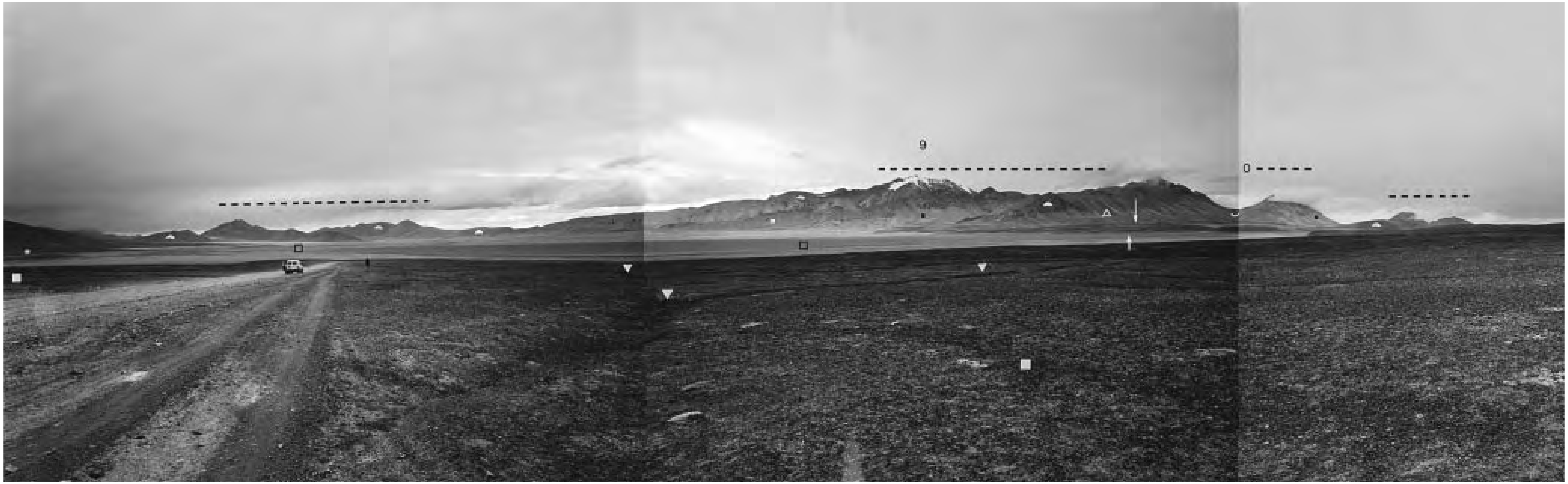
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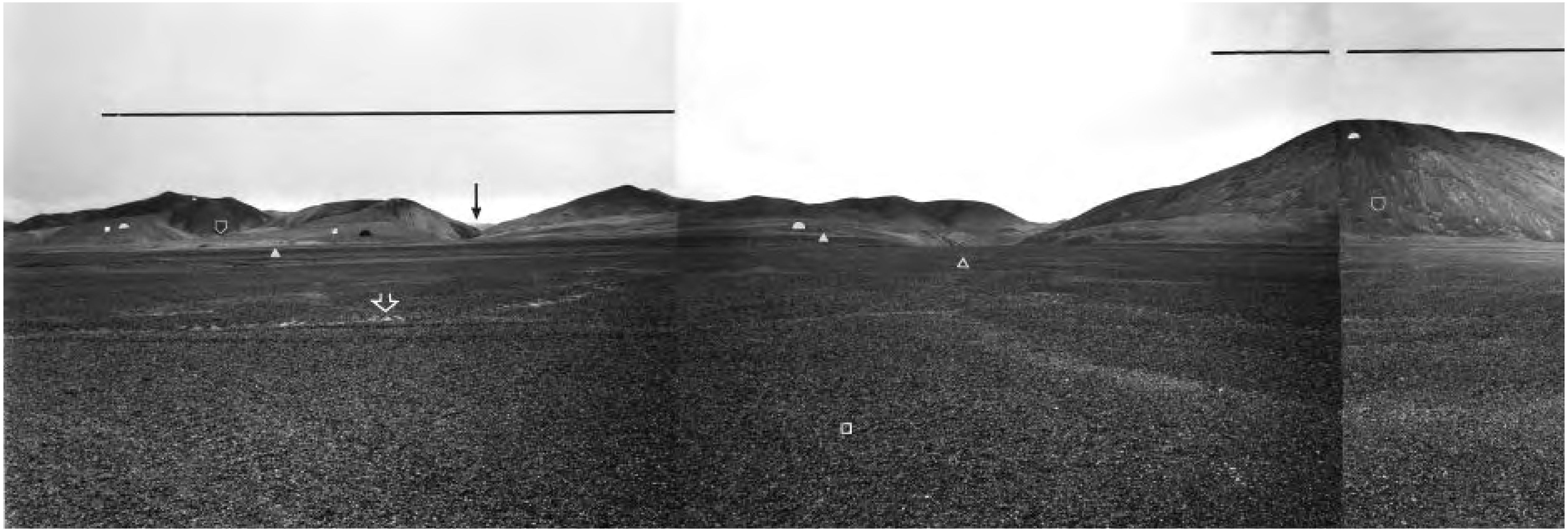

