Calculation of the ELA: $4450-1600=2850$; $2850:2=1425$; $1425+1600=3025$). This remarkably low orographic snow-line can be reduced to the overshadowing of the narrow valley glacier by the 1500–2000 m-high dividing crest (Figure 11 No. 46) to the W-adjacent Irkhuwa Khola.

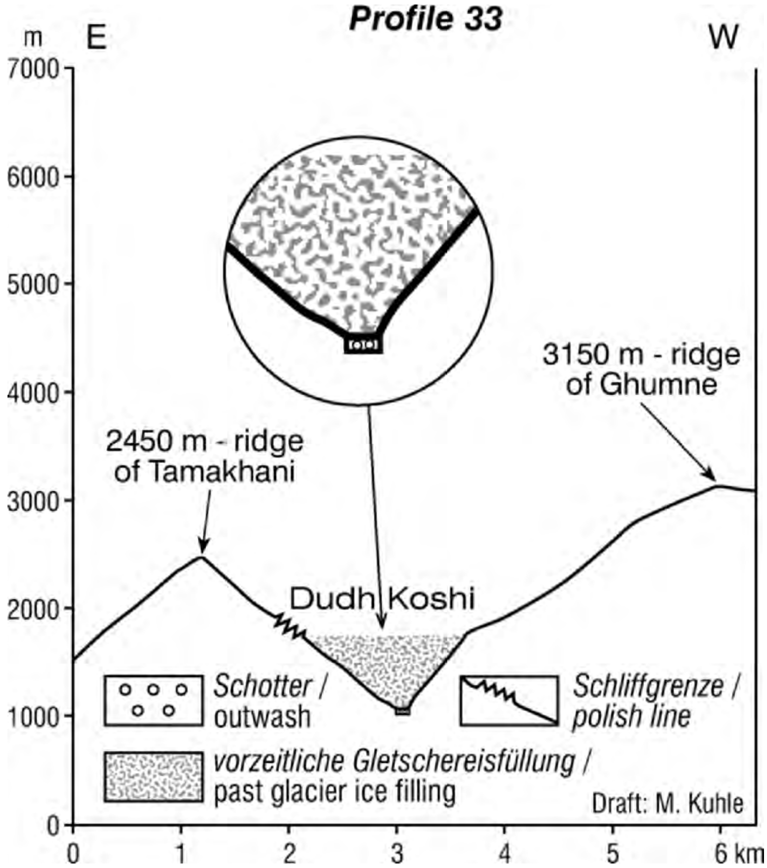


Figure 57. (Profile 33) Cross-section (not exaggerated) seen down-valley across the Dudh Koshi Nadi from the Tamakhani ridge up to the Ghumne ridge. This is a V-shaped valley cross-profile, the flanks of which are nearly stretched; the orographic left flank has been abraded up to ca. 1650 m a.s.l.; it is slightly undulated. Below, the right flank is slightly convex, i.e. it becomes somewhat steeper in the direction of the talweg. Accordingly, the glacier filling of this cross-profile, reconstructed for the last glacial period (Würmian: ca. 60–18 Ka = Stage 0; Table 1), had its level about 1650 m. The Dudh Koshi river transports gravels in the form of a transport body across the rock ground of its box-shaped cross-profile. The Würmian ice thickness down to the rock floor of the valley amounted to ca. 650 m. The Ice Age glacier surface in this profile lay ca. 1950–2050 m below the local Würmian ELA. Locality: Figure 4.

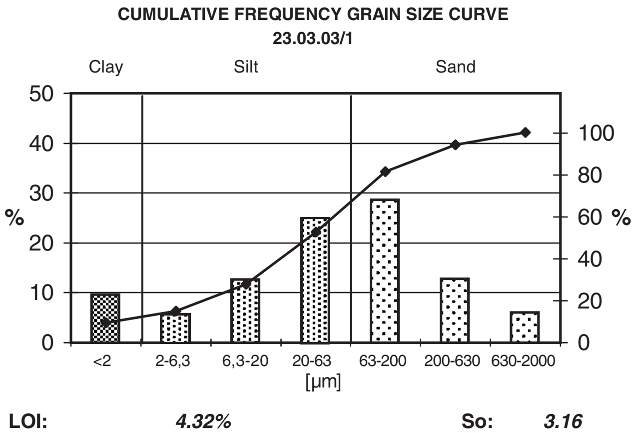


Figure 58. (Grain size diagram 23.03.03/1) Ground moraine cover in the orographic right valley flank of the Imja Drangka above the Mondara locality between the Phortse and Trashinga settlements at 4160 m a.s.l. The matrix has been taken from a dug exposure of a High Glacial (Stage 0; Table 1) ground moraine cover, 1.6 m below the surface of the moraine slope. The primary maximum is with 29% in the medium sand; the secondary peak with 5% is in the clay. The bimodal course of the cumulative curve of the fine material matrix is typical of moraine and also the markedly high portion of clay. Sorting coefficient according to Engelhardt (1973, p. 133) So = 3.16 (So = $\sqrt{Q3/Q1}$); the loss of ignition (LOI) amounts to 4.32%. Locality: Photo 105 ■ on the very right; Figure 3: 23.03.03/1; see also Figure 37. Sample No. 28. Sampling: M. Kuhle.

2.4. The Ice Age Arun glacier

Coming from the N, the Arun Nadi leads down from S-Tibet. In this antecedent Himalaya transverse-valley the regressive erosion of the Arun river has led to a gorge-shaped incision reaching up to ca. 3600 m, i.e. as far as the Kada valley chamber (Figure 4). There the flat, wide high valley bottom of the upper, i.e. Tibetan, Arun valley (Arun Chu) with its source branches Pum Qu and Dzarka Chu sets in, covered with glaciofluvial gravel accumulations and terraces. This region of Tibet's S-margin with the upper course of the Arun Nadi was the subject of the author's detailed Quaternary-geological and geomorphological investigations during his expedition in 1989 (cf. Figure 1 No. 10) (Kuhle, 1991a). He has reconstructed a ca. 1400 m-thick High Glacial glacier in the Kharta Chu (Figure 4) (ibid.: 203; 219–223), which at 3630 m a.s.l. – more exactly in the Kada valley chamber – flowed into the Arun Nadi (cf. Figure 4). From there the nearly 2000 m-thick High Glacial Arun parent glacier – as one of the large S-Tibetan outlet glaciers of the Tibetan ice, i.e. the S-Tibetan ice stream network (Figure 2 Section 1 and N of it) – flowed down from the S-

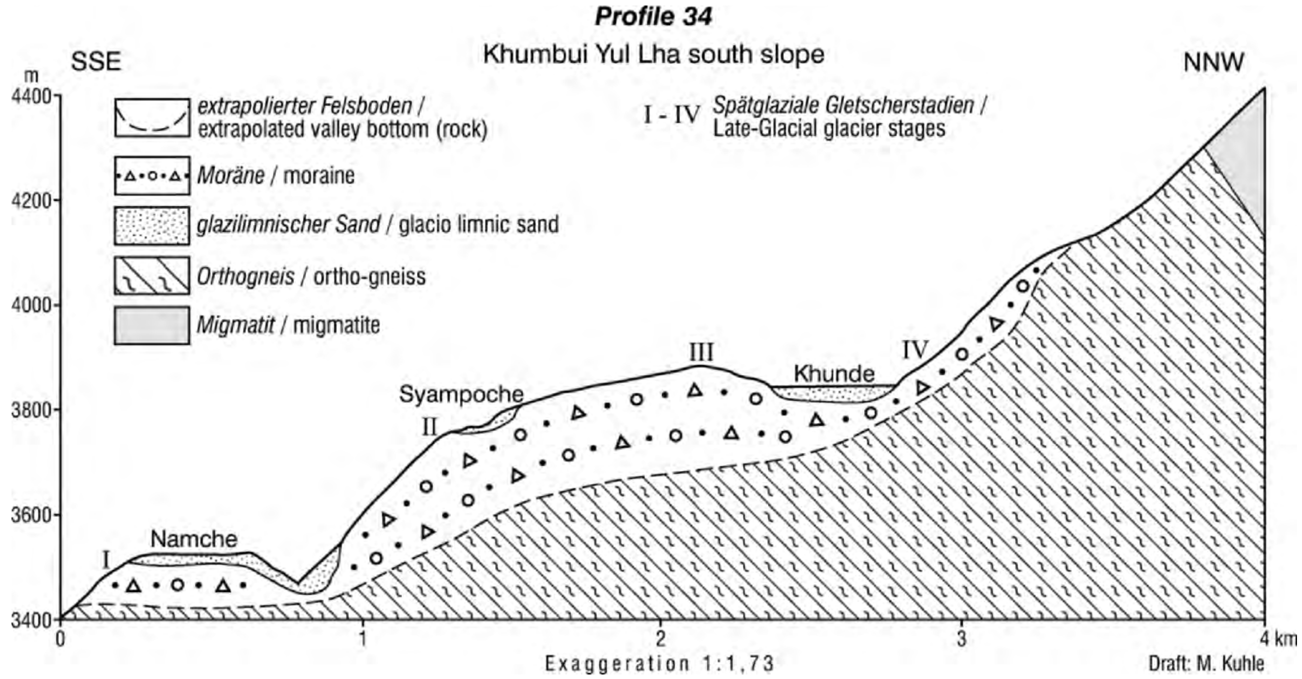


Figure 59. (Profile 34) Profile of the Khumbui Yul Lha (Figure 3 No. 74) S-slope from 4400 m a.s.l. down to the rock pedestal below the Namche Bazar settlement at 3400 m a.s.l. The outcropping rocks consist of orthogneiss and migmatites, which are united into 'Lower Tibetan mica gneisses of many varieties' (6b in Nepal Geological Map 125,000, 1985, No. 72I-B). Moraines of the Ghasa-Stage (I), the Taglung-Stage (II) near the Syampoche settlement, the Dhampu-Stage (III) and the Sirkung-Stage (IV) below and above the Khunde settlement have been recorded (Table 1). Locality: Figure 3.

margin of the plateau through the steep Arun Nadi toward the S (Kuhle 1991a: 200–204, 213–219, 229/230; Figure 43). Even during the Late Glacial (Stage I; Table 1) this Arun outlet glacier still had a thickness of at least 1130 m. From the valley chamber of Kada, from ca. 3600 m a.s.l., up to the inflow of the Barun glacier reconstructed in this study, the Arun outlet glacier has flowed down to 1100 m a.s.l. over a distance of 66 km. At the same time the Arun glacier received a further inflow from the orographic right side by the junction of the Ice Age Kangshung- i.e. Karma glacier from the Karma Chu (see Figure 4). In its source areas this ca. 50 km-long tributary glacier flowed down from the E-flanks of Mt. Everest (No. 1), Makalu (No. 3) and Chomo Lönzo (ibid.: 222/223, Photo 96; 225–229; 229/230 Figure 43) and from the N-flanks of Lhotse (No. 2), Lhotse Shar, Shar Tse (Peak 38; No. 10), Pethangtse and Chomo Lönzo (ibid.: 225; 227–229). Its reconstructed High Glacial ice thickness in the middle Karma Chu (Kangshung valley), still 20 km away from the inflow into the Arun Nadi, amounted to at least 1300 m at a contemporary height of the valley bottom of 3780 m a.s.l. (Kuhle 1991a: 204–210; 222/223, Photo 96). Due to their thickness of 2000 m and at least 1300 m these two tributary streams, the Arun outlet-, i.e. parent glacier, coming down from S-Tibet, and the Ice Age Kangshung- or Karma glacier with their joint tongue – that of the Arun main glacier – have reached the inflow of the Barun glacier situated 27 km away (Section 2.1.5). The ice thickness of the Arun main valley glacier is the question treated in the following text.

As background information we ought to call to mind that the Ice Age Barun glacier (see Section 2.1.5) in the area of the Barun gorge, 6 km away from its inflow into the Arun valley (Figure 11, Pro. 6), had still a thickness

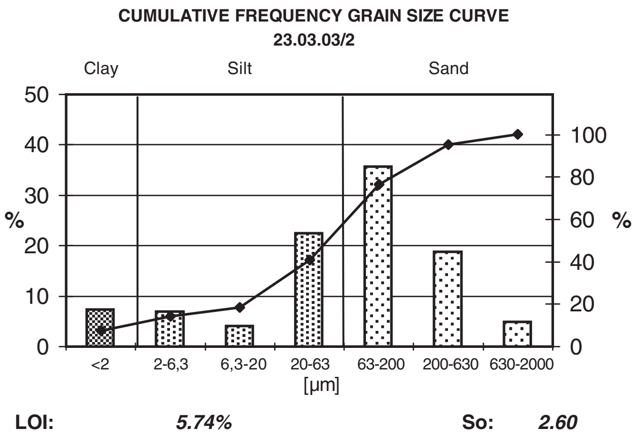


Figure 60. (Grain-size diagram 23/03/03/2): Ground moraine cover in the orographic right valley flank of the Imja Drangka W above the Trashinga settlement at 3800 m a.s.l. The matrix has been taken from a High- to early Late Glacial (Stages 0–I; Table 1) ground moraine overlay from a dug exposure 1 m below the surface of the moraine slope. The primary maximum with 36% has been developed in the fine sand; the secondary peak with a good 7% is in the clay. The bimodal course of the cumulative curve of the fine material matrix is typical of moraine and also the strikingly high – i.e. with regard to slope debris too high – clay portion. Sorting coefficient calculated according to Engelhardt (1973, p. 133) So = 2.6 (So $= \sqrt{Q3/Q1}$), the loss of ignition (LOI) amounts to 5.74%. Locality: Figure 3: 23/03/03/2; near Photos 150 and 152; Photo 151 below ■ small; see also Figure 37 Sample No. 29. Sampling: M. Kuhle.

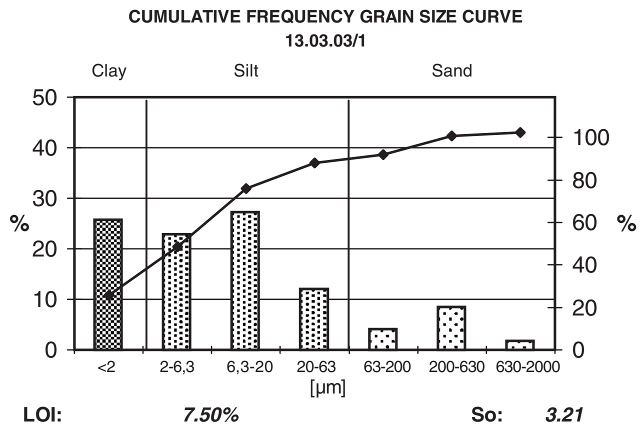


Figure 61. (Grain-size diagram 13/03/03/1) Ground moraine covering a landscape of roches moutonnées and polish depressions on the lee-side of a roche moutonnée in the area of the orographic right valley flank of the Imja Drangka at 3790 m a.s.l., S above the influx of the hanging valley of Khumjung into the lower Imja Drangka, ESE of the Khumjung settlement. The matrix has been taken from the High- to early Late Glacial (Stages 0–I; Table 1) cover of ground moraine from a digging below the moraine surface. The primary maximum with 27–28% has been developed in the middle silt; the secondary peak with a good 26% is in the clay: the bimodal (inclusive of the large components as the boulders and the skeleton portion, the course of the curve would be trimodal) course of the cumulative curve of the fine material matrix is typical of moraine matrix. The extremely high clay portion here is also typical of moraine. Sorting coefficient calculated according to Engelhardt (1973, p. 133): So = 3.21 (So $= \sqrt{Q3/Q1}$); the loss in ignition (LOI) is 7.5%. Locality: Figure 3: 13/03/03/1; near Panorama 155; see also Figure 37, Sample No. 13. Sampling: M. Kuhle.

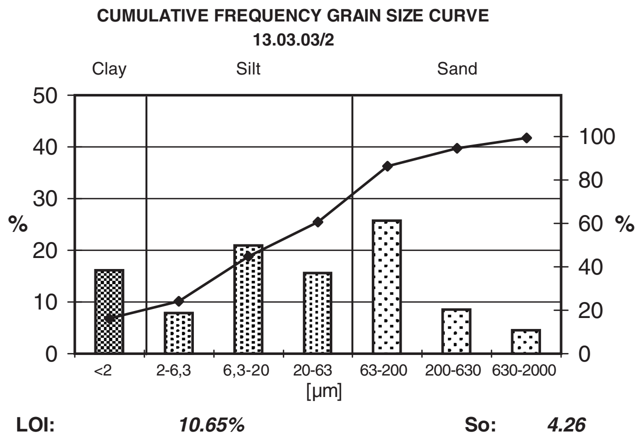


Figure 62. (Grain size diagram 13.03.03/2) End moraine in the orographic right valley flank of the hanging valley of Khunde and Khumjung at 3860 m a.s.l.; the matrix originates from the Late Glacial end moraine of the Dhampu-Stage (Stage III; Table 1); it has been taken from a digging 30 cm below the moraine surface. The primary maximum of the fine material matrix is with 26% in the fine sand; the secondary peak with 21% is in the middle silt, the third peak with a good 16% is in the clay. The here even trimodal (inclusive of the large components as the boulders and the skeleton portion, the course of the curve would be quadramodal) course of the cumulative curve of the fine material matrix is typical of moraine; the possibility of an alternative development of slope debris is lacking anyway, because a mountain slope does not exist here. The sorting coefficient calculated according to Engelhardt (1973, p. 133) is So = 4.26 (So $= \sqrt{Q3/Q1}$), the loss in ignition (LO1) is 10.65%. Locality: Figure 3: 13.03.03/2; Figure 59 III; Photo 151 between III and IV; see also Figure 37, Sample No. 14. Sampling: M. Kuhle.

of ca. 800 m (Figure 13). Accordingly, it must have reached the Arun Nadi, too.