← *Photo 199.* Taken at ca. 5400 m (aneroid measurement: 5230 m asl) from ca. 3 km WNW of the locality of Photo 198, in the area of the ca. 5400 m-pass (Figure 2, No. 161) over the Aksai Chin, somewhat NW of its culmination (34°43′10" N/80°12′ E). Directions: from facing WNW (left margin) via N and E (on both sides of the centre) up to ESE (right margin). (☐) mark a lake basin, in which a nearly round lake has remained, being 4 km in diameter (☐ right). Behind, a ca. WNW–ESE-stretching mountain massif rises up to 6480 m (No. 9). It is still locally glaciated. During the High Glacial (LGM = Stadium 0) it has been completely covered by the inland ice, the minimum surface height of which (– – 0 – –) is confirmed by the rounding of the mountains (◓) (Figure 2, No. 162). Summit No. 9, however, already towered above the inland ice cover during the Late Glacial (cf. since Stadium I; cf. Table 1) and thus has been sharpened into an approximate glacial horn (Figure 2, below No. 161). (■) is the glacial ground- and ablation moraine sheet preserved from the lake basin as far as up the slopes. (▼) show tundra polygons (frost wedge- or frost crack polygons), i.e., postglacial permafrost indicators. They are typical of the Arctic, mostly developing there in ground moraine as well. (◡) is a classically glacigenic transfluence pass, evidenced by the trough-profile. (↓) are classic indicators of ground scouring in the form of exaration rills gouged into a roche moutonnée. (↑) points to a postglacial cliff, marginally undercutting this roche moutonnée. (△) are cone forms only a few metres-thick, consisting of Ice Age ground moraine shifted down-slope and a thin cover of frost debris. (Photo M. Kuhle.)

← *Photo 200.* At ca. 5200–5250 m (aneroid measurement: 5000 m asl), ca. 4.5 km NW from the viewpoint of Photo 199, from the SW margin of the same up-silted lake basin (Figure 2, Nos. 162-163; 34°44′40" N/ 80°08′30" E). Directions: facing SSW (left margin) via W (left of the centre) up to NW (right margin). This very high Tibetan plateau landscape of the Aksai Chin-Lingzi Thang, where vegetation is completely absent, is marked by rounded mountain- and hill ridges (◓ right) from sedimentary bedrocks (silt- and sandstone). Several of the slopes are lineated by exaration rills or -furrows, arranged crossways to the incline (◓ black and white, centre), as defined for classically glacigenic ground- and flank polishing characteristics. A light erratic ground moraine overlay (■) occurs on the dark bedrock in the underlying bed (⇩). This ground moraine has been exposed by microfluvial rills (▲ right) and fluvial lateral erosion (▲ left). Some slopes have been relieved from the ground moraine by flushing (⇩). Down-slope transport can also be evidenced by solifluction forms (◡). (△) is a flat alluvial fan, developed by a temporary stream through the side valley. It consists of washed and slightly shifted ground moraine. (⇓) shows the clayey ground moraine matrix. (↓) is a late Late Glacial spillway (probably Stadia III–IV). Its V-shape in this rock threshold results from a sudden, very heavy glacier lake outbreak into an adjacent lake basin. (– –) is the minimum surface height of the High- to early Late Glacial inland ice (LGM = Stadium 0 to Stadium I or even II; cf. up-lift of the ELA during this sequence of Stadia), derived from the glaciogeomorphology. (Photo M. Kuhle.)

accumulated at the foot of the valley slope. Not only are smooth, round-polished rock faces of valley flanks covered by this ground moraine, but also rough glacigenic rock areas with slip-off slopes are wearing such a veil-like ground moraine cover. Despite the rinsing, this ‘ground moraine veil’ has been preserved very well because of the roughness of the underground. As a glacial lubricant it might have even reduced and in part prevented the increased smoothing of the rocks by glacier polishing. Ground moraine covers of this kind have also been mapped on the valley flanks of the upper Yarkand valley as far as 800 and more metres above the thalweg (Figure 2, Nos. 186 and 188).

9. Conclusions from the field data presented here with regard to the overall picture of the Ice Age glaciation of Tibet and the surface-efficiency of the ELA depression for this glaciation

The investigation area treated is shown in Figure 1, No. 20. The results of the field work are shown in Figure 2. The glaciogemorphological and glaciogeological indicators Nos. 1–189 provide evidence for an inland glaciation which has completely covered Central- and W Tibet and in many places was more than 1000–1400 m thick. Figures 10, 19, 32 and 35 present cross-profiles of the inland ice with sections of the research area concerned (Figure 1, No. 20). This is area I2 between Mt. Everest in the SE and above the Karakorum in the NW in Figure 12. The inland ice area indicated in Figure 12 as I2, which – according to earlier results from surrounding areas under investigation by the author (Kuhle, 1982–1997b) – has been interpolated as an inland ice sheet, is confirmed by these new field observations. The Central- to W Tibetan Ice Age (LGM) inland ice areas concerned and their extended outlet glaciers which in the S flowed down through the Himalaya, and in the NW from the edge of the plateau into the valleys of the Kuenlun, were situated in the precipitation shadow of the Himalaya and Karakorum. Today they are part of the most arid regions of the whole of Tibet. This suggests, that – in order to develop an inland ice – Tibet must have been either colder and more humid or very much colder than at present.

In order to make clear in which way the build-up of the ice has taken place during the uplift of Tibet, i.e., at the lowering of the ELA against the relief surface, two Central-Tibetan test areas have been chosen (Figures 36 and 37). Figures 36 and 37 concern sections of the investigation areas Nos. 4, 9 and 11 (Figure 1) (cf. Figures 12 and 35). In test area Tibet 8 (Figure 36) the highest summit towering above the Tibetan plateau rises to 6986 m, the one of test area Tibet 12 (Figure 37) is 6928 m high. These are the highest elevations in the glacier feeding areas. The Tibetan high plain extends between 3353 m, i.e., 4542 m asl and those summits in these test areas. ELA = 5700 m (Figure 36) and ELA = 5900 m (Figure 37) are the particular modern snow line altitudes. ELA-893 and ELA-5759 indicate the current surfaces of the glacier feeding areas (in km^2), lying above these snow lines. ELA-600 shows the particular increase in the glacier feeding area at an ELA-depression by 600 m relative to present-day conditions, or at an uplift of Tibet (i.e., of the entire relief) by 600 m, and ELA-600: 21146 and 47593 indicate the extent of the feeding areas (in km^2), which are pertinent to the particular test areas. ELA-1200 shows the increase in the glacier feeding area at an uplift of 1200 m; the pertinent surface dimensions concern the feeding areas which result from the uplift. The related surfaces of glacier ablation enlarged the total area of the glacier surfaces by ca. half of these feeding area surfaces. In comparison with the total basal surface of the test areas it becomes obvious that at ca. ELA-800 to ELA-1200 the test areas have been completely covered with ice. ELA-600 corresponds to a snow line depression by 600 m and ELA-1200 by 1200 m, compared with the present-day relief. The snow line depression by 600 m occurred for the last time during the late Late Glacial (Stadium IV) and the depression by 1200 m (to 1300 m; see Table 1) during the Last High Glacial (LGM; Stadium 0; Würm) (cf. Kuhle, 1997b, Figure 45, p. 119).

10. The global-climatic importance of the Tibetan Ice and its function as a trigger for the Quaternary Ice Ages – an Ice Age hypothesis (in a very simplified and schematized way)