First the empirical data are to be introduced showing that the Arun glacier has actually reached the confluence with the Barun glacier. The area discussed here is the valley chamber of the Sibrung settlement (Figures 4 and 11). Opposite the exit of the Barun Khola the orographic left flank of the Arun Nadi has been polished during past ages. Currently it crumbles away because of fluvial untercutting (Photo 27). The past smoothing has polished back a mountain spur; it is glacigenic and reaches up to at least 250 m above the talweg. Ground moraine sheets far higher up cover the abraded rock faces over large parts and continue on the denudation terrace above (Photo 27). Up the Arun valley glacigenic flank abrasions and postglacial crumblings can be diagnosed on both slopes. Remnants of ground moraine have also been found. In many places they are displaced into debris flow fans. There are also large, flushed-free moraine boulders (Figure 11 half-left above No. 48). A little more than 1 km down from the Barun Khola junction, the orographic left past polish forms are repeated on the hard, outcropping gneisses, which make up a further glacigenic triangular form. The younger crumblings also occur again (Photo 28; Figure 11 half-left below No. 48). In the slope depressions on both sides of this truncated spur accumulations of ground moraines are preserved. The reconstructed trim-line of the High Glacial Arun glacier, verified by these indicators, ran about 2100 m. A corresponding ice level on both valley flanks becomes understandable on account of the roughness, abruptly increasing from 2100 to 2200 m toward above in Profile 8 (Figure 15). Here, remnants of ground moraine are situated between ca.

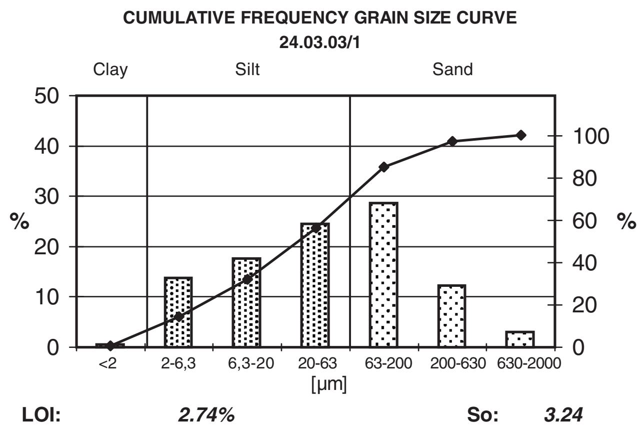


Figure 63. (Grain size diagram 24.03.03/1) Fluvially reshaped ground moraine cover on a rock spur between the valley head of the hanging valley of Khunde and Khumjung and the Kyajo Drangka at 4200 m a.s.l. The matrix originates from a digging 30 cm below the moraine surface in a rock depression. The primary or secondary maximum of the moraine material is with 29% in the fine sand; the primary or secondary peak has been developed in the large components, as the boulders and the skeleton portion, so that at least a bimodal course of the curve can be observed. The clay (1%) is nearly completely washed-out; the sorting coefficient calculated according to Engelhardt (1973, p. 133) amounts to So = 3.24 (So $= \sqrt{Q3/Q1}$). This is again typical of pure moraine; the loss in ignition (LOI) is 2.74%. Locality: Figure 3: 24.03.03/1; Photo 155 ▲; see also Figure 37, Sample No. 30. Sampling: M. Kuhle.

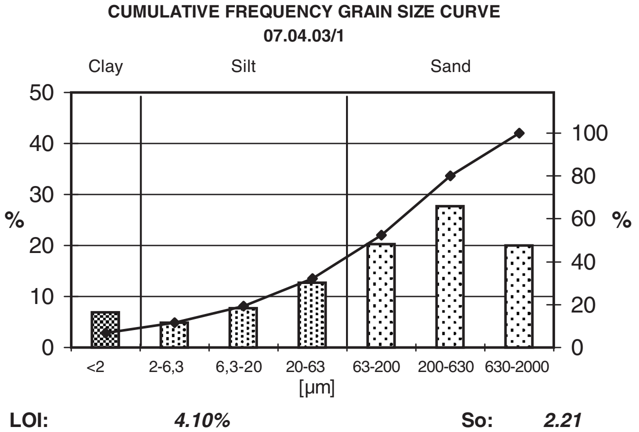


Figure 64. (Grain size diagram 07.04.03/1) Ground moraine in the orographic right flank of the lower Imja Drangka at 3600 m a.s.l., NE of the Namche Bazar settlement; the matrix has been taken from a High Würmian to early Late Glacial ground moraine (Stages 0–I; Table 1) from a digging 30 cm beneath the current moraine surface below a boulder the size of a hut. The primary maximum of the fine material matrix is with a good 27% in the middle sand; the secondary peak with 7% is in the clay. The bimodal (inclusive of the large components as the boulders and the skeletal portion the course of the curve would be trimodal) course of the cumulative curve of the fine material matrix is typical of moraine matrix. The high clay portion is also typical of moraine. There is no possibility for an alternative development of slope debris, because a mountain slope with underlying rock does not exist. The sorting coefficient calculated according to Engelhardt (1973, p. 133) amounts to S = 2.21 (So $= \sqrt{Q3/Q1}$); the loss in ignition (LOI) is 4.1%. Locality: Figure 3: 07.04.03/1; Photo 157 ■ on the left below; Figure 59 below II; see also Figure 37 Sample No. 46. Sampling: M. Kuhle.

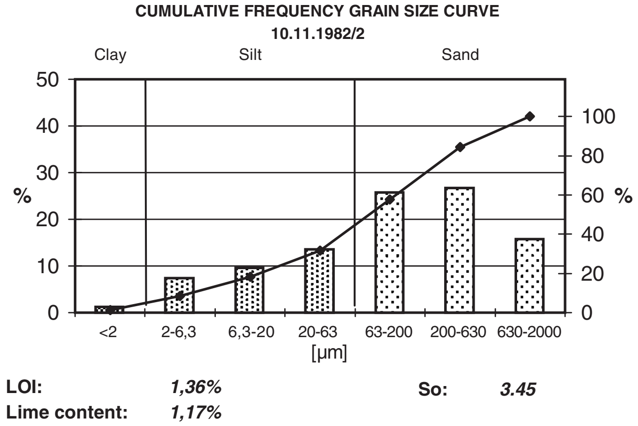


Figure 66. (Grain size diagram 10.11.1982/2) Glaciolimnic to glaciofluvial sand on a ground moraine cover and below a ground moraine slope, E above the Namche Bazar settlement at ca. 3550 m a.s.l. in the area of the orographic right valley flank of the Imja Drangka (cf. Photo 158); the material has been taken from an exposure 0.8 m beneath the sediment surface below a gneiss boulder one metre in size, 3 m above the sampling of Figure 65. The maximum of the material with a good 27% is in the middle sand and with 26% in the fine sand; further maxima are lacking. The portions of coarse sand, silt and clay (2%) are remnants. They prove that washed-out moraine is concerned. The sorting coefficient calculated according to Engelhardt (1973, p. 133) So = 3.45 (So $= \sqrt{Q3/Q1}$) and the lime content of 1.17% point to this, too. The loss in ignition (LOI) amounts to 1.36%. Locality: Figure 3: 10.11.1982/2; Figure 59 on the right of Namche Bazar; cf. Figure 65. Sampling: M. Kuhle.

1350 and 1800 m. Similar to the lower Barun Khola cross-profile (Figure 13), the Arun Nadi cross-profile, too, shows a gorge-like narrow V-shaped form within its lower cross-section near the talweg (Figure 15, Profile 8 below ca. 1800 m). This can be explained here, ca. 2600–1600 m below the synchronous High Glacial snow-line (ELA = 3300–3600 m) and below a 3–4 times wider upper region of the valley cross-profile with a trough-character (Figure 15 Profile 8 above ca.

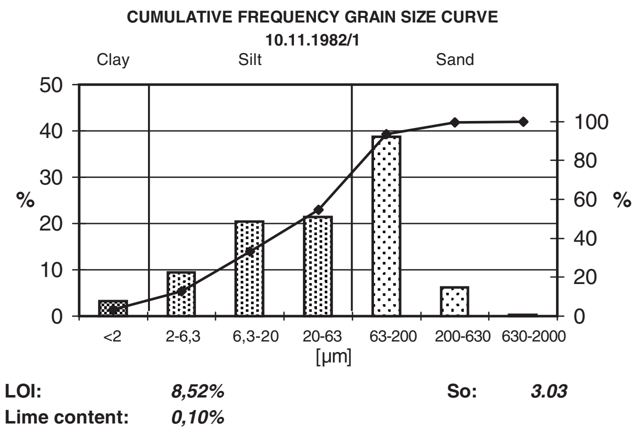


Figure 65. (Grain size diagram 10.11.1982/1) Glaciolimnic to glaciofluvial sand on a ground moraine cover and below a ground moraine slope E above the Namche Bazar settlement at ca. 3550 m a.s.l. in the area of the orographic right valley flank of the Imja Drangka (cf. Photo 158). The substrate has been taken from an exposure 0.25 m below the sediment surface, 3 m below the sampling of Figure 66. The maximum of the material with 39% is in the fine sand; further maxima are lacking. The silt- and mainly the clay-portions (3–4%) are remnants which provide evidence of a washed-out moraine. This indicates, too, the sorting coefficient calculated according to Engelhardt (1973, p. 133) So = 3.03 (So $= \sqrt{Q3/Q1}$) and the lime content of 0.10%. The loss in ignition (LOI) amounts to 8.52%. Locality: Figure 3: 10.11.1982/1; Figure 59 on the right of Namche Bazar; cf. Figure 66. Sampling: M. Kuhle.

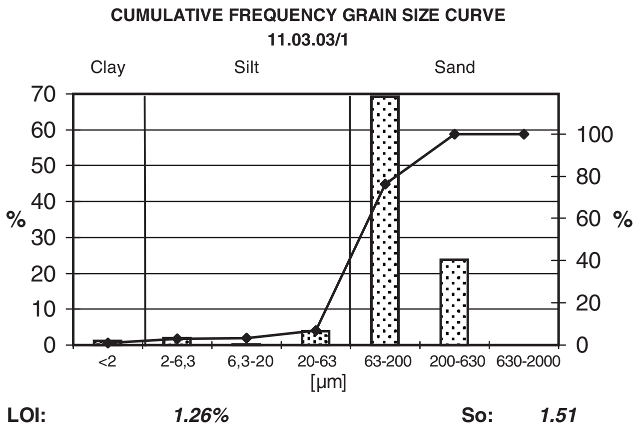


Figure 67. (Grain size diagram 11.03.2003/1) Glaciolimnic to glaciofluvial sand on a Late Glacial (Stage I; Table 1) ground moraine cover (see Figure 68), SE above the Namche Bazar settlement at 3520 m a.s.l. in the area of the orographic right valley flank of the Imja Drangka. The material has been taken from an exposure 1.3 m below the sediment surface. The only maximum of the material has been developed with approx. 70% in the fine sand. The portions of 24% mainly middle sand and ca. 6% silt and clay, are remnants. They prove that moraine substrate from the area of a lateral sander or -lake is concerned, which has already been washed-out and displaced. The sorting coefficient calculated according to Engelhardt (1973, p. 133) of only So = 1.51 (So $= \sqrt{Q3/Q1}$) points to this, too. The loss in ignition (LOI) amounts to 1.26%. Locality: Figure 3: 11.03.2003/1; Photo 156 second ▼ from the left; Figure 59 Namche Bazar; see Figure 37 No. 8; cf. Figures 65 and 66. Sampling: M. Kuhle.

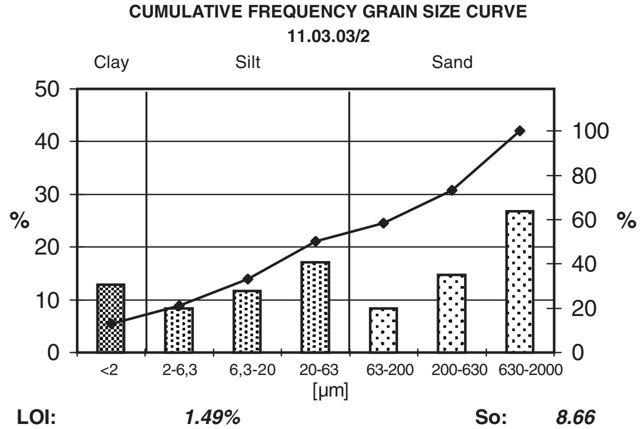


Figure 68. (Grain size diagram 11.03.2003/2) Ground moraine cover S above the Namche Bazar settlement at 3510 m a.s.l. in the area of the orographic left valley flank of the Nangpo Tsangpo Drangka. The material has been taken from a digging 1.0 m below the sediment surface. The primary maximum of the fine material matrix has been developed with a good 26% in the coarse sand, the secondary peak with 17% is in the coarse silt and the tertiary peak with ca. 13% is in the clay. The trimodal (inclusive of the coarse components as the boulders and the skeleton portion the course of the curve would even be quadramodal) course of the cumulative curve of the fine material matrix is typical of lodgement till (ground moraine) matrix; the relatively very high clay portion is also typical of moraine. There is no possibility for an alternative development of slope debris, because a mountain slope with underlying rock does not exist. The sorting coefficient calculated according to Engelhardt (1973, p. 133) amounts to So = 8.66 (So $= \sqrt{Q3/Q1}$) and is extremely great. This also argues for ground moraine *in situ*. The loss in ignition (LOI) amounts to 1.49. Locality: Figure 3: 11.03.2003/2; Photo 156 third ▼ from the left; Photo 159 in the foreground on the right; Figure 59 I; see Figure 37 No. 9. Sampling: M. Kuhle.

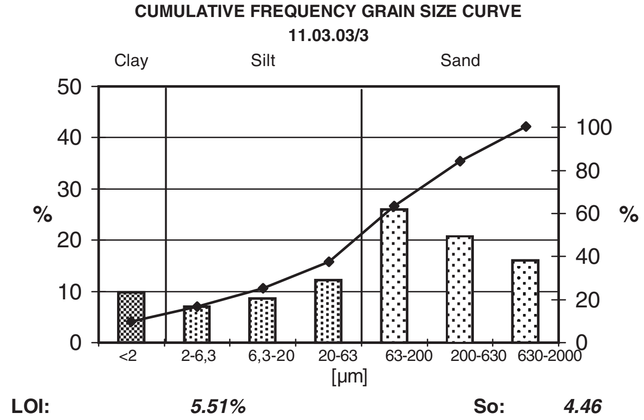


Figure 69. (Grain size diagram 11.03.2003/3) Early Late Glacial (Stage I; Table 1) material of ground moraine on the slope NE above the Namche Bazar settlement at 3530 m a.s.l. on the medial moraine inset between Imja Drangka and Nangpo Tsangpo Drangka. The material has been taken from a digging 0.4 m below the slope surface. The primary maximum with 26% has been developed in the fine sand, the secondary peak with 10% is in the clay. The bimodal (inclusive of the large components as the boulders and the skeletal portion the course of the curve would be trimodal) course of the cumulative curve of the fine material matrix is typical of ground moraine. The relatively high clay portion is also typical of moraine. The possibility of an alternative development of slope debris does not exist, because the slope concerned is no mountain slope underlaid with rock, but has been made up from decametre-thick loose material. The sorting coefficient calculated according to Engelhardt (1973, p. 133) amounts to So = 4.46 (So $= \sqrt{Q3/Q1}$) and is relatively great. This also argues for moraine. The loss in ignition (LOI) amounts to 5.51. Locality: Figure 3: 11.03.2003/3; Photo 159 ▼ on the right; Figure 59 below II; see Figure 37 No. 10. Sampling M. Kuhle.

1800 m), by subglacial meltwater erosion and postglacial linear erosion of the Arun river (see also Photos 27 and 30). The remnants of the trough valley bottom make up the denudation terraces upon which the ground moraines – at higher altitudes of slope – could be better preserved (Figure 15; Photos 27, 30, 32, 34 ■).

According to the data mentioned, the ice thickness of the Arun parent glacier amounted to a good 1000 m in the Barun confluence. Owing to this, the ice thickness of the Barun glacier (see above), which due to the significant valley incline was important in the lower Barun Khola (see Section 2.1.5), can be reduced to a backflow caused by the abutment of the main valley glacier with its level at 2100 m a.s.l. This means that the surface of the Barun tributary glacier ought to have fallen away relatively steadily and evenly from ca. 2600 down to 2100 m over a distance of 6 km, whilst the talweg of the Barun Khola becomes steeper in this area of the valley exit (Section 2.1.5). In this context, the important thickness of the steep Barun glacier provides an indirect proof of a thick Arun glacier.

2.4.1. *Glaciofluvial gravels (sander) in the Lamobagar Gola valley chamber*

Between the junction of the Leksuwa Khola and the Lamobagar settlement the valley bottom is built up by post-High Glacial accumulations. They consist of glaciofluvial gravels, which between the current basal gravel floor of the Arun river and its tributaries (Photos 27 and 37 ○; 39 □) up to the highest preserved gravel terraces (Photos 29, 30, 33, 37□) show three to four terrace levels. They can be described as being of glaciofluvial origin, because the upper catchment area of the discharging water – 33 km away from the upper Barun Khola (Figures 4 and 11) – is still glaciated and during past ages has even been stronger glaciated. Accordingly, these gravel deposits in the Arun valley bottom have been flushed out from past moraines, i.e. gravel fields or sanders are concerned (cf. Table 1). Because these gravel fields are gravel floors canalized by the Barun- and Arun valley which do not extend here continuously from the current or past glacier termini and end moraines, but – as it is typical of the Himalaya – at steep escarpments are interrupted by gorge stretches in the bedrock, they can be explained as 'indirect sanders or gravel floors' which develop a 'gravel floor step' (Kuhle, 1983a: 336–342). The highest preserved terrace (Photo 29 □ 4–3; Figure 11 Nos. 4–3 below No. 48) belongs to the Late Glacial glacier positions of the Ghasa- or Taglung Stage (I or II; cf. Table 1). This gravel terrace proves that the Arun valley bottom at about 1000–1100 m a.s.l. has already been free of ice at least during the younger Stage II.

The more the Late Glacial to historical glacier termini have melted back, i.e. the further they lay away from the valley area described, the greater was the distance to the beginning of the gravel fields down-valley

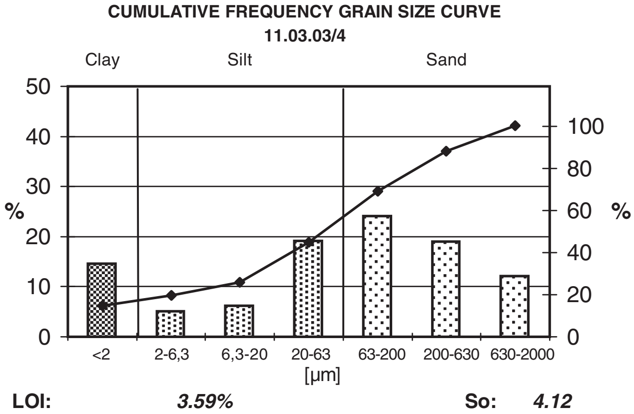


Figure 70. (Grain size diagram 11.03.2003/4) Early–Late Glacial (Stage I; Table 1) material of ground moraine on the orographic left inner slope of lateral moraine in the Tsangpo Drangka WNW above the Namche Bazar settlement at ca. 3600 m a.s.l., at the medial moraine inset between Imja Drangka and Nangpo Tsangpo Drangka. The material has been taken from a digging 0.6 m below the slope surface. The primary maximum of the fine material matrix is with ca. 24% in the fine sand, the secondary peak with 15% is in the clay. The bimodal (inclusive of the large components as the boulders and the skeletal portion the course of the curve would be trimodal) course of the cumulative curve of the fine material matrix is typical of ground moraine matrix; the relatively high clay portion is also typical of moraine. An alternative development of slope debris is impossible, because the mountain slope concerned is not underlaid with rock, but has been made up from decametre-thick loose rock. The sorting coefficient calculated according to Engelhardt (1973, p. 133) amounts to So = 4.12 (So $= \sqrt{Q3/Q1}$) and is relatively great. This also pleads for moraine. The loss in ignition (LOI) amounts to 3.59. Locality: Figure 3: 11.03.2003/4; Photo 156 ▼ on the very right; see Figure 37 No. 11. Sampling: M. Kuhle.

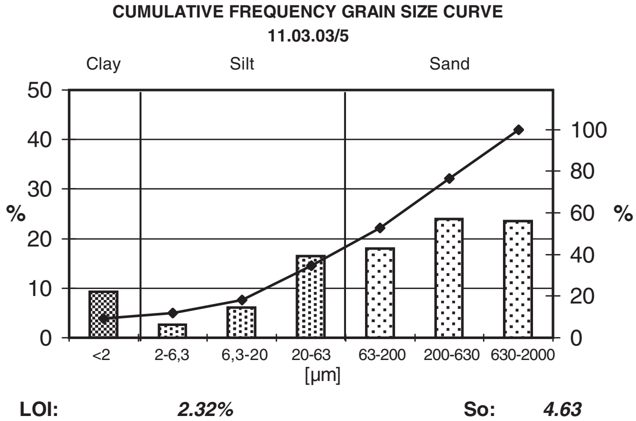


Figure 71. (Grain size diagram 11.03.2003/5) Early–Late Glacial (Stage I, Table 1) material of a ground moraine pedestal of the moraine inset between Imja- and Nangpo Tsangpo Drangka, WNW above the Namche Bazar settlement at ca. 3570 m a.s.l.; the sampling material has been taken from a digging 0.9 m below the slope surface. The primary maximum of the fine material matrix is with ca. 24% in the middle sand; the secondary peak with 10% is in the clay. The bimodal (inclusive of the large components as the boulders and the skeleton portion trimodal) course of the cumulative curve of the fine material matrix is typical of lodgement till (ground moraine) matrix; the relatively high clay portion is also typical of moraine. Alternative development of slope debris is impossible, because the mountain slope concerned is not underlaid with rock, but has been made up from decametre-thick loose rock. The sorting coefficient calculated according to Engelhardt (1973, p. 133) amounts to So = 4.63 (So $= \sqrt{Q3/Q1}$) and is relatively great. This also argues for moraine. The loss in ignition (LOI) amounts to 2.32. Locality: Figure 3: 11.03.2003/5; Photo 159 ▼ on the left; see Figure 37 No. 12. Sampling: M. Kuhle.

from the end moraines. This has the regular consequence that the river has cut further and further into the older gravel fields and that the corresponding younger gravel fields of this river – which are always connected with a new glacier advance – are situated lower and lower in the valley bottom. They are incised in the course of a new glacier retreat and, accordingly, develop lower and lower terraces (Troll, 1924, 1926). Here, these are the glacier-mouth gravel-floor terraces (gravel-fields) of the Neoglacial Stage V, i.e. gravel field No. −0 (Photo 37 □ −0) up to the Historical Stage X, i.e. gravel-field No. −6 (Photo 29 □ −6). A further result of the increasing distance – in this case of decakilometres – of the beginnings of the gravel fields, i.e. the corresponding glacier mouths, is the interruption of the gravel fields by steep escarpments, i.e. a 'gravel floor step' (see above). From this derives the integration and mixture of several glacier floors into a single gravel body. This is the case down-valley of the Leksuwa Khola junction. Here, the gravels of the neoglacial up to recent glacier positions of Stage X form only one terrace (Photo 30 □ −0 to −6; Figure 11 No. −0 to −6 below No. 48; Table 1). Between the lowest and the highest – only preserved in remnants – early-Late Glacial gravel floor terrace (Nos. 4–3), late Late Glacial terrace remnants are situated belonging to the Dhampu- or Sirkung Stage (cf. Table 1) (Photo 31 and 33 □). Generally, the accumulations, which can be described as gravels of an advance, have been developed most markedly in the course of especially strong glacier advances. This was the case worldwide during the Holocene at the beginning of the Neoglacial (Nauri Stage V) and in historical times during the Little Ice Age (Stage X). Owing to this, the two lowest terraces are indicated as Nos. −0 and −6 and Nos. −0 to −6.

The morphoscopic analysis of a sample taken from the second-lowest gravel floor terrace (Photo 31 □) (Figure 6, No. 13) which shows 57% glacially crushed against only 30% lustrous SiO_2-grains, indicates the large portion of morainic material which has contributed to the build-up of these terraces. So, the conclusion may be drawn that the terrace has been made up on an eroded ground moraine. Accordingly, even the fine matrix has not been transported over a long distance, but has only been displaced on a small scale. In terms of geomorphology this can be suggested, because all over the valley slopes above the terraces ground moraine has been found (Photo 31 □).

2.4.2. The Ice Age Arun main glacier in the valley chamber of Lamobagar Gola (Figure 4)

Between the Leksuwa Khola junction and Lamobagar, High Glacial (Stage 0, Table 1) ground moraine remnants are preserved in depressions parallel to the slope (Photo 30■ 0) and, on fluvially undercut slopes, partly exposed (Photo 29▼ on the left; 30■ below). The postglacial dissection of the ground moraine (→ ←) proves that remnants are concerned. Owing to second-

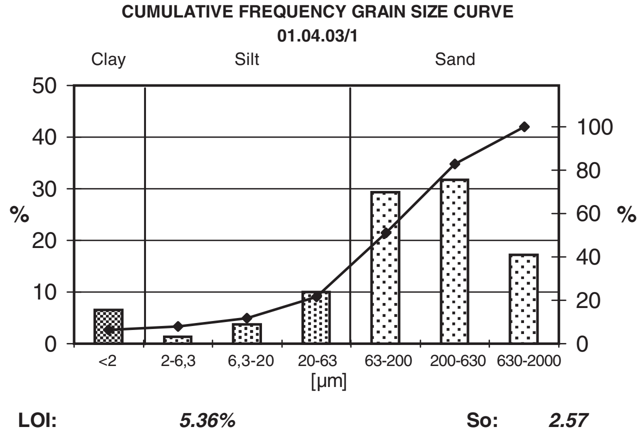


Figure 72. (Grain size diagram 01.04.2003/1) Fine material matrix of ground moraine re-sedimentated in a debris cone at 4700 m a.s.l., taken from an exposure. The primary maximum of the fine material matrix with ca. 32% has been developed in the middle sand, the secondary peak with 6.5% is in the clay. The bimodal course of the cumulative curve of the fine material matrix (i.e., inclusive of the larger components as the boulders and the skeletal portion, trimodal course of the curve of the entire material) is typical of lodgement till (ground moraine) matrix. The relatively high clay portion is also typical of moraine; a possibility of an alternative development of slope debris can be ruled out, because erratic boulders are contained in the matrix; the sorting coefficient calculated according to Engelhardt (1973, p. 133) is So = 2.57 (So $= \sqrt{Q3/Q1}$) and is relatively insignificant regarding moraine. This depends on the displacement through debris flows. The loss in ignition (LOI) is 5.36%. Locality: Figure 3: 01.04.2003/1; Photo 168 +; see Figure 37 No. 37. Sampling: M. Kuhle.

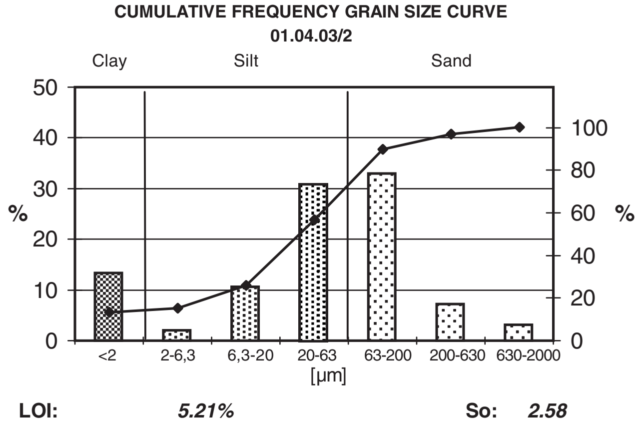


Figure 73. (Grain size diagram 01.04.2003/2) Fine material matrix of ground moraine on the slope at 4610 m a.s.l. taken from a 0.3 m-deep digging. The primary maximum of the fine material matrix with ca. 32.5% is in the fine sand, the secondary peak with ca. 14% is in the clay. The bimodal course of the cumulative curve of the fine material matrix (i.e., inclusive of the large components as the boulders and the skeletal portion, the trimodal course of the curve of the entire material) is typical of lodgement till (ground moraine) matrix. The very high clay portion is also typical of moraine. The possibility of an alternative development of slope debris can be ruled out, because round-edged boulders are in the matrix, which have been transported down-valley from far away, i.e. which have not weathered out from the bedrock *in situ*. The sorting coefficient calculated according to Engelhardt (1973, p. 133) is So = 2.58 (So $= \sqrt{Q3/Q1}$) and is relatively insignificant. This pleads for a solifluidal displacement of the moraine material close to the surface since the deglaciation. The loss in ignition (LOI) is 5.21%. Locality: Figure 3: 01.04.2003/2; Photo 169 ↓; see Figure 37 No. 38. Sampling: M. Kuhle.

ary processes of incision and undercutting down-slope connected to this, an accumulation of very large moraine boulders (○) occurs on the valley bottom, which have fallen down to the talweg. In a Tertiary process they have been more or less embedded into the gravel floors (□).

The slope-parallel depressions covered with ground moraine (■ 0) are bordered by down-slope rock ribs rounded by glacigenic flank polishing (∩; Photos 31 and 32 ∩). A corresponding geomorphological sequence, demonstrated here by the orographic left valley flank, is obvious in many places; naturally also on the orographic right side. So, for instance, at the Lamobagar Gola bridge, where ground moraine below an early-Late Glacial [Ghasa-Stage I (Table 1) or older, perhaps a pre-Ghasa stagnation after Kuhle, 1982: 80/81, 87, 91, 98, 113, 153] lateral moraine ledge (Photo 32 ■ I) has been dissected since deglaciation, i.e. subaerially (△), and large boulders have been secondarily dislocated (so perhaps ○; definitely □). The selective sediment analysis of this ground moraine (Figure 6 No. 12) shows the high proportion of SiO_2 in plutonites, granites and metamorphites of the Himalaya main ridge and the S-margin of Tibet. With somewhat more than 43% of glacially crushed grains and almost 39% lustrous quartz grains a fluvial sedimentation component is indicated, as it is typical of ground moraines deposited very far below the snow-line (here: ca. 2400 m). 18% eolian grain-forms point to katabatic winds and poverty of vegetation during the late glacial period which here was free of ice. A confusion of glacially crushed grains with freshly weathered grains of bedrock *in situ* can be ruled out because of the thickness of the loose rocks and the intermixing with grains of the forms 'lustrous' and 'dull'.

Owing to these glacial forms (Figure 11 half-left below No. 48; see also Figure 4 locality of the photos) a High Glacial ice thickness of ca. 1000–1100 m is evidenced in this valley section, too (Photo 32 ‒ ‒ ‒) (see Section 2.4).