In consequence of the subduction of the Indian subcontinent under the Eurasian plate, Tibet has been uplifted above the snow line and completely glaciated step by step for the first time during the early Pleistocene (maximum as in Figure 12) (Kuhle, 1987d, 1988). This process of glaciation becomes understandable with the help of Figures 36 and 37 by way of the test areas under investigation here. The uplift of Tibet as one of the great events of the earth’s history coincides with the onset of the Ice Age 5.5 to 2.5 million years ago (Flohn, 1988, pp. 181f). It has triggered the build-up of the Nordic lowland ices by the initial glaciation of Tibet and in consequence the true High Glacial. The névé surfaces of the Tibetan ice reflected 85% – in part even more than 90% (measurements at 6500–6650 m asl on the Mt. Everest N slope after Kuhle, 1987d, 1989; Kuhle and Jacobsen, 1988) – of the incoming radiation energy, whilst debris surfaces transform 80–85% of this global radiation into long-wave heat-radiation, heating the atmosphere. Therefore the absolute amount with which a given ice surface intervenes in the heat balance of the earth is the greater, the nearer it is situated to the equator and the higher its altitude lies above sea level. At an incoming radiation of 1000–1300 W/m^2 (on average 1180 W/m^2) at 6000 m asl and 30° N (Mt. Everest N slope), the negative effect on the heat balance is at least four times that of a glaciation at 60° N at sea level (Kuhle, 1987d, 1989). Thus, the Tibetan inland ice with an extent of ca. 2.4 million km^2 (Figure 12) and a surface reaching altitudes of 5000 to 7000 m asl (Figures 10, 19, 32 and 35) between 27 and 40° (the position of the N Sahara and the Mediterranean Sea), has caused an albedo-dependent energy loss of considerable dimensions (Kuhle, 1985c–1994b). Out of the albedo-dependent energy loss of the earth-atmosphere of at least 10% of the global radiation, calculated for the worldwide total area of the Last Glacial (LGM) glaciers, already 32% (i.e., one third of the total loss) falls to the loss that was induced by the uplift of the Tibetan inland ice (Bielefeld, 1993, pp. 99ff). According to the discontinuing relationship between the depression of the ELA into the relief, i.e., uplift of the relief above the ELA and the resulting glaciation area, every topography has a characteristic graph of its glaciation potential (Figures 38, 36, 37). With regard to the Tibetan upland and its marginal mountain ranges, the following exponential course of the graph is derived: according to an ELA depression of 1400 m – as it is the case at present – into the existing high mountain relief, which towers above the surfaces of the plateau, a catchment area of only 6% has been developed, whilst an additional ELA depression by only 200–300 m (250 m) raises the increase in surface to 13%, i.e., by the factor 5.8. At a further depression by 300 m are already obtained 24%, and at an ELA of −1000 m compared with today (according to a decrease in temperature of ca. −5 °C) 54% of the total area become a catchment area (the rate of the increase in surface per 100 m ELA depression increases from 0.4 to 3.7 (−600 m) recently as far as 6.3 (−1200 m) (cf. also Figures 36 and 37). Supposing that the present Tibetan plateau will be uplifted by further 250 m (isostatically, see below) (at a recently confirmed amount of uplift of 1 cm/yr this could be attained within approx. 25 000 years), 7% of additional surface would primarily be obtained as glacier catchment area owing to the climatic change with altitude. At an advance of the glaciation, following this process, and a self-increase of the glacier surface by several 100 m – 200 m are to be expected here as a minimum – this corresponds to a real extent of the catchment area of ca. 22% and thus, at a ratio of 2:1 of feeding- to ablation area, to a glaciation surface of 33%, i.e., one-third of the total area of Tibet would be covered with glaciers. In this case the high effect of the albedo, caused by subtropical values of the incoming radiation at a high sea level, would already mean an absolute loss of 1% of the global energy balance and in consequence lead to an increase of the Nordic glaciation processes. At a feed-back loop like this, a further climatically-induced ELA depression into the topography must be assumed, combined with an exponential surface increase and albedo-dependent losses in energy (Figure 38, graph I). This means, that the albedo-effective position of the Tibetan glaciation was possibly an important trigger of the worldwide cooling phase. For the Tibetan plateau and its surrounding marginal mountain ranges a completely covering glaciation in the form of an inland ice sheet is documented by geomorphological indicators (Figure 1 and especially Figure 2). In the central plateau areas and depressions its average thickness of 1500 m increased as far as 3000 m (Figures 10, 19, 32, 35) (Kuhle, 1987d, 1989, 1994b). Analogous to the Fennoscandian glaciation area, a glacioisostatic lowering by 600–700 m is supposed to be probable (Kuhle, 1989, p. 276; 1993c, p. 146). From that result the following consequences: an isostatic reaction can only be expected in delay, i.e., under the pressure of a maximum ice burden. An average lowering by 650 m (Figure 38, graph III) according to a relative rise in temperature of ca. 3 °C, actually led to a reduction of the glaciation, but – under glacial climate conditions of absolutely at least −5 °C and an extent of the catchment area of 68% – the total area remained glaciated and the absolute loss in radiation continued. However, a local additional warming up of the climate by 2 °C (i.e., a rise of the ELA by 400 m, for instance by the orbital variations (Croll, 1875; Milankovic, 1941) was able – in contrast to Phase I – to bring about a destabilization and thus a breaking apart of the inland glaciation into autochthonous mountain glaciations, i.e., a removal of the secondary ice increase, and thus a return of the glaciation to the real topographic situation. In consequence, an abrupt deglaciation took place with the result that the Tibetan plateau again became the most important heating surface of the earth's atmosphere. Assuming here, as in the initial stadia (see above), an ice thickness of at least 200 m at the snow line altitude, this would correspond – with regard to the remaining postglacial −3 °C – to a surface of the catchment area of only 12%, i.e., under recent climatic conditions (−0 °C) of 5%. This means that the glaciation would be less than at present, where nearly 2/3 of the isostatic lowering has already been rescinded (Figure 38, Graphs II and III).

During the Pleistocene, the schematized sequence of the Ice Age-triggerings by the Tibetan High Plateau and the cyclical interglacial re-warmings up to the current level of temperature, was as follows: (1) Tibet has been uplifted above the snow line (ELA) and glaciated. (2) The resulting reflection of the incoming subtropical radiation energy back into space led to the cooling-down of the atmosphere, to the depression of the snow lines and to the build-up of the Nordic inland ices. These lowland ices, located with their centres between 50° and 70° N, which were less energy-effective, obtained an extent of altogether more than 26 million km^2. (3) During the Quaternary a re-warming by ca. 2–3 °C (mainly in the northern hemisphere) took place, caused by the orbital variations (Croll, 1875; Milankovic, 1941), from which derived a global rise of the ELA by ca. 400–600 m. (4) In Tibet this rise of the snow line first led only to the melting of the marginal low outlet glacier tongues, whilst the inland ice remained on the plateau, so that the cooling continued. However, in the area of the Nordic inland ices, where the inclination of the surface was only insignificant up to its edges, the rise of the ELA caused a decisive and very important loss in the glaciation area amounting to many millions of km^2 (cf. Kuhle, 1987d). In consequence, the connected loss in albedo and the global gain in energy amplified the re-warming of the atmosphere. (5) Now this re-warming also gave rise to an increasing melting of the Tibetan ice. However, its complete melting was only possible because, during every glacial period, the plateau has again been pressed by the glacio-isostatic lowering (Figure 38) into a lower and warmer level. In the other areas of glacial inland ice (Andrews, 1970, and others) the glacio-isostatic lowering has also led to an accelerated interglacial melting-down and has thus contributed to the re-warming.

This study is to be brought to an end with the following objective consideration: supposing that Tibet has never

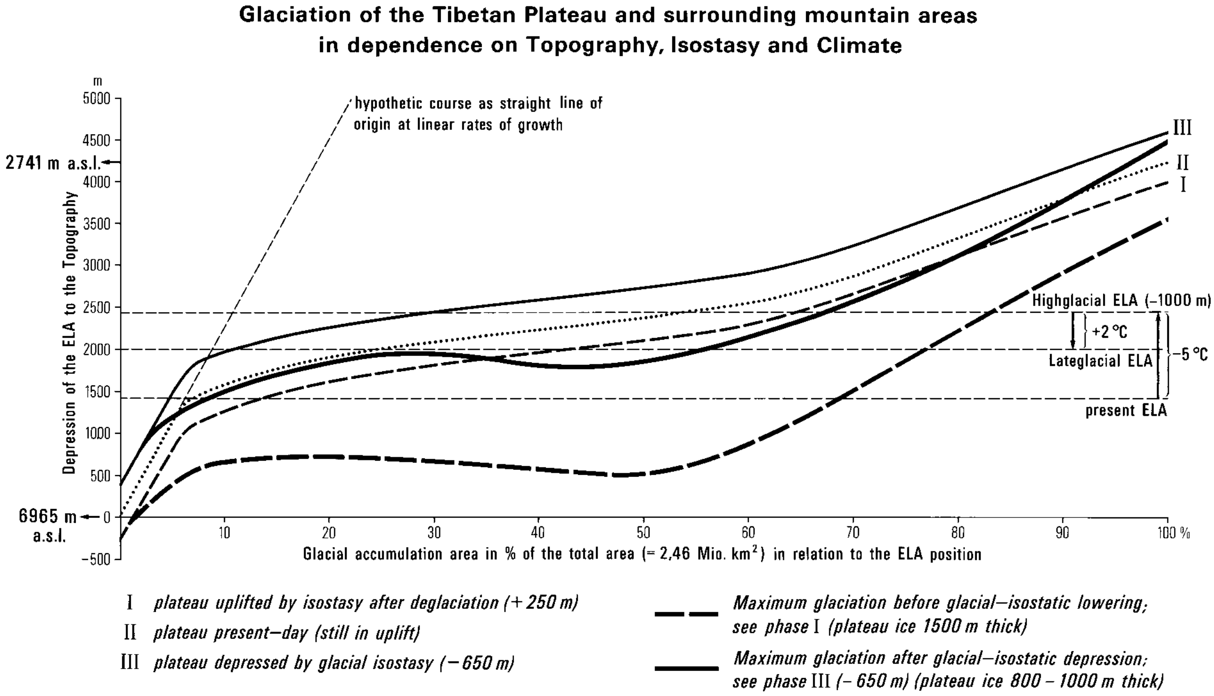

Figure 38. Topographically-controlled rates in surface increase of the glacier catchment areas in dependence of the relative amount of the snow line (ELA) depression. I: at an orogenic-isostatically uplifted plateau (+250 m); II: at the recent position of the plateau surface; III: at a glacio-isostatic lowering of the plateau surface (−650 m). The diagrams concern a total surface of 2 464 121 km^2, which for the calculation has been subdivided into 29 areas. The key points of the recent surface diagram concern the average maximum summit height (6965 m asl) and minimum height (2741 m asl) respectively, of the 29 areas.