The polishings in the gneiss bedrock (Photo 31 ∩, ▲) left behind by this valley glacier have polished out the middle to upper valley flanks in a slightly-concave fashion, so that a gorge-shaped trough valley has come into being (▽). The bend of the slope separates them from the V-shaped form (⇩) developed fluvially i.e. subglacially (see above). Today the potholes preserved in the talweg (↓; Photo 32 ▼; Figure 11 between Nos. 48 and 49 on the right) are wasted away fluvially. They are thus an indicator of past subglacial meltwater erosion and development of ravines in the trough valley ground below the High- to perhaps still early-Late Glacial (pre-Ghasa Stagnation 1–2 up to not later than Ghasa Stage I) Arun parent glacier (Figure 11 between Nos. 48 and 49). The preserved glacier striae (Photo 32 ←) are already situated in the area of the gneiss wall of the subglacial ravine, i.e. in its upper section. Accordingly, it is obvious that the warm (−0 °C) hanging ice of the glacier ground has polished into the upper part of the cross-section of the ravine and thus must have secondarily widened the fluvioglacial ravine. In fact, the

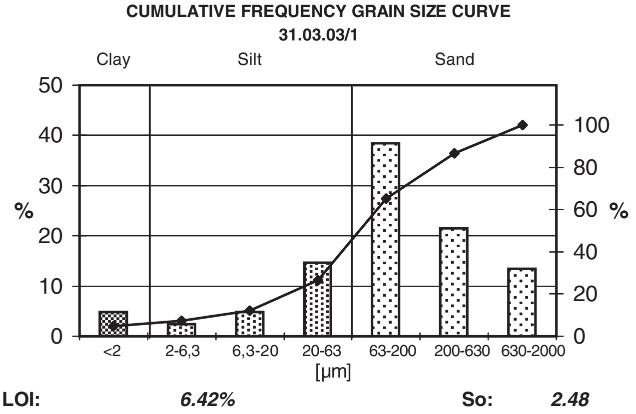


Figure 74. (Grain size diagram 31.03.2003/1) Fine material matrix of ground to lateral moraine at 4570 m a.s.l., taken from a horizontal moraine surface from a depth of 0.3 m. The primary maximum with ca. 38% is in the fine sand, the secondary peak with ca. 5% is in the clay. The bimodal course of the cumulative curve of the fine material matrix (i.e., inclusive of the large components as the boulders and the skeletal portion trimodal course of the entire material) is typical of till (moraine) matrix; the clay portion is also typical of moraine. The possibility of an alternative development of slope debris has to be ruled out, because the valley slope is 350 m away and the matrix has been taken between round-edged and erratic boulders, which have travelled downslope from far away, but not from boulders weathered out from the bedrock *in situ*. The sorting coefficient calculated according to Engelhardt (1973, p. 133) is So = 2.48 (So $=\sqrt{Q3/Q1}$). This is not too great and argues for a cryoturbate and insignificantly fluvial displacement of the moraine material close to the surface since the deglaciation. The loss in ignition (LOI) amounts 6.42%. Locality: Figure 3: 31.03.2003/1; Photo 169+; see Figure 37 No. 35. Sampling: M. Kuhle.

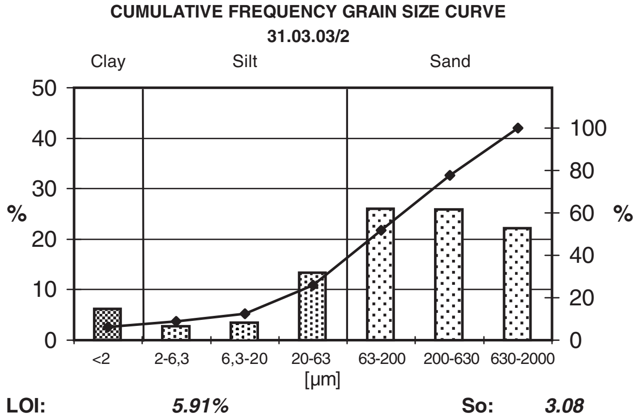


Figure 75. (Grain size diagram 31.03.2003/2) Fine material matrix of ground to lateral moraine at 4555 m a.s.l. taken from a depth of 0.4 m from an almost not sloping moraine surface. The primary maximum of the fine material matrix with 26.5% is in the fine sand, the secondary peak with 6.5% is in the clay. The bimodal course of the cumulative curve of the fine material matrix (i.e., inclusive of the large components as the boulders and the skeleton portion, trimodal course of the curve of the entire material) is typical of till (moraine) matrix; the relatively large clay portion is also typical of moraine. The possibility of an alternative development of slope debris can be ruled out, because the valley slope, inclusive of a counter slope, is 250 m away. In addition, round-edged and erratic boulders, travelled down-valley from far away, but not boulders weathered out from the bedrock *in situ*, are contained in the material. The sorting coefficient calculated according to Engelhardt (1973, p. 133) amounts to So = 3.08 (So $=\sqrt{Q3/Q1}$); the loss in ignition (LOI) amounts to 5.91%. Locality: Figure 3: 31.03.2003/2; Photo 169 →; see Figure 37. Sampling M. Kuhle.

marginal rocks of the ravine have been bevelled into a V-shape by back polishing (Photo 31 in the middle between ■ and ↓).

The moraine ledge (Photo 32 ■ I) 120 m above the valley bottom, classified as lateral moraine of Ghasa Stage (I), which might also belong to the somewhat earlier 'pre-Ghasa Stagnation (1 or 2)' (see above), is not necessarily an indicator of the Late Glacial glacier surface. Instead of a lateral moraine a youngest, increasingly thicker ground moraine packing of the valley glacier body could also be concerned, which had become narrower during the Late Glacial. This has been undercut secondarily, so that it received a working edge, appearing like the upper edge of a lateral moraine or kames.

2.4.2.1. The whale back-roche moutonnée with potholes and glacier striae near Lamobagar Gola at 1100 m a.s.l. (Figure 11 No. 49). At the southern margin of the Lamobagar Gola settlement a roche moutonnée is situated in the middle of the valley. Isolated from the two valley flanks by incisions (Figure 11 No. 49; Photos 33 and 34 ∩), it towers 70 m above the Arun river. It has been developed in the gneiss bedrock and shows a markedly flat lee slope (Photo 33 ∩), i.e. a roche moutonnée of the type 'whale back' is concerned. It has been polished into a nearly perfectly streamlined form and, owing to this, is an indicator of a substantial ice documenting a High Glacial ice thickness of about or over 1000 m (see above) in this valley cross-profile.

The roche moutonnée is covered by a scatter of round-edged boulders up to some metres lying in an unstable position (○). Besides well-preserved roundings of abrasion, polishings and glacier striae (Photo 35 ∩ and ⇑) it shows perfectly preserved potholes up to several metres deep on its culmination (Photo 36 ○; 33 ⇓). They are partly filled with ground moraine (■). They originated from a Late Glacial ice cover diminishing in thickness. Due to the roche moutonnée the glacier has buckled upwards, so that stationary crevasses have been developed, through which the supraglacial water has permanently struck the culmination of the roche moutonnée at a steep angle on exactly one point up to a depth of at least several decametres. At the same time it has excavated the pothole. The stationary formation of crevasses up to the glacier surface necessary for this depends on an ice thickness which has amounted to far less than 1000 m during the Late Glacial (pre-Ghasa Stagnation or Ghasa Stage I). Typical of a feedback of the development of glacier mills and potholes, such as this, is their locality on a convex full-form, because here the postglacial subaerial Arun river was unable to become effective in this way. Accordingly, potholes on roches moutonnées are a very strong indicator. Due to the very thick ice in this valley chamber they were unable to develop here during the High Glacial. Owing to this, these potholes are an indicator of dating.

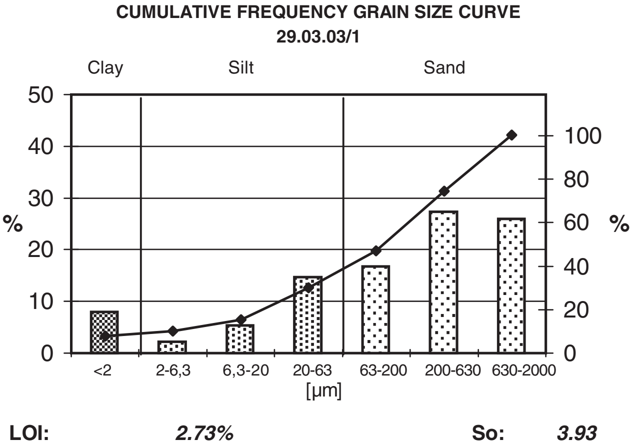


Figure 76. (Grain size diagram 29.03.2003/1) Fine material matrix taken from a ground moraine pedestal at 4800 m a.s.l. from a depth of 0.3 m. The moraine surface is slightly sloping. The primary maximum with 27.5% is in the middle sand, the secondary peak with 8% is in the clay. The bimodal course of the cumulative curve of the fine material matrix (i.e., inclusive of the large components as the boulders and the skeletal portion, the trimodal course of the curve of the entire material) is typical of till (moraine) matrix; the relatively large clay portion is typical of moraine, especially in the high mountain relief. The possibility of an alternative development of slope debris can be ruled out, because a decametre-thick accumulation of loose rock with separately embedded round-edged boulders is concerned, but not boulders in size of a metre, weathered out from the bedrock *in situ*. The sorting coefficient calculated according to Engelhardt (1973, p. 133) is So = 3.93 (So $=\sqrt{Q3/Q1}$); the loss in ignition (LOI) amounts to 2.73%. Locality: Figure 3: 29.03.2003/1; Photo 171 ○; Photo 173 on the left of IV vertically below No. 4; see Figure 37 No. 33. Sampling M. Kuhle.

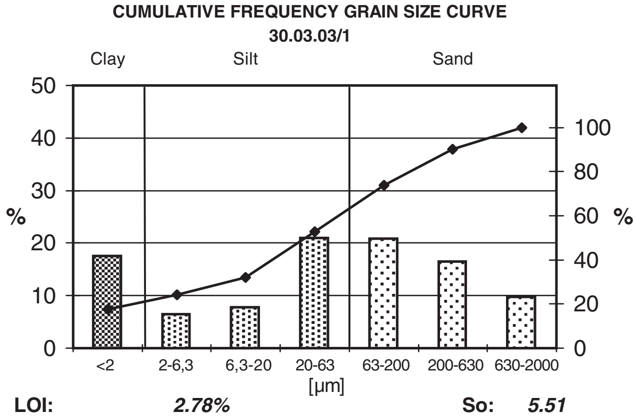


Figure 77. (Grain size diagram 30.03.2003/1) Fine material matrix from a ground moraine pedestal at 4830 m a.s.l. taken from a digging depth of 0.3 m from an only slightly sloping moraine surface. The primary maximum is with 31.5% in the coarse silt, the secondary peak is with 18% in the clay. The bimodal course of the cumulative curve of the fine material matrix (i.e., inclusive of the large components as the boulders and the skeletal portion, the trimodal course of the curve of the whole material) is typical of till (moraine) matrix. The comparatively very large clay portion is typical of moraine, especially in the high mountain relief. The possibility of an alternative development of slope debris can be ruled out, because decametre-thick accumulations of loose material are concerned with separately embedded, round-edged boulders, but not boulders the size of a metre, weathered out from the bedrock *in situ*. The sorting coefficient calculated according to Engelhardt (1973, p. 133) is with So = 5.51 (So $=\sqrt{Q3/Q1}$) high; the loss in ignition (LOI) amounts to 2.78%. Locality: Figure 3: 30.03.2003/1; Photo 171 ■ on the right margin; Photo 173 IV vertically below No. 4; see Figure 37 No. 34. Sampling M. Kuhle.

A further indication of dating is provided by glacier striae (Photo 35⇑;). Because of its coarse-crystalline condition, the outcropping gneiss is unfavourable in regard to their development. Nevertheless, traces of glacier polishings are still clearly visible on this roche moutonnée – despite their naturally only weak development in the gneiss. This argues in favour of a relatively young, i.e. Late Glacial origin (pre-Ghasa Stagnation or Ghasa Stage I; Table 1) or a preservation by a cover of ground moraine since deglaciation – or both of them.

In any case, a ground moraine covering is proved by the potholes (Photo 36 ■). The overlying scatter of round-edged, unstable boulders, metres in size (Photo 34 ○), as a moraine remnant also points to a moraine mantling of the entire roche moutonnée. In the meantime the matrix ought to have been washed out, i.e. removed from the convex rock faces. This mantling by moraine (ground-, inner- and lastly surface moraine) might have taken place in the proximity of, i.e. directly at the glacier terminus during the last decades of the ablation process.

Sub-to postglacially the Arun river has undercut and basally steepened the roche moutonnée on its E-side. Ground moraine with round-edged and facetted boulders up to metres in size has been attached to its W-side (Photo 33 ○). Its surface has been flattened glaciofluvially (□). This surviving accumulation fills the pre-Pleistocene section between the then Tertiary 'riegel' – from which the roche moutonnée has been developed during the subsequent glaciation – and the right-hand Arun valley flank.

2.4.3. The Ice Age Arun main glacier in the valley section between the Lamobagar Gola and Num settlements (Figure 4) and the reconstruction of its maximum surface height

On the orographic left Arun valley flank ground moraine remnants are situated ca. 1 and 1.5 km below the roche moutonnée of Lamobagar Gola (cf. Section 2.4.1), ca. 350 m (Photo 33 ■), i.e. ca. 300 m (Photo 34 ■ black) above the talweg. On the orographic right side, a further km down-valley, coarse-blocky ground moraine has also been preserved at a relative height of 400 m (■ white; Figure 11 on the right and left of No. 49 and below and half-right below No. 49). At the foot of the slopes, where slope incisions come to an end (e.g. Photo 37 ▼ white), debris flow fans have regularly been developed since deglaciation (□ –0 is a gravel terrace which contains, i.e. has buried and mantled a debris flow fan. See also ▽ or Figure 11 below No. 49) in which parts of the ground moraine material dislocated down-slope have been re-sedimentated.

Considering the moraine remnants, the maximum past glacier trim-line would have to be reconstructed at 350, 300 and 400 m above the current talweg. Again somewhat further down-valley (locality: Photo 37; Figure 4) an iron-shaped ground moraine cover (■)

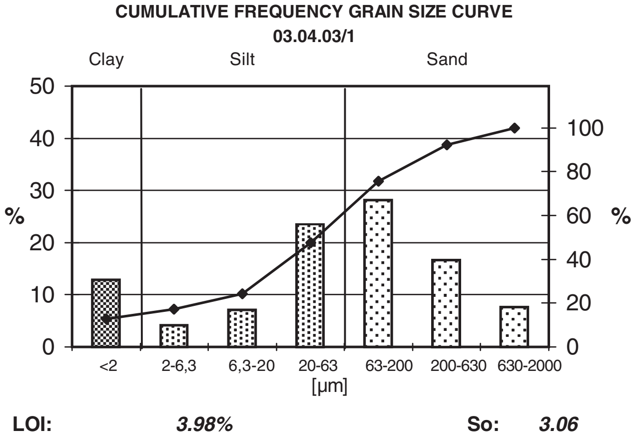


Figure 78. (Grain size diagram 03.04.2003/1) Fine material matrix taken from a ground moraine pedestal (pedestal moraine) at 4725 m a.s.l. from a digging-depth of 0.4 m from a slightly sloping moraine surface. The primary maximum with 28% is in the fine sand, the secondary peak with 13.5% is in the clay. The bimodal course of the cumulative curve of the fine material matrix (i.e., inclusive of the large components as the boulders and the skeletal portion, the trimodal course of the curve of the entire material) is typical of till (moraine) matrix. The comparatively very large clay portion is typical of moraine, especially in the high mountain relief. The possibility of an alternative development of slope debris can be ruled out, because a decametre-thick accumulation of loose material is concerned with separately embedded, round-edged boulders, but not boulders in size of a metre, weathered out from the bedrock *in situ*. The sorting coefficient calculated according to Engelhardt (1973, p. 133) is So = 3.06 (So $=\sqrt{Q3/Q1}$); the loss in ignition (LOI) amounts to 3.98%. Locality: Figure 3: 03.04.2003/1; Photo 177 below IV white in the foreground; 184 IV black on the right above; see Figure 37 No. 40. Sampling: M. Kuhle.

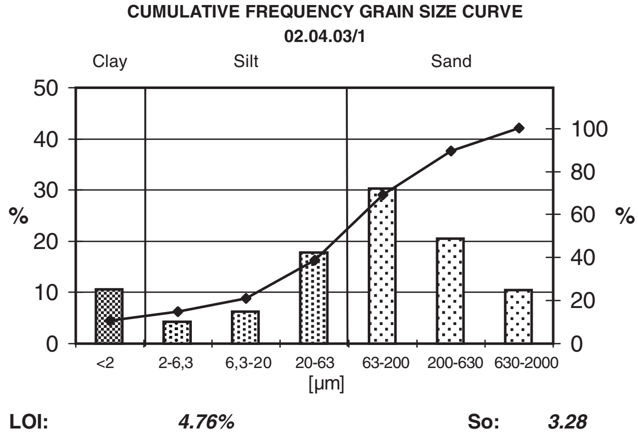


Figure 79. (Grain size diagram 02.04.2003/1) Fine material matrix from a ground moraine pedestal (pedestal moraine) at 4300 m a.s.l. taken from a digging-depth of 0.4 m from a slightly sloping moraine surface. The primary maximum with at least 30% has been developed in the fine sand, the secondary peak with ca. 11% is in the clay. The bimodal course of the cumulative curve of the fine material matrix (i.e., inclusive of the large components as the boulders and the skeletal portion, the trimodal course of the curve of the entire material) is typical of till (moraine) matrix. The comparatively very large clay portion is typical of moraine, especially in the high mountain relief. The possibility of an alternative development of slope debris can be ruled out, because the accumulation of decametre-thick loose material is concerned with separately embedded, round-edged boulders, but not boulders in size of a metre, weathered out from the bedrock *in situ*. The sorting coefficient calculated according to Engelhardt (1973, p. 133) is So = 3.28 (So $=\sqrt{Q3/Q1}$); the loss in ignition (LOI) amounts to 4.76%. Locality: Figure 3: 02.04.2003/1; Photo 184 above ■ on the right below; 191 above ■ white; see Figure 37 No. 39. Sampling: M. Kuhle.

witnesses to a past glacier trim-line at least 550 m above the talweg (– – –). As is shown by the heterogeneous altitudes of the highest moraine findings on the valley flanks, simultaneously laid down by the glacier, a continuous height of the glacier trim-line cannot be reconstructed by them. Accordingly, the highest occurrences of ground moraine, which at the same time are situated furthest down-valley, establish the minimum height of the High Glacial trim-line. As far as the ground moraines down-valley of Lamobagar Gola are concerned, it can be suggested that the glacier has even filled the valley receptacle much further upward. The highest occurrences of ground moraine on the slope have been (a) primarily the least in thickness, because the rate of ground moraine sedimentation down to the valley floor increases in dependance on the timing of deposit and the process and (b) removed the fastest, because they have been free of ice for the longest since the ablation process and, accordingly, have been removed. This is evidenced by e.g. flank polishings (∩) situated above the preserved covers of ground moraine. Only in places where ground moraines pass into a bank formation further above, i.e. into a lateral moraine- or kames terrace, do they provide more than merely a mark of the minimum thickness of the past glacier. Only this glacigenic bank formation definitely fixes the exact past trim-line, as long as no glacigenic flank polishings are preserved higher up-slope.