been more extensively glaciated than at present – an interpretation which numerous authors have followed without any reservations up to only a few years ago – its current uplift of ca. 1 cm/yr (Chen, 1988) would raise the plateau within the next 60 000 years – even without a cooling as a result of changing parameters of the earth's orbit – over the modern snow line to such an extent that it might become totally glaciated. Thus, something would only happen in the future that the author already suggests for the past. But can something which is supposed to be probable in the future be improbable in the past? Or will we have totally to exclude the complete glaciation of Tibet as being proved to be physically impossible?

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Typical debris accumulation forms and formations in High Asia

A glacial-history-based concept of the origin of Postglacial debris accumulation landscapes in subtropical high mountains with selected examples from the Hindu Kush, the Karakoram and the Himalayas

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Abstract

An abridged version of a geomorphological inventory and typology of Postglacial debris accumulations in High Asia is presented, with selected examples from the Hindu Kush, the Karakoram and the Himalayas. The debris accumulations were surveyed in the course of four research expeditions lasting a total of ten months in selected valley systems of High Asia (the eastern Hindu Kush, the northwestern Karakoram, the Nanga Parbat massif (Pakistan), the Ladakh and Zanskar ranges, the Nun Kun massif, the Kumaon and Garhwal Himalayas with the Kamet, Trisul and Nanda Devi massifs (India) and in the central Himalayas with the Kanjiroba, Annapurna, Manaslu and Makalu massifs (Nepal)). The study areas being widely scattered, a supraregional comparison of the debris accumulations proved possible. The debris accumulations are considered in centre-to-periphery sequences from the mountain interior to the mountain fringes, and in vertical sequences, i.e. altitudinal zones, taking into account their topographical relationship to adjoining elements of the landscape. Supraregional and climate-specific types of debris accumulation are distinguished and it is recognized that the debris accumulations of the Karakoram and the Himalayas resemble each other more closely with increasing elevation.

The core of the study is the dominant role played by past glaciation in the formation of Postglacial debris accumulations in the high mountains of Asia. This glacial-history-oriented concept of debris accumulation stands in sharp contrast to previous opinions about the genesis of the debris accumulation landscape in the extreme high mountains of Asia. The study shows that at many places morainic deposits mask extensive portions of the valley sides up to several hundred metres above the valley floor. These moraines are the main debris sources and exert a strong influence on, or even suppress, the purely slope-related formation of debris accumulations. Resedimentation of morainic material in combination with additional talus delivery leads to numerous characteristic composite types of debris accumulations, which are here termed transitional glacial debris accumulations. Various stages in the transition from moraine to slope-related debris accumulations were observed, making it necessary to consider the evolutional element in the development of debris accumulations by taking into account both genetic series of debris accumulations and formations of debris accumulations. A significant proportion of debris accumulations are also due to collapse processes which result from pressure release at the valley sides after deglaciation and occur in the course of glacial trough valleys being transformed into more stable fluvial V-shaped valleys.

The residual morainic landscape has left debris accumulations that are basically similar in study areas of different climate – i.e. in the Hindu Kush and the Karakoram on the one hand, and the Himalayas on the other. The age classification of the debris accumulations was based on the location of the slope-derived debris accumulations in relation to the corresponding stages of glaciation.

Introduction

Postglacial debris accumulations in High Asia: A glacial-history-based concept of the formation of debris accumulations

During a study on the typology of Postglacial debris accumulations in High Asia it was established that many of the debris accumulations in the Hindu Kush, the Karakoram and the Himalayas are due to the resedimentation of morainic deposits. Especially in the semi-arid mountain regions, where the frequent occurrence of debris accumulations points to extremely intensive weathering processes, secondary debris production, i.e. the redeposition of glacial sediments, exceeds primary debris production in many places. The classic categories of debris accumulations – talus cones, alluvial cones, mudflow cones and related forms – apply only to a limited extent when classifying debris accumulations in High Asia. Here, a further category has been added: *transitional glacial debris accumulations as a typical index form of the secondary debris accumulation landscape*. This category comprises the transformation by slope processes of glacial deposits into composite debris accumulations of slope-derived and glacial material, a transition that may take as long as 10 000 years. The seemingly homogeneous, largely conical appearance of the debris accumulations causes them to be attributed overhastily to the above-mentioned three traditional categories of debris accumulations and often leads to a mistaken interpretation of their origin. Cone-shaped residual debris accumulations that have been *eroded out of the morainic material*, are similar in shape to talus cones; however, the point is that they are *erosional rather than depositional landforms*. Many valleys display a conspicuous disproportion between catchment size and the size of the debris accumulations. This apparent paradox can only be explained by taking into account the remobilizing of morainic material – an important component of debris accumulations – in the catchment areas. In addition, the Postglacial transformation of *glacially over-steepened trough valleys into more stable V-shaped valleys* results in many different *collapse-induced debris accumulations*. The mistaken identification of glacial deposits as slope-related debris accumulations is considered to be a major contributing factor in the controversy about the extent of the Last Glacial Maximum (LGM) and the Late Glacial in High Asia.

Study areas

The selected study areas lie along a 2500-km W–E transect spanning the arc of the Hindu Kush, the Karakoram and the Himalayas (27–37° N/72–88° E) (Figure 1). They comprise selected valley systems in the eastern Hindu Kush, the northwestern Karakoram, the western Himalayas (Nanga Parbat, Nun Kun massif, Garhwal and Kumaon Himalayas), eastern Karakoram, the Ladakh and Zankar ranges and the central Himalayas (Dolpo, Annapurna, Manaslu and Makalu massifs). The study areas have precipitation gradients ranging from perhumid (>5000 mm/yr) to arid conditions (<100 mm/yr) in the mountain valleys. The most dramatic variation in precipitation occurs at the main Himalayan Ridge, whose windward southern slope has the highest precipitation values in the study area, whereas its leeward northern slope has desert-like levels.

Current research

Up to now, debris accumulations and their classification in the mountains of High Asia – the Hindu Kush, the Karakoram, and the Himalayas – have been largely neglected, although they are common occurrences in the valleys owing to the extreme relief energy in these mountains. One of the earliest and also very precise descriptions relating to this topic was presented by DREW (1873) for study areas in the upper Indus river in Ladakh. More recent research has tended to pay more attention to mass movements than to associated deposits, i.e. many studies are primarily process-oriented – and therefore also application-oriented – rather than form-related. Brunsden et al. (1984) presented a fundamental study of talus cones in the northwestern Karakoram. Kuhle (1982, 143–147) described talus cones, mudflow cones and related debris accumulations as periglacial landforms in his monograph on the geomorphology of the Dhaulagiri-Annapurna-Himalayas. Fundamental work with very detailed comparisons on talus cones and talus slopes in Spitsbergen and Scandinavia was published by Rapp (1957, 1959, 1960a, b). For work on primary weathering processes, see Gerber (1963, p. 337), Hewitt (1989, p. 14), Goudie et al. 1984, p. 390), Whalley et al. (1984, pp. 525–627), Kuhle (1987, p. 20) and Hall (1998).[1] The extremely contrary opinions on the extent and timescale of glaciation in the Karakoram and Himalaya valleys (e.g. DAINELLI 1922–1934, de TERRA 1938, v. WISSMANN 1959, HORMANN 1974, DERBYSHIRE et al. 1984, HASERODT 1989, KUHLE 1989, 1994, 1996b) and the consequently very different views about the provenance of debris accumulations suggest that it is necessary to find criteria to distinguish between accumulations of glacigenic and primarily slope-related origin so as to be able to apply debris accumulations appropriately as palaeoclimatic indicators, and to avoid misinterpreting morainic deposits as purely slope-related or *vice versa*. Up to now, *moraine, slope-related and purely fluvial accumulations* have been treated *as separate features* in the literature. By contrast, the following study will show the extent to which *all three are interrelated* and describe which *typical composite debris accumulations* occur in the mountains of High Asia.

The interaction between the formation of postglacial debris accumulations and glacial history in the high mountains of Asia

The extent of glaciation during the Last Glacial Maximum and the Late Glacial, with its glacial valley shaping and legacy of glacial sediments, may be considered the most important supraregional geoparameter in the distribution of debris accumulations in the mountains of High Asia. It is the primary control of the distribution of Postglacial debris accumulations. The Late Glacial moraine relicts that are preserved in all the study areas and that mask the valley interior up to several hundreds of metres above the valley floor, were and are transformed by slope processes in many different ways during Postglacial time, thus producing a wealth of composite debris accumulations, the ‘transitional glacial debris accumulations’ mentioned above (Figure 2). They are often mistaken for purely slope-related debris accumulations. Especially in the middle valley sections, debris accumulation processes are influenced by a residual debris accumulation landscape of morainic material. The *dual structure consisting of Late Glacial morainic material at the base and overlying Postglacial debris deposits* plays a major role in debris accumulation typology. Secondary debris accumulations of redeposited morainic material as well as passive debris-accumulation formation, i.e. the dissection of a formerly intact morainic cover into cone-shaped debris

[1] Hall (1998) criticizes the excessive importance attributed to frost weathering processes and considers thermal stress to be a major form of weathering in areas of water shortage.