In the most downward area of the section of the Arun valley discussed here, a glacigenic bank formation such as this (Figure 11 No. 51; Figure 16 left half of Pro. 9; Figure 4 Pro. 9; Photos 46 and 47) is situated near the Num settlement, a good 700 m above the talweg at 1430 m a.s.l. Here, 14 km down-valley from the ground moraine remnants near Lamobagar (see above) and at a height of the valley floor of only just 730 m a.s.l., the Arun parent glacier was even 180 m thicker than can be recognized by the ground moraine remnant situated 550 m above the talweg 14 km up-valley (down-valley from Lamobagar, see above). At Profile 8 (Figure 15) the ice thickness still amounted to 1100 m (Section 2.4), 22 km down the Arun valley near Num (Profile 9, Figure 16) to a good 700 m (cf. Figure 4). Owing to this, between these two ice thicknesses being definitely from the glacial period (Profiles 8 and 9), a consistent decrease in ice thickness – as a function of a steady down-valley incline of the glacier surface – has to be interpolated.

In an Arun valley cross-profile situated somewhat down-valley from Profile 9 on the orographic right side near the Murmidada settlement, the valley glacier lay, strictly speaking, even somewhat higher, i.e. 830 m instead of 700 m above the talweg. But both the moraines (Photo 46 upper ■ white and ■ black) are to be classified as synchronous lateral moraines of the Arun parent glacier during the last glacial period (Stage 0,

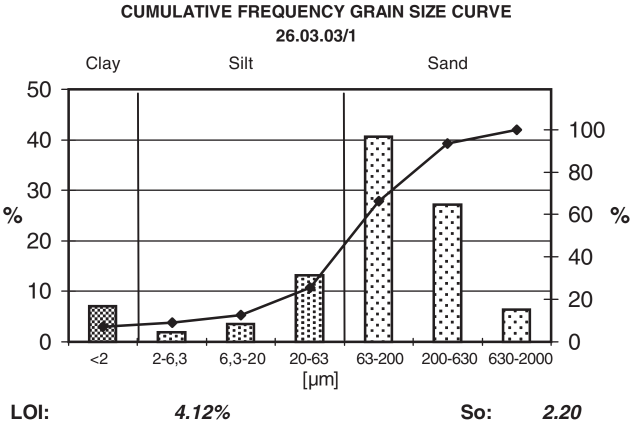


Figure 80. (Grain size diagram 26.03.2003/1) Fine material matrix from a ground moraine pedestal (pedestal moraine) with a cover of local moraine at 4385 m a.s.l., taken from a digging-depth of 0.5 m from a slightly sloping moraine surface. The primary maximum with at least 40% is in the fine sand, the secondary peak with 7% is in the clay. The bimodal course of the cumulative curve of the fine material matrix (i.e., inclusive of the large components as the boulders and the skeletal portion, the course of the curve of the whole material is trimodal) is typical of till (moraine) matrix; the relatively large clay portion is typical of moraine, especially in the high mountain relief. The possibility of an alternative development of slope debris can be ruled out, because a decametre-thick accumulation of loose rock is concerned, containing numerous round-edged and facetted boulders, but not polymict boulders in size of a metre, weathered out from the bedrock *in situ*. The sorting coefficient calculated according to Engelhardt (1973, p. 133) is So = 2.20 (So $= \sqrt{Q3/Q1}$); the loss in ignition (LOI) amounts to 4.12%. Locality: Figure 3: 26.03.2003/1; Photo 188 ↓; 191 IV on the left of ■ white; see Figure 37 No. 31. Sampling: M. Kuhle.

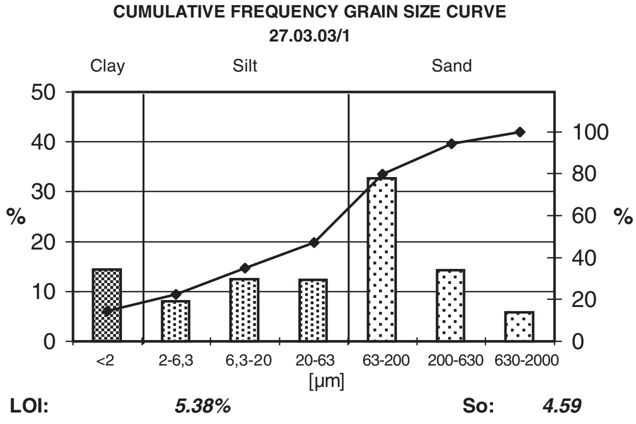


Figure 81. (Grain size diagram 27.03.2003/1) Fine material matrix from a ground moraine pedestal (pedestal moraine) with a cover of local moraine at 4380 m a.s.l. taken from a digging-depth of 0.3 m from a plane moraine surface. The primary maximum of 32% is in the fine sand, the secondary peak of almost 15% is in the clay. The bimodal course of the cumulative curve of the fine material matrix (i.e., inclusive of the large components as the boulders and the skeletal portion, the trimodal course of the curve of the whole material) is typical of till (moraine) matrix. The very large clay portion is typical of moraine, especially in the high mountain relief. A possibility of alternative development of slope debris can be ruled out, because a decametre-thick accumulation of loose rock is concerned, containing numerous round-edged and facetted boulders, but not polymict and also erratic boulders in size of a metre, weathered out from the bedrock *in situ*. The sorting coefficient calculated according to Engelhardt (1973, p. 133) So = 4.59 (So $= \sqrt{Q3/Q1}$) is high, the loss in ignition (LOI) amounts to 5.38%. Locality: Figure 3: 27.03.2003/1; Photo 178 IV white in the foreground on the left; 184 IV on the right above ∩; 188 IV white, small; 191 above IV, white; see Figure 37 No. 32. Sampling: M. Kuhle.

Table 1) with the corresponding highest preserved glacier trim-line (––– and ––– 0) (see below).

After this reconstruction of the highest past glacier trim-line which applies to the section of the Arun valley treated here, indicators of the Ice Age glaciation will be introduced belonging to this altitude of the glacier trim-line in the lower Arun Nadi, in the 14 km-long section between Lamobagar Gola and Num.

From the confluence of the Wan Khola down the Arun Nadi, gneiss rocks abraded into the shape of roches moutonnées (Photo 38; Figure 4; 11 half-right below No. 49) are preserved on the orographic left side. Parts of them are cloaked by ground moraine. At the same time the subglacial work of the meltwater becomes obvious through flush bowls. On the orographic right valley flank, too, well-preserved glacigenic flank polishings on outcropping gneiss banks can be observed between 100 and 400 m above the talweg (Photo 39; Figure 4; 11 between Nos. 49 and 50). Up to the valley chamber of the Lunsun settlement, between the inflow of the hanging valleys Thado Khola from the right and Amsuwa Khola from the left into the Arun Nadi, ground moraines have survived in the area of the lower valley slopes from ca. 50 to 400 m above the Arun talweg (Photo 40 ■). Orographic left glacigenic flank abrasions (▲) reach several 100 m higher up, as far as 1640 m a.s.l. They have polished a mountain spur into a glacigenic triangle-slope (Figure 11 half-right above No. 50). The polish line reaches up to 690 m above the talweg (–––).

In the downward valley section between Amsuwa Khola (Photo 40 ↓) and the Arun Nadi cross-profile near the Gadhidada settlement (Photos 40–45; Figure 4; 11 No. 50), highest Ice Age trim-lines of the Arun glacier are verifiable about a minimum altitude of 1550 m a.s.l. (–––). This corresponds to an ice thickness of ca. 650–750 m. Remnants of the High Glacial trough valley form are preserved at many points of the ground moraine and in the abraded rock further up-slope (Photo 40 the two ■ on the very right; 41 ■ black; 42 the two ■ on the left; 44 ■). This trough form with polished-back truncated spurs, triangular slope facettes (Photo 41 and 42▲) and a ground moraine overlay makes up the upper glacigenically widened valley cross-profile. Below, cut into the trough valley ground, a V-shaped form is preserved which has been created subglacially (Figure 11 between Nos. 50 and 51). It has been developed syngenetically by subglacial meltwater erosion below the hanging valley glacier ground. Due to flank abrasions preserved in some parts (Photos 41–45 ∩ and ▲) and potholes (Photo 44 ●), combinations of glacigenic flank polishing and subglacial work of the meltwater are recognizable ca. 580 m above the Arun talweg. Subglacial effects of meltwater such as these are typical of glacier margins (Tietze, 1958, 1961. This applies the more, because the locality is 2000 m below the Ice Age snow-line.

On the polish- and abrasion faces postglacial crumblings are unambiguously verifiable. However, on the

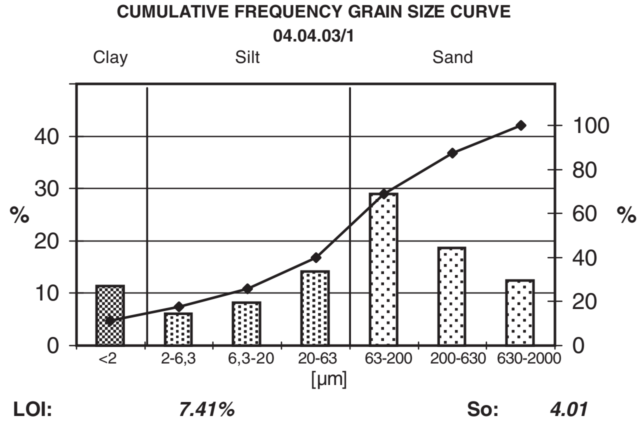


Figure 82. (Grain size diagram 04.04.2003/1) Fine material matrix from an outer slope of lateral moraine at 4100 m a.s.l., taken from an exposure from a depth of 0.8 m. The primary maximum of 29% has been developed in the fine sand, the secondary peak of 12% is in the clay. The bimodal course of the cumulative curve of the fine material matrix (i.e., inclusive of the large components as the boulders and the skeletal portion, the course of the curve of the whole material is trimodal) is typical of till (moraine) matrix; the large clay portion is typical of moraine, especially in the high mountain relief. A possibility of an alternative development of slope debris can be ruled out, because an accumulation of decametre-thick loose rock is concerned, isolated from the mountain slope through several small valleys, i.e. counter slopes, with numerous embedded, round-edged and facetted, polymict boulders, among them erratics. The sorting coefficient calculated according to Engelhardt (1973, p. 133) So = 4.01 (So = $\sqrt{Q3/Q1}$) is high; the loss in ignition (LOI) amounts to 7.41%. Locality: Figure 3: 04.04.2003/1; Photo 189 ↓; see Figure 37 No. 41. Sampling: M. Kuhle.

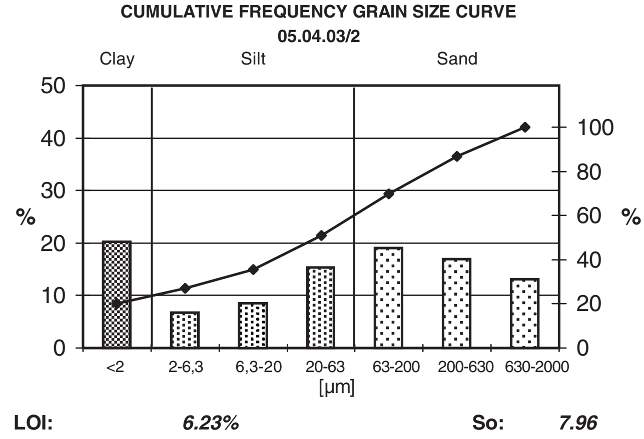


Figure 84. (Grain size diagram 05.04.2003/2) Fine material matrix from a ground moraine ridge at 4550 m a.s.l., above the talweg of Langmoche, taken from a digging-depth of 0.4 m. The primary maximum is with 20.5% in the clay, the secondary peak with 19.5% is in the fine sand. The bimodal course of the cumulative curve of the fine material matrix (i.e., inclusive of the large components as the boulders and the skeletal portion, the course of the curve of the whole material is trimodal) is typical of till (moraine) matrix; the extremely large clay portion is typical of detrital moraine, especially in a high mountain relief. Here, an accumulation of decametre-thick loose rock is concerned, containing numerous round-edged and facetted, polymict boulders up to the size of metres or a hut, without a connection to a rock- or weathering slope. The sorting coefficient calculated according to Engelhardt (1973, p. 133) So = 7.96 (So = $\sqrt{Q3/Q1}$) is extremely high. The loss in ignition (LOI) amounts to 6.23%. Locality: Figure 3: 05.04.2003/2; Photo 183 IV white; see Figure 37 No. 43. Sampling: M. Kuhle.

resistant gneiss faces they are comparably rare. Therefore they have only insignificantly reshaped the faces of flank polishing (cf. e.g. Photo 45 ⇓).

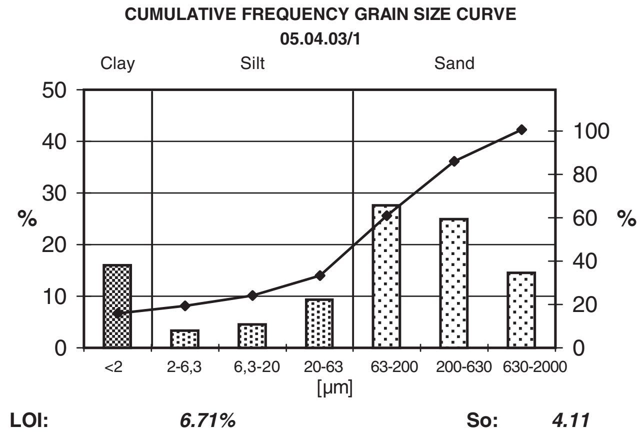


Figure 83. (Grain size diagram 05.04.2003/1) Fine material matrix from a ground moraine cover at 4200 m a.s.l., 300 m above the talweg of the Bote Koshi, taken from an exposure from a depth of 0.9 m. The primary maximum of 27% is in the fine sand, the secondary peak of 16% is in the clay. The bimodal course of the cumulative curve of the fine material matrix (i.e., inclusive of the large components as the boulders and the skeletal portion, the course of the curve of the whole material is trimodal) is typical of till (moraine) matrix. The very high clay portion is typical of moraine, especially in the high mountain relief. A decametre- thick accumulation of loose rock is concerned, containing numerous round-edged and facetted, polymict boulders up to metres or hut-size. The sorting coefficient calculated according to Engelhardt (1973, p. 133) So = 4.11 (So = $\sqrt{Q3/Q1}$) is high; the loss in ignition (LOI) amounts to 6.71%. Locality: Figure 3: 05.04.2003/1; Photo 189 ↑; see Figure 37 No. 42. Sampling: M. Kuhle.

2.4.4. Short insertion as to the Ice Age glaciation of the Jaljale Himal, which discharges to the E via the Ikhuwa and Leksuwa Khola into the Arun Nadi (Figure 4; Figure 11 on the right of No. 50).

The Ice Age Ikhuwa glacier has not reached the Arun main valley glacier. It ended ca. 4.8 km away from the inflow of the Ikhuwa Khola into the Arun Nadi. In the Jaljale Himal the height of the catchment area of the Ikhuwa glacier amounts to a maximum of 4803 m and up to about 4400 m a.s.l. on average. At an ELA about 3500 m the W-exposed valley glacier concerned reached down to ca. 2600 m. In glacial times the Jaljale Himal showed a continuous glaciation of its mountain crest with a 45 km-extension in a NNE/SSW direction and a ca. 30 km-wide W/E extension. Shorter valley- and ramifying cirque glaciers were connected to it (Figure 4; 11 far from the right of Nos. 48, 49, 50, 51). In addition to the common glacigenic forms of erosion and the moraines, evidences of this glaciation are provided by several modern lakes e.g. in the cirques, so the Seto Pokhari (27°35′12″ N/37°29′20″ E). Also the Leksuwa glacier which was N-parallel to the Ikhuwa glacier, did not nearly reach the Arun main valley glacier.

2.4.5. The Ice Age glaciation of the lower Arun valley from the Num settlement up to the terminus of the glacier tongue at ca. 500 m a.s.l.

In the context of the reconstruction of the trim-lines the synchronously sedimentated area of moraine terraces near the Num and Murmidada settlements, a good 700–

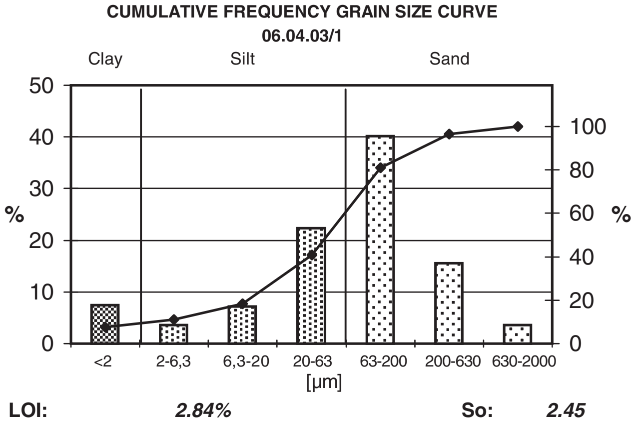


Figure 85. (Grain size diagram 06.04.2003/1) Fine material matrix of anthracite-coloured drift clay from a ground moraine ridge with a peripheral modification by lateral moraine at 3910 m a.s.l., 110 m above the talweg of the Arabtsen-Drangka, taken from a digging-depth of 0.6 m. The primary maximum with at least 40% is in the fine sand, the secondary peak with at least 7% is in the clay. The bimodal course of the cumulative curve of the fine material matrix (i.e., inclusive of the large components as the boulders and the skeletal portion, the course of the curve of the whole material is trimodal) is typical of till (moraine) matrix; the relatively large clay portion is typical of detrital ground moraine, especially in a high mountain relief. This is a decametre-thick accumulation of loose rock with numerous embedded round-edged and facetted, polymict boulders up to the size of metres or a hut, isolated from a rock- or weathering slope by a counter slope. The sorting coefficient calculated according to Engelhardt (1973, p. 133) is So = 2.45 (So $=\sqrt{Q3/Q1}$); the loss in ignition (LOI) amounts to 2.84%. Locality: Figure 3: 06.04.2003/1; Photo 199 ↓; see Figure 37 No. 44. Sampling: M. Kuhle.

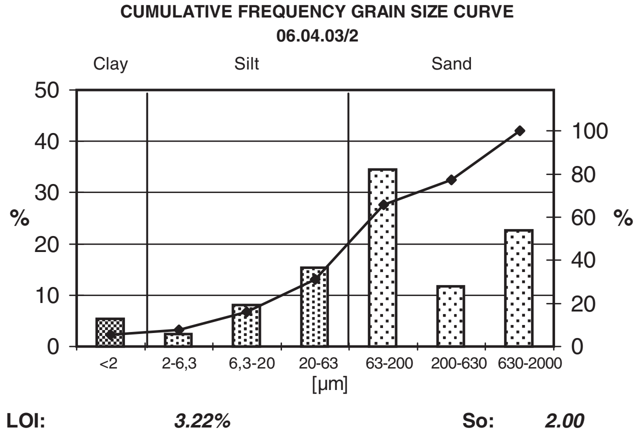


Figure 86. (Grain size diagram 06.04.2003/2) Fine material matrix taken from a ground moraine cover at 3670 m a.s.l., ca. 200 m above the talweg of the Nangpo Tsangpo Drangka. Sampling depth: 1.3 m (exposure). The primary maximum with 34.5% is in the fine sand, the secondary peak with 5.5% is in the clay. The bimodal course of the cumulative curve of the fine material matrix (i.e., inclusive of the large components as the boulders and the skeletal portion, the course of the curve of the whole material is trimodal) is typical of till (moraine) matrix. The very large clay portion here is typical of moraine, especially in the high mountain relief. This is a decametre-thick accumulation of loose rock with numerous embedded, edged, round-edged and facetted, polymict boulders in size of metres. The sorting coefficient calculated according to Engelhardt (1973, p. 133) amounts to So = 2.0 (So $=\sqrt{Q3/Q1}$; the loss in ignition (LOI) amounts to 3.22%. Locality: Figure 3: 06.04.2003/2; Photo 203 below ■ white on the left; 204 ↑; see Figure 37 No. 45. Sampling: M. Kuhle.

830 m above the Arun talweg, has already been described (see Section 2.4.3).

These moraines, found at a low altitude above sea-level of only 1430–1550 m such as this and at the same time at a great altitude above the valley bottom, are of fundamental importance with regard to the Ice Age glacier reconstruction. Accordingly, the following data are necessary for their understanding.

The up to 2.5 m (Photo 46), i.e. 3 m-long (Photo 47) augen-gneiss boulders on the orographic left lateral moraine terrace of the Num settlement have travelled up to here over a distance of ca. 50 km, i.e. they are erratic (Figure 16 left half of the profile). They are associated with crystalline schist boulders (phyllites), so that one may speak of a polymict block packing. Different metamorphic sedimentary rocks as e.g. thin-bedded mica schists outcrop in the sub-surface. The erratic boulders are round-edged or even somewhat more strongly rounded (Photo 46 and 47 ○). On this nearly horizontal terrace form preserved at an acute angle (Figure 11 No. 51) they are embedded into a decametres-thick matrix. According to laboratory analyses it is undoubtedly glacigenic (Figure 6 No. 1; Figure 4: 22.11.94/1). 80% of the quartz grains are glacially crushed. Due to the decametres-thickness of the loose material from which the samples have been taken, and also due to the erratics contained, an *in situ* weathering of the bedrock in the underlying area can be ruled out. In addition, the topographic position and the arrangement of the positions (Photos 46 and 47) make clear that moraine is concerned. An accumulation of debris flow a good 700 m above the talweg, which with the exception of these terrace remnants has been completely removed by erosion has to be ruled out, because this is extremely improbable and unprecedented. Beyond it, it would not correspond with the result of the morphoscopic analysis according to which only ca. 20% of the grains are fluvially polished, but 80% are glacially crushed. Several decametres below toward the NW, a further – here ledge-shaped – moraine planation is situated (Figure 11 No. 51).

On the cross-profile under discussion the orographic right Arun Nadi flank shows a deposit of ground moraine which corresponds with that of the lateral moraine terrace of Num, i.e. it comes to approx. the same height (Figure 16; Photo 47 ■ on the very right). A related orographic right moraine form, that is a remnant of a lateral moraine terrace, was found near the Murmidada settlement (or Navgaon) (Photo 46 second ■ from the left; 47 second ■ from the right) at 1550 m a.s.l., 830 m above the Arun Nadi talweg (Figure 11 No. 52). Here, the proportion of glacially crushed quartz grains even reaches 90% (Figure 6 No. 2; Figure 4: 22.11.94/2). The large boulders contained in this matrix are not erratic in the true sense, because they might come from the comparatively short north-north-western Arun side valley, the Kasuwa Khola (see Section 2.3). Owing to this, their mere material does not testify to an Arun parent glacier.

Further down the valley remnants of a ground moraine cover are preserved on the orographic right side. In many places they are several deca- to hundred metres lower than that of the Murmidada lateral

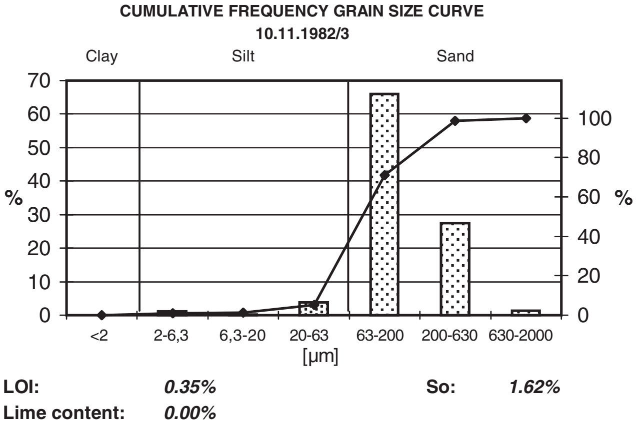


Figure 87. (Grain size diagram 10.11.1982/3) Glaciolimnic sand on the orographic left side, at ca. 2530 m a.s.l., ca. 20 m above the Dudh Koshi river, taken from an exposure. The only maximum is with 66% in the fine sand; the medium sand is involved with 28%. Clay and the bimodal course of the curve, typical of moraine, are completely lacking. This is a metre-thick homogeneous accumulation of loose rock without boulders. The sorting coefficient calculated according to Engelhardt (1973, p. 133) is So = 1.62 (So $=\sqrt{Q3/Q1}$); the loss in ignition (LOI) amounts to 0.35%. Locality: 27°42′58″ N/86°43′23″ E, down-valley of the junction with the Thado Koshi; Figure 4: 10.11.1982/3 at Pro. 29; Photo 221 on the left of. ↘ Sampling: M. Kuhle.

moraine (Photo 46 ■ on the left; 47 third and fourth ■ from the right). Corresponding ground moraine remnants are also situated on orographic left rock cornices, several hundred metres above the Arun talweg

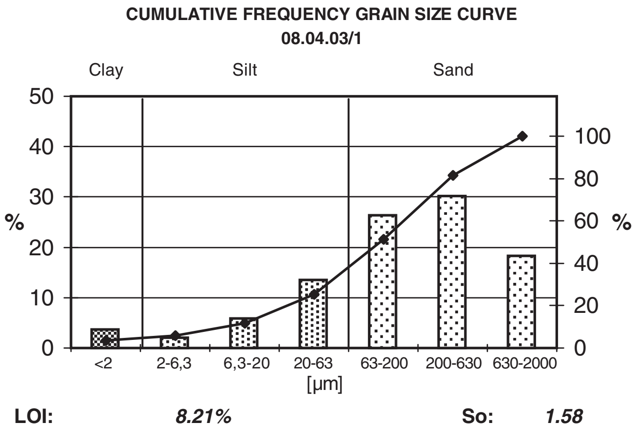


Figure 88. (Grain size diagram 8.4.2003/1) Fine material matrix from a 200 to 350 m-thick ground moraine pedestal (Photo 223) at 2720 m a.s.l. on the orographic left side, ca. 200 m above the Bote Koshi river, taken from an exposure ca. 9 m below the surface. The primary maximum is with 30% in the fine sand, the secondary peak with 4.5% is in the clay. The bimodal course of the cumulative curve of the fine material matrix (i.e., inclusive of the large components as the boulders and the skeleton portion, the trimodal course of the curve of the entire material) is typical of till (moraine) matrix. It is an accumulation of loose material with numerous embedded, edged, round-edged and facetted polymict boulders up to metres in size. The sorting coefficient calculated according to Engelhardt (1973, p. 133) is So = 1.58 (So $=\sqrt{Q3/Q1}$). It argues in favour of a secondary sorting through water – just as the not too high content of clay. The loss of ignition (LOI) amounts to 2.81%. Locality: 27°42′39″ N/86°43′50″ E, down-valley of the junction with the Thado Koshi; Figure 4: 8.4.2003/1 at Pro. 29; Photo 223 ■ on the right; 227 in the middle between the two 0 above; see Figure 37 No. 47. Sampling: M. Kuhle.

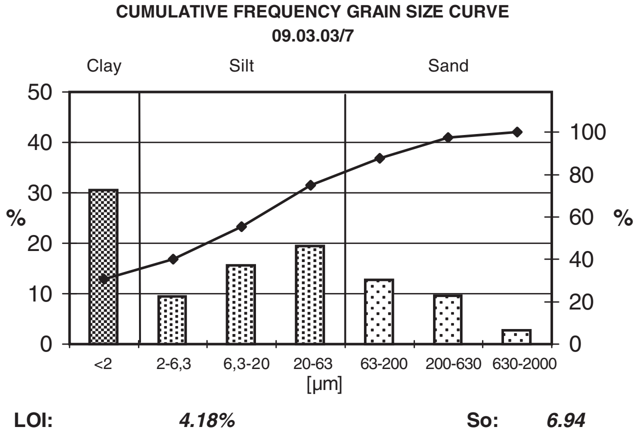


Figure 89. (Grain size diagram 9.3.2003/7) Fine material matrix from an orographic right Late Glacial (Stage I; Photo 226 ■ large) lateral- to ground moraine at 2770 m a.s.l. at the exit of the Handi Khola, on the orographic left side ca. 770 m above the main valley talweg of the Dudh Koshi Nadi, taken from an excavation exposure 2.6 m below the surface. The primary maximum is with 31% in the clay, the secondary peak with 20% is in the coarse silt. The bimodal course of the cumulative curve of the fine material matrix (i.e., inclusive of the large components as the boulders and the skeleton portion, the trimodal course of the curve of the entire material) is typical of till (moraine) matrix; especially in the high mountain relief concerned, the clay portion, which in this case is extremely large, is already a very hard indicator of moraine. This is a decametre-thick accumulation of loose rock with numerous embedded, angular, round-edged and facetted polymict boulders up to metres in size; the sorting coefficient calculated according to Engelhardt (1973, p. 133) amounts to So = 6.94 (So $=\sqrt{Q3/Q1}$); the loss of ignition (LOI) is 4.18%. Locality: 27°40′50″ N/86°44′10″ E, exit of the Handi Khola; Figure 4: 9.3.2003/7 between Pro. 29 and 30; Photo 226 ■ large; 231 below I; see Figure 37 No. 7. Sampling: M. Kuhle.

(Photo 47 second ■ from the left). On this valley flank, on which still very active spring-line erosion has displaced and partly completely removed a large part of the loamy and thus water-damming ground moraine in the form of saturation flows (Figure 11 on the left of No. 51), samples have been taken from ground moraine covers at 1235–1360 m a.s.l., 80–200 m lower than the Num moraine terrace (see above) and 535–660 m above the Arun river (27°33′15″ N/87°16′ E; Figure 4: 16.12.94/1). Here, too, the same picture (Figure 6 No. 14): nearly 75% of the quartz grains contained are glacially crushed.

In this valley cross-profile (Figure 16) – as in the entire past Arun Nadi up-valley – the interlocking of two cross-profiles becomes obvious: on top, in the region of the Ice Age glacier trim-line, a 3.5-km wide, trough-like excavation area and below an at most 1 km wide, V-shaped valley form (Figure 16; Figure 11 above No. 51 and between Nos. 51 and 53). Here, too, the latter has been incised by subglacial meltwater erosion, 2300–2600 altitude metres below the High Glacial (Würm, Stage 0; Table 1) snow-line and preserved by an infilling with ground moraine. In some places the work of the subglacial meltwater is proved by past potholes in the phyllite bedrock (gneiss schists). Potholes such as this, which are dependant on supraglacial meltwater gushing through glacier mills in the hanging glacier ice,

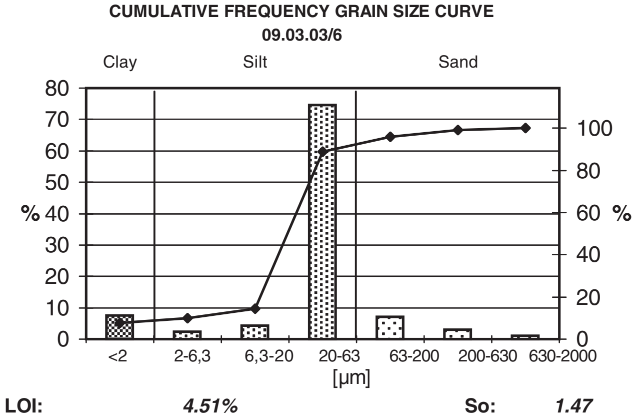


Figure 90. (Grain size diagram 9.3.2003/6) Matrix of glaciolimnic material (Stage I; Photo 226 behind the lateral moraine ramp I) from down-valley of the exit of the Handi Khola at 2520 m a.s.l., approx. 700 m on the orographic left, above the main valley talweg of the Dudh Koshi Nadi, taken from an excavation exposure 2 m below the surface. The primary maximum is with 57% in the coarse silt, the secondary peak is with 8% in the clay. The bimodal course of the cumulative curve of the fine material matrix is typical of nearby morainic deposits, from which the material has been washed out. In the high mountain relief the clay portion, which, with regard to a limnic sediment with a supremacy of coarse silt such as this is extremely high, is an indicator of moraine as initial material. This is a decametre-thick accumulation of loose rock reaching up to ca. 2700 m a.s.l. The sorting coefficient calculated according to Engelhardt (1973, p. 133) amounts to only So = 1.47 (So = $\sqrt{Q3/Q1}$) and argues in favour of a sorting by water. The loss of ignition (LOI) amounts to 4.51%. Locality: 27°40′30″ N/ 86°43′50″ E; Figure 4: 9.3.2003/6 between Pro. 29 and 30; Photos 227, 229 and 231: □; see Figure 37 No. 6. Sampling: M. Kuhle.

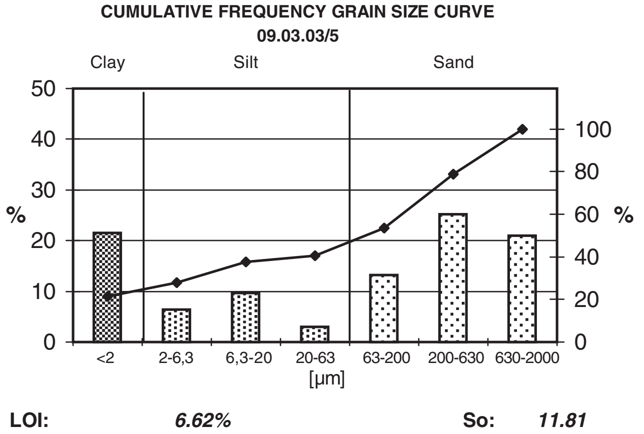


Figure 91. (Grain size diagram 9.3.2003/5) Fine material matrix from a remnant of ground moraine cover at 2630 m a.s.l. on the orographic left side, at least 900 m above the Dudh Koshi river, taken from an exposure 1 m below the surface. The primary maximum is with 26% in the medium sand, the secondary peak with 22% is in the clay, a third peak with 10% is in the medium silt. The trimodal course of the cumulative curve of the fine material matrix (i.e., inclusive of the large components, as the boulders and the skeleton portion, quadramodal course of the curve of the entire material) is typical of till (moraine) matrix; anyway, the very large clay portion is – especially in the steep relief – a very hard indicator of moraine. Here, a metre-thick accumulation of loose rock is concerned, containing embedded angular, round-edged and facetted boulders up to metres in size. The sorting coefficient calculated according to Engelhardt (1973, p. 133) attains the extreme value So = 11.81 (So = $\sqrt{Q3/Q1}$), which also suggests moraine. The loss of ignition (LOI) amounts to 6.62%. Locality: 27°40′20″ N/86°43′50″ E, N above the Surke settlement (Surket), down-valley of the Handi Koshi-junction; Figure 4: 9.3.2003/5 at Pro. 30; Photo 228 on the right above ■ black; see Figure 37 No. 5. Sampling: M. Kuhle.

are situated 10–15 m above the current Arun talweg at 700 m a.s.l. (27°34′ N/87°16′40″ E; Figure 11 between Nos. 51 and 52).

Due to the extreme dynamic of the crumblings between the inflows of Kasuwa- and Irkhuwa Khola, glacier polishings with unambiguous rock abrasions are only preserved on a small-scale. So, for instance, on the orographic right side ca. 270 m above the Arun river (Photo 48; Figure 11 half-right above No. 52).

However, looking from the opposite valley flank, the rounding glacigenic abrasion (Photos 47 and 49▲) and back-polishing of triangular-shaped faces between valley junctions, which have been developed from truncated spurs (Figure 11 No. 52), can be diagnosed beyond doubt. In a downward prolongation of the lateral moraines of Murmidada an abrasion line is also evident, though it is incomplete (Photo 47 – – – and – – – on the left of the second ■ up to the fourth ■; Photo 49 – – – above▲ and – – – on the right).

Considering their approx. corresponding sea-level, the lateral moraines of the Arun parent glacier on the opposite valley flanks near Num on the orographic left and Murmidada on the orographic right side (Photos 46 and 47) have been classified as being synchronous. During the last glacial period (Stage 0; see Table 1) the reconstructed thickness of the Arun glacier amounted to a good 700–830 m (see above and Section 2.4.3; Figure 16). The highest pertinent preserved glacier trimline is also confirmed by polish- and abrasion lines following the remnants of the lateral moraine terraces down-valley (see above: Photo 46 and 47 – – – and – – – 0; Photo 49 – – –). The data introduced here, which provide strong evidences of ice thicknesses, present significant indicators from which one must suggest that Profile 9 (Figure 16) is still ca. 20–25 km away from the lowest margin of the Arun glacier tongue (see below).

The inflow of the High Glacial (Stage 0; Würm) Irkhuwa glacier into the Arun parent glacier has already been proved in detail (see Section 2.2). In addition it has been shown that during the Ghasa Stage (I), or one of the two pre-Ghasa Stagnations, the tongue end of the Late Glacial Irkhuwa glacier had a persistent position somewhat above the junction with the Arun Nadi. Here, the glacier has scoured out its own small tongue basin in the bedrock (Photo 50 ▽ white).

The mouth of the High Glacial (Stage 0) Irkhuwa glacier is not merely evidenced by the orographic left lateral moraine (0 ■; Figure 11 below No. 52 on the left), but also by a down-valley lateral- or kame terrace in the immediate junction with the Arun Nadi at 1120 m a.s.l. (Figure 11 below No. 52 on the right; Photo 49 ■ on the right of ▽). The level of this kame terrace situated a good 420 m above the Arun river (□) at the direct exit of the Irkhuwa Khola, becomes only understandable through the existence of an Arun parent glacier, against which the tongue of this side glacier has pushed and the abutment of which has dammed up the Irkhuwa glacier.

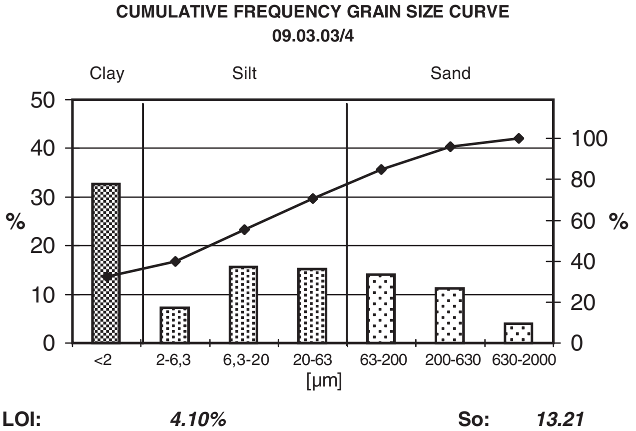


Figure 92. (Grain size diagram 9.3.2003/4) Fine material matrix of an orographic left ground moraine pedestal at 2480 m a.s.l., ca. 780 m above the Dudh Koshi river, taken from an exposure 3 m below the surface. The primary maximum with 33% is in the clay, the secondary peak with 16% is in the medium silt. The bimodal course of the cumulative curve of the fine material matrix (i.e., inclusive of the large components as the boulders and the skeleton portion, trimodal course of the curve of the entire material) is typical of till (moraine) matrix. The here very high clay portion is typical of moraine, especially in the high mountain relief. It is a decametre-thick accumulation of loose rock with numerous embedded, edged, round-edged and facetted boulders up to metres in size. The sorting coefficient calculated according to Engelhardt (1973, p. 133) amounts to So = 13.21 (So $= \sqrt{Q3/Q1}$). This is an extremely high value, which also speaks in favour of moraine; the loss of ignition (LOI) amounts to 4.1%. Locality: 27°40′20″ N/86°43′20″ E, N above the Surke settlement (Surket); Figure 4: 9.3.2003/4 at Pro. 30; Photo 227 ■ white on the right below; 228 ■ white; see Figure 37 No. 4. Sampling: M. Kuhle.

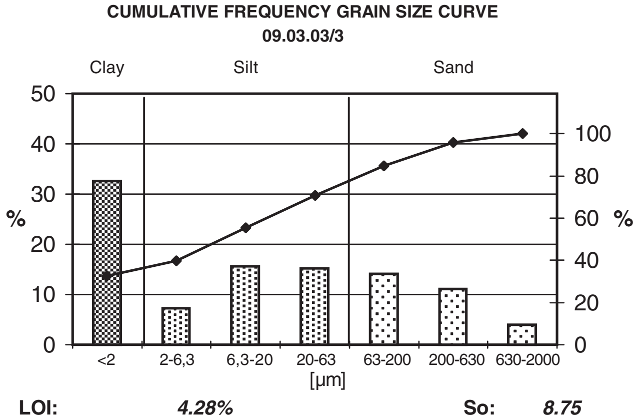


Figure 93. (Grain size diagram 9.3.2003/3) Fine material matrix from a ground moraine cover at 2440 m a.s.l., ca. 740 m above the Dudh Koshi river, taken from an excavation exposure 1.5 m below the surface. The primary maximum with 33% is in the clay, the secondary peak is with 16% in the medium silt as well as in the coarse silt. The bimodal course of the cumulative curve of the fine material matrix (i.e., inclusive of the large components as the boulders and the skeleton portion, trimodal course of the curve of the whole material) is typical of till (moraine) matrix. The here extremely high clay portion is typical of moraine, especially in the high mountain relief. This is a metre-thick accumulation of loose material with embedded edged, round-edged and facetted boulders up to metres in size. The sorting coefficient calculated according to Engelhardt (1973, p. 133) attains the high value of So = 8.75 (So $= \sqrt{Q3/Q1}$); the loss of ignition (LOI) amounts to 4.28%. Locality: 27°40′10″ N/86°43′10″ E, N up-valley of Surke; Figure 4: 9.3.2003/3 at Pro. 30; Photo 228 below ■ white and on the right of 0 white; see Figure 37 No. 3. Sampling: M. Kuhle.

Down-valley from the Irkhuwa Khola inflow the following glacier traces are evident: a boulder the size of a house is situated immediately down from the Irkhuwa Khola junction in an unstable slope position ca. 110 m above the Arun river (Photo 50 ○). It has to be classified as moraine boulder. Above, on the same orographic right slope, glacial band polishings of outcropping edges of the stratum (Photo 49 ∩; Figure 11 half-right above No. 53) and a polish line (––– on the very left) are preserved. On the orographic left side at 1120 m a.s.l., several remnants of a ground moraine cover continue on rock heads isolated by the down-slope removal (■ on the very left; Figure 11 on the far right of No. 53). Up and down the Arun Nadi from the Apsuwa Khola joining from the orographic right (Photo 51∨) perfect band polishings of outcropping edges of the strata are preserved (∩ and ▲), which have abraded back the mountain spurs between the inflows of the tributary valleys into classic glacigenically triangle-shaped slopes (▲) (Figure 11 No. 53). From the trim-line near Num and Murmidada running a good 700–800 m above the Arun, the polish line (–––) falls away to ca. 400–370 m above the Arun (▼) over a horizontal distance about 7–8 km. Again 7 km further down the Arun Nadi remnants of ground moraine covers (Photo 52 ■), which partly peter out upward into glacigenic remnants of lateral forms (↓) and rounded rock heads (∩; Figure 11 below No. 53) testify to a trim-line (Photo 52 –––) at 800 m a.s.l. and thus a remaining thickness of the Arun main glacier of at most 280 m.

This thickness has been measured from the trim-line down to the Arun talweg. However, the valley cross-profiles show a significantly narrower lower V-shaped cross-section, which as a subglacial meltwater gully has syngenetically been set into the bottom area of the upper cross-profile widened by the Arun glacier (Figure 11 below No. 53). Besides this space between glacier bottom and subglacial meltwater talweg a decametres-thick pedestal of ground moraine can be suggested, on which the Arun glacier tongue was placed as a dam glacier tongue. In the meantime this probable ground moraine pedestal has been completely removed by fluvial activities. Corresponding observations have been described from the lower Thak Khola (Dhaulagiri Himalaya) between the Tatopani settlement and the lowest ice margin position of the High Glacial Thak Khola glacier near the inflow of the Sansar Khola (Kuhle, 1982: 48–51; 1983a: 125–128; cf. also v. Klebelsberg, 1949, Vol. 2: 828).

The orographic left side valleys of lower catchment areas (Figure 11 between Nos. 54 and 51), which even during the Ice Age were not glaciated, as e.g. the Kaguwa Khola (Photo 52 foreground) and Rate Khola (Photo 51 foreground) with their fully developed, purely fluvial slope-gully landscape with steep gullies (⇓) caused by heavy monsoonal rainfalls, contrast with

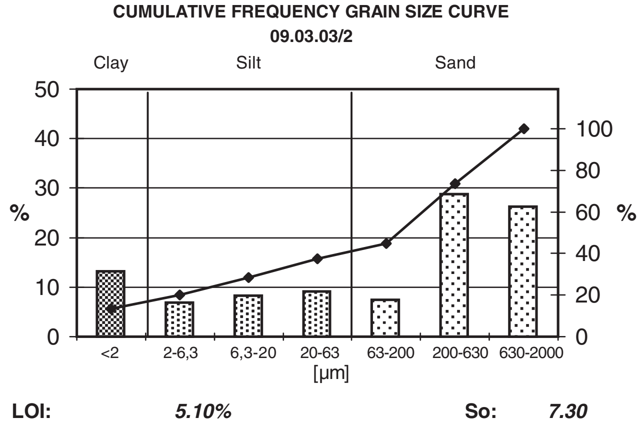


Figure 94. (Grain size diagram 9.3.2003/2) Fine material matrix of moraine at 2380 m a.s.l., ca. 680 m above the Dudh Koshi river, taken from an excavation exposure from a depth of 1.1 m. The primary maximum is with 29% in the medium sand, the secondary peak with 14% is in the clay, a third peak of at least 9% is in the coarse silt. The trimodal course of the cumulative curve of the fine material matrix (i.e., inclusive of the large components as the boulders and the skeleton portion, the quadramodal course of the curve of the whole material) is typical of till (moraine) matrix. The high clay portion is – with regard to accumulations in the high mountain relief – typical of moraine. This is a metre-thick accumulation of loose material; the sorting coefficient calculated according to Engelhardt (1973, p. 133) attains the high value of So = 7.30 (So $=\sqrt{Q3/Q1}$); the loss of ignition (LOI) amounts to 5.1%. Locality: 27°40′ N/86°43′20″ E, on the slope E above Surke; Figure 4: 9.3.2003/2, at Pro. 30; Photo 231 on the right above 0 below; see Figure 37 No. 2. Sampling: M. Kuhle.

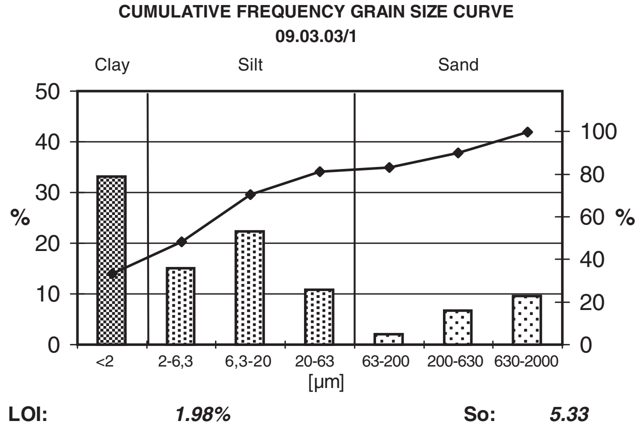


Figure 95. (Grain size diagram 9.3.2003/1) Fine material matrix from a ground moraine cover at 2490 m a.s.l., ca. 790 m above the Dudh Koshi river taken from an excavation exposure, ca. 3 m below the surface. The primary maximum is with 34% in the clay, the secondary peak with 22.5% is in the medium silt, the third peak is with 10% in the coarse sand. The trimodal course of the cumulative curve of the fine material matrix (i.e., inclusive of the large components as the boulders and the skeleton portion, the quadramodal course of the whole material) is typical of till (moraine) matrix; the here extremely high clay portion is, especially in the high mountain relief, a characteristic of moraine. This is a metre-thick accumulation of loose rock with embedded boulders up to metres in size. The sorting coefficient calculated according to Engelhardt (1973, p. 133) amounts to So = 5.33 (So $=\sqrt{Q3/Q1}$); the loss of ignition (LOI) is 1.98%. Locality: 27°39′45″ N/86°43′30″ E, SE down-valley on the slope above Surke; Figure 4: 9.3.2003/1 at Pro. 30; Photo 229 on the left above 0; see Figure 37 No. 1. Sampling: M. Kuhle.

the 'polished valley flank type' of the Arun main valley (∩ and ▲).

From the Num- up to the Simle settlement, i.e. over a distance of 14.5 km, the Arun parent glacier has decreased from an ice thickness of a good 700–830 m to ca. 250 m (at most 280 m, see above). At a correspondingly continuous decrease in ice thickness the Arun parent glacier ought to have had its lowest ice margin ca. 6.5–7 km further down-valley near the Sankhuwatar settlement at the mouth of the Sankhuwa Khola (Figure 4) at 27°27′ N/87°08′45″ E about 450 m a.s.l. (Figure 11 above No. 54). In earlier publications the author has already cited this ice margin position, though with the slightly differing coordinates 27°24′ N/87°08′30″ E (Kuhle, 1997b: 125; 1998a: 87) based on the somewhat inexact One Inch-Map (1964) and the ONC-Map (Operational Navigation Chart, 1978, H-9). In the meantime, the map-sheet Khadbari of the 1:25,000 Nepal-mapwork (2787 09B, 1996) and thus a more exact quotation of the coordinates is available. The distance of ca. 21–22 km from the undoubted lateral moraine forms near the Num and Murmidada settlements (see above) up to this locality of the glacier tongue end is – with regard to the valley decline from 710 to 450 m a.s.l. and the decrease in ice thickness of ca. 750 m – an extrapolation value of appropriate probability, which through the numerous glacigenic indicators on this stretch (cf. Photos 46–52 ‒‒‒) receives an evident confirmation.

Down-valley from the High Glacial ice margin position of the Arun glacier a related glaciofluvial terrace area sets in. To this belongs the large-scale preserved main terrace, a good 60 m-high, of the High Glacial (Stage 0 = last glacial period, Würm, last High Glacial Maximum) ice margin position at 450 m a.s.l. as a connected glacier mouth gravel floor (gravel field, sander No. 5; cf. Table 1) (Figure 11 No. 54). During the deglaciation up to the Holocene this gravel floor has been cut a good 60 m-deep, so that the 100–700 m-wide, 60 m-high terrace forms have developed. The samples taken ca. 18–22 km away from the Ice Age glacier margin (Figure 11 No. 54) down the Arun Nadi (No. 55; Figure 4 sample 19.12.94) up to ca. 250–200 m a.s.l. down to the valley chamber of Tumlintar, confirms the glaciofluvial sediment-type of the terrace (Figure 6 No. 15). The morphoscopy shows the fluvial reshaping of a glacigenic sediment. 49% of the grains are glacially crushed and almost 47% of them are lustrous (fluvial). This proves the proximity of a past glacier margin the meltwater of which has displaced the moraine material. In morphoscopic terms it has been reshaped at the same time, but not completely reworked. The 4.3% aeolian grains point to a markedly more arid environment than today and to past cold katabatic winds from the glacier, channelled by the Arun Nadi.

The red weathering supports the conclusion that the surface of the gravel floor has been fossilized since ca. 18–17 Ka (see above).

Table 1. Glacier stages of the mountains in High Asia, i.e. in and surrounding Tibet (Himalaya, Karakorum, E-Zagros and Hindukush, E-Pamir, Tien Shan with Kirgisen Shan and Bogdo Uul, Quilian Shan, Kuenlun with Animachin, Nganclong Kangri, Tanggula Shan, Bayan Har, Gangdise Shan, Nyainquentanglha, Namche Bawar, Minya Gonka) from the pre-Last High Glacial (pre-LGM) to the present-day glacier margins and corresponding sanders (glaciofluvial gravel fields and gravel field terraces) with their approximate age (after Kuhle, 1974–2003)

Glacier stage	Gravel field (Sander)	Approximated age (YBP)	ELA-depression (m)
−I = Riß (pre-last High Glacial maximum)	No. 6	150,000–120,000	ca. 1400
0 = Würm (last High Glacial maximum)	No. 5	60,000–18,000	ca. 1300
I–IV = Late Glacial	Nos. 4–1	17,000–13,000 or 10,000	ca. 1100–700
I = Ghasa-Stage	No. 4	17,000–15,000	ca. 1100
II = Taglung-Stage	No. 3	15,000–14,250	ca. 1000
III = Dhampu-Stage	No. 2	14,250–13,500	ca. 800–900
IV = Sirkung-Stage	No. 1	13,500–13,000 (older than 12,870)	ca. 700
V–′VII = Neo-Glacial	Nos. −0 to −2	5500–1700 (older than 1610)	ca. 300–80
V = Nauri-Stage	No. −0	5500–4000 (4 165)	ca. 150–300
VI = Older Dhaulagiri-Stage	No. −1	4000–2000 (2050)	ca. 100–200
′VII = Middle Dhaulagiri-Stage	No. −2	2000–1700 (older than 1610)	ca. 80–150
VII–XI = Historical glacier stages	No. −3 to −6	1700–0 (= 1950)	ca. 80–20
VII = Younger Dhaulagiri-Stage	No. −3	1700–400 (440 resp. older than 355)	ca. 60–80
VIII = Stage VIII	No. −4	400–300 (320)	ca. 50
IX = Stage IX	No. −5	300–180 (older than 155)	ca. 40
X = Stage X	No. −6	180–30 (before 1950)	ca. 30–40
XI = Stage XI	No. −7	30–0 (= 1950)	ca. 20
XII = Stage XII = recent resp. present glacier stages	No. −8	+ 0 to + 30 (1950–1980)	ca. 10–20

2.4.6. Information as to the extent of the High Glacial Apsuwa glacier

The Apsuwa Khola (Photo 51 v and below No. 48; Figure 4), the SW parallel valley of the Irkhuwa Khola, has a catchment area rising up to 6213 m, the double-summit of Ekrate Dada (Photo 51 and Figure 11 No. 48) and, accordingly, is still currently glaciated. At a cautious, i.e. rather too high, estimation of the orographic snow-line (ELA) about 3600 m a.s.l. in a SE-exposition and a medium altitude of the catchment area of ca. 5200 m, the lowest ice margin position is about 2000 m a.s.l (calculation of the lowest glacier tongue end of the High Glacial Apsuwa glacier according to medium altitude of the catchment area and ELA: $5200-3600=1600$; $3600-1600=2000$) (Figure 11 half-left above No. 53). Owing to this and in contrast to the NE-adjacent Irkhuwa glacier, the Ice Age Apsuwa glacier terminal has not reached the Arun parent glacier. It lay at approx. 27°36′18″ N/87°08′32″ E, at most 13 km away from the confluence with the Arun main valley (Figure 11 between No. 48 and 53). Only this lowest section of the Apsuwa Khola is depicted in Photo 51 (v). In geomorphological terms this High Glacial ice margin position is marked by a change in the cross-profile of the Apsuwa Khola (Figure 11 half-left above No. 53). Above, i.e. up-valley from an altitude of the talweg about 2000 m a.s.l, at the place where the glacier terminal was situated, the valley has been widened glacigenically (Photo 51 below No. 48). Despite the steepness of the up-valley course of the talweg, it additionally receives the characteristics of a trough-shaped, widened, gorge-like V-shaped valley or a gorge-like trough (Figure 11 half-right below No. 48). That is to say, its rock slopes are concavely steepened by glacigenic flank polishing from a flat lower slope towards above, in the way characteristic of glacigenic cross-valleys in the High Himalaya (see Kuhle, 1980, 1982: 55, 1983a: 154, 155). Down-valley from 2000 m altitude of the talweg, a narrower and only just V- and gorge-shaped, increasingly angular valley course sets in (Figure 11 half-left above No. 53). Its cross-profiles are also typical of uninterrupted fluvial linear erosion during the Ice Age (Photo 51 v).

2.4.7. Summary of Section 2, i.e. summary of the High Glacial extension of the Barun–Arun glacier system and its tributary glaciers

During the last glacial period (Stage 0; Table 1) a dendritic valley glacier system has joined in the Arun parent glacier. It has been fed by the S-Tibetan ice stream network (Kuhle, 1991a) as well as by the Karma-, Barun- and Irkhuwa-glaciers and, accordingly, has also been nourished by the High Himalaya (Figure 4). This composition of the parent glacier resulted from the arrangement of the Arun Nadi as an antecedent Himalayan transverse valley leading down from the Tibetan Plateau. The Arun outlet glacier descending from there, i.e. from the valley chamber of Kada (Figure 4), was ca. 110 km long and flowed down to ca. 450 m a.s.l up to the inflow of the Sankhuwa Khola (27°27′ N/87°08′45″ E) (Figures 4 and 11). The tributary streams and glaciers of the Arun parent glacier, also reconstructed in this chapter, are the Barun- and Irkhuwa-glacier (Figure 4). They flowed down from the Khumbakarna Himalaya SE- to SSE-slope, from the Makalu- and Chamlang massif (Figure 3), up to the junction with the Arun parent glacier over a length of 61, i.e. 40 km, as far as 1100 and 700 m a.s.l (Figures 4 and 11). The whole length of the Barun glacier, including the fully 33 km-long

Table 2. C14-datings from the Khumbu Himalaya

No.	Material	Altitude (m a.s.l.)	Locality	Depth of sample (m)	Underlying substratum	Recent vegetation cover	δ 13C (‰)	C14 age (years before 1950)	Comments
1	Soil	4410	Adjacent valley of Dole (Dole Drangka), end moraine; 27°52′32″ N /86°43′21″ E	0.3	Moraine, unconsolidated rock – metamorphosed graywacke	Cyperaceae turf	−26.0	2050 ± 105	See Figure 19, No. 1
2	Peat	4400	Adjacent valley of Dole, tongue basin; 27°52′21″ N /86°43′24″ E	0.25	Gneiss gravel	Alpine turf and moist alpine scrub	−24.8	2400 ± 140	See Figure 19, No. 2
3	Muds of acid alpine moor soil	4230	Adjacent valley of Dole, end moraine; 27°52′10″ N /86°43′30″ E	0.5	Glacial till – gneiss and metamorphosed graywacke	Moist alpine scrub	−24.8	4165 ± 150	See Figure 19, No. 3
4	Humus soil and peat	4440	Machhermo Khola (Drangka), lateral to end moraine; 27°54′06″ N /86°43′03″ E	0.2	Moraine material, sand with blocks of gneiss	See No. 2	−23.8	2350 ± 295	See Figure 19, No. 4
5	Soil	4910	Lateral depression right of the N gozumpa glacier; 27°58′45″ N /86°41′30″ E	0.12	Glacio- fluvial sand, sand bar material	See No. 1	−25.1	3345 ± 550	See Figure 19, No. 5
6	Peat of hummocks	5230	340 m-high pedestal ground moraine terrace right of the Ngozumpa glacier; 27°59′16″ N /86°41′01″ E	0.6	Coarse moraine blocks of graywacke and gneiss	Alpine turf	−24.5	2705 ± 235	See Figure 19, No. 6
7	Root wood from Rhodiola	5350	Lateral depression of adjacent valley glaciers above and right of the Ngozumpa glacier; 28°01′55″ N /86°41′03″ E; orogr. left lateral valley of Lhabtshan E-Glacier and in the tongue basin of Lhabtshan 5560 m-summit south glacier	0.40–0.42	Lateral fan – sand on coarse moraine blocks: gneiss and granite	Alpine turf	−23.0	290 ± 70	See Figure 19, No. 7
8	Root wood from Rhodiola	5350	See No. 7	0.5	See No. 7	Alpine turf	−24.7	440 ± 80	See Figure 19, No. 8
9	Peat from hummocks	4745	On the delta of Gokyo-Tsho (lake) (west); 27°57′ N/86°41′17″ E	0.5–0.55	Glaciofluvially reworked moraine with gneiss	Alpine turf	−24.4	1165 ± 110	See Figure 19, No. 9
10	Peat	4290	On alluvial soil in tongue basin in the Arabtsen valley near Thengpo; 27°49′20″ N/86°36′35″ E	0–0.05	Glaciofluvial sand on glacial till with metamorphosed sedimentary rock	Alpine turf	−22.8	320 ± 130	See Figure 3, No. 10
11	Wood	3550	West of Namche Bazar; 27°48′12″ N/86°42′40″ E	0.7, digging	Glaciofluvial or glaciolacustrine sands on lodgement till	Alpine scrub	−26.3	Younger than 1955; 14C-content (% modern) 113.5 ± 1.7	See Figure 3, No. 11; 400 m higher than the talweg of the Bhote Koshi

Table 2. (Continued)

No.	Material	Altitude (m a.s.l.)	Locality	Depth of sample (m)	Underlying substratum	Recent vegetation cover	δ 13C (‰)	C14 age (years before 1950)	Comments
12	Wood (two pieces)	3780	Syampoche; 27°48′30″ N /86°42′55″ E	1.30, digging	Glaciofluvial sands on medial moraine	Alpine scrub	−21.0	Younger than 1955; 14C-content (% modern) 100.0 ± 0.9	See Figure 3, No. 12; 800 m higher than the talweg of the Bhote Koshi
13	Wood	4030	North–north-east above Khumjung; 27°49′21″ N /86°43′25″ E	0.50, exposure	Orographic right end- or lateral moraine	Alpine scrub	−20.0	210 ± 50	See Figure 3 No. 13, 800 m higher than the talweg of the Imja Drangka (Khola)
14	Wood	3840	Western margin of Tengboche; 27°50′12″ N /86°45′50″ E	1.50, exposure	Glaciofluvial sands of former glacier bank	Alpine forest	−23.9	Younger than 1955; 14C-content (% modern) 104.2 ± 0.7	See Figure 3, No. 14, 350 m higher than the talweg of the Imja Drangka
15	Wood	4300	East above Pheriche; 27°53′39″ N /86°49′48″ E	0.60, digging	Lateral moraine	Alpine scrub	−22.2	Younger than 1955; 14C-content (% modern) 102.3 ± 1.0	See Figure 3, No. 15, 180 m higher than the talweg of the Khumbu Drangka (Khola)

tongue of the Arun parent glacier from the confluence of the two ice streams up to the lowest joint ice margin position at 450 m a.s.l (see above), amounted to 94 km.

During the High Glacial the ice thicknesses of the Barun- and Irkhuwa glacier amounted to at least 1300 (Figures 10 and 12), i.e. 1400–1600 m according to the underlying thickness of the ground moraine (2.1.4.) and 1100 m (Figure 14; cf. Figure 4). At low-lying valley floors of merely ca. 1100 and 720 m a.s.l, the lower Arun parent glacier has even just reached 1100 (Figure 15; cf. Figure 4) and 700–830 m (Figure 16; Photo 47). In the feeding areas of the source branches of the Barun glacier, the Barun- i.e. Upper- and Lower Barun sub-stream, the altitudes of the valley glacier levels lay at 6200–6450 m (Figures 7–10), so that ice transfluences have taken place across 6070–6275 m-high passes into the N-adjacent Kangchung Nadi (Khola) or Karma Chu, into the W-adjacent Imja Khola and into the E-adjacent Arun Nadi (Figure 3; 11). Due to additional transfluences from or into the Kharta valley via the Karma Chu – and also via the upper Arun Nadi – a further connection to the S-Tibetan ice stream network (Kuhle, 1991a) has existed in the N. There was also a most important, a fully 500 m-transfluence to the SW-adjacent Irkhuwa glacier across the Iswa La (Figures 3,4 and 11 No. 47). Here, the joint Barun–Irkhuwa glacier level situated above this pass has dropped from the Barun glacier surface at ca. 5900 m a.s.l down to the Irkhuwa glacier level at ca. 5300 m.

The current height of the snow-line in the catchment area of the Barun- and Irkhuwa glacier, being the source areas of the Ice Age Arun glacier in the Himalaya SSE-slope, amounts to 5450 m a.s.l. This is a 200 m lower value than has been calculated for the S-side of the Kangchendzönga Himal situated 100 km further to the E (Kuhle, 1990: 420). The calculation is based on the current orographic ELA of the S-exposed hanging glacier of the Chamlan group in the left Barun valley flank at 5300 m a.s.l (2.1.4.) and of the Irkhuwa glacier in a SE-exposition at 5600 m a.s.l (2.2.).

The glacier tongue of the S-glacier of the Chamlan-group discussed here, ends at 4590 m. From this follows a difference in height of 4140 m to the lowest ice margin position of the Ice Age Barun–Arun parent glacier at 450 m a.s.l (see above). Accordingly, a snow-line depression of 2070 m has existed (calculation of the ELA-depr.: $4590-450=4140$; $4140:2=2070$). As to the Irkhuwa glacier terminus at 4100 m a.s.l the difference in height to the end of the parent glacier at 450 m a.s.l. is 3650 m. Thus, the ELA-depression was 1825 m (calculation of the ELA- depr.: $4100-450=3650$; $3650:2=1825$). For the S- to SE-exposition an ELA-depression of 1950 m can be calculated ($2070+1825=3895$; $3895:2=1947.5$).

This is to say that the Ice Age snow-line of the Arun glacier system, i.e. in the relevant area of the Himalaya S- to SE-exposition, has run at ca. 3500 m a.s.l. ($5450-1947.5=3502.5$) – an ELA-value confirmed by the reconstructed High Glacial cirque glaciers and the