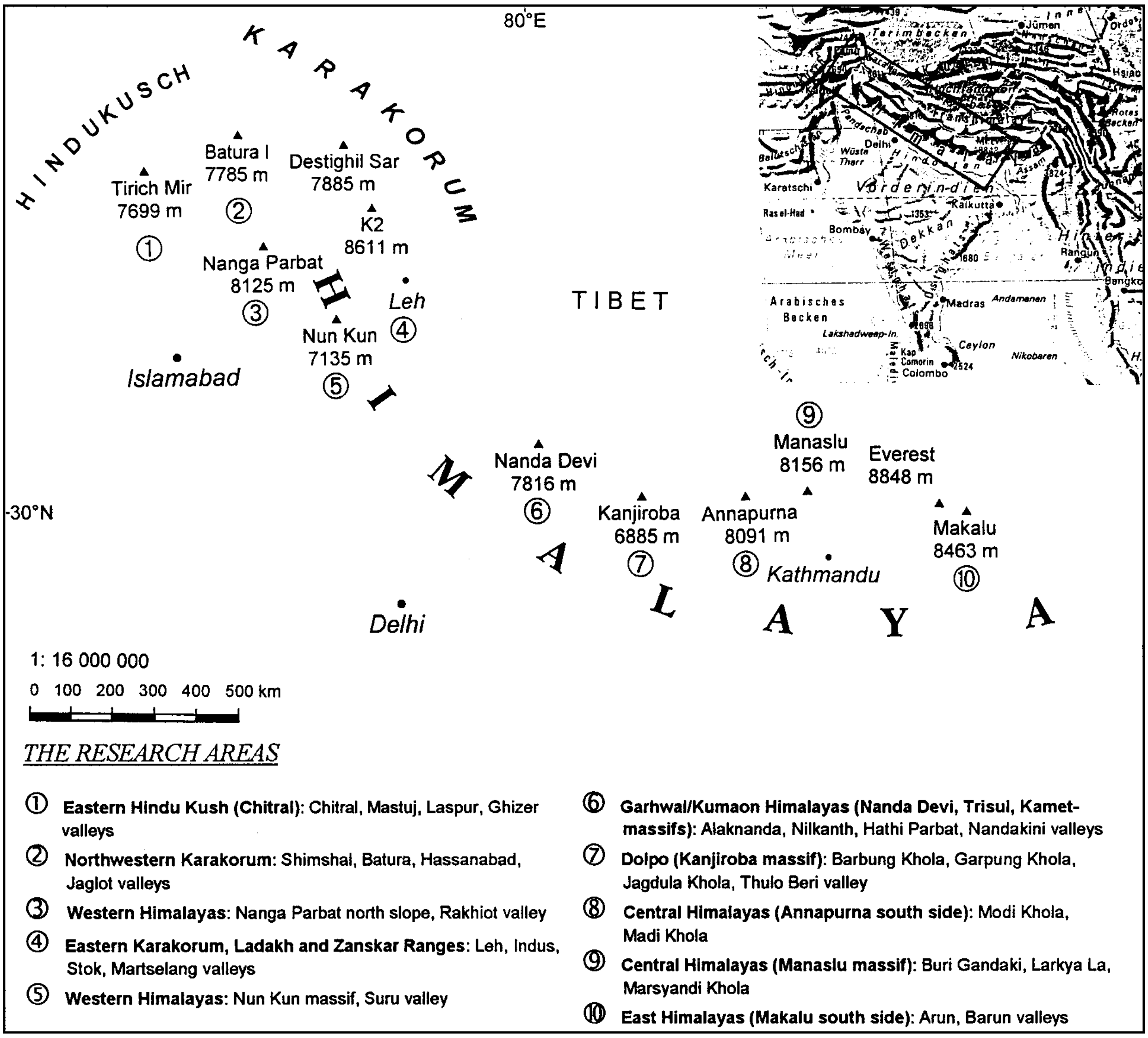


Figure 1. Location of research areas.

features, dominates in many parts of the mountains over primary debris accumulation.

Even in the arid mountain regions, where morainic deposits are particularly evident owing to the absence of vegetation, a possible glacial origin of the Postglacial debris accumulations has apparently not been taken into consideration, present climatic conditions being extremely unfavourable as regards glaciation.

Glacially influenced debris accumulations occur down to the low elevations of the study area, i.e. *well below 1000 m asl.* Glacial shaping of relief is responsible for most of the collapse debris accumulations. The results of studies on the distribution of glacially influenced debris accumulations do not confirm the minimalist estimate of the extent of glaciation in High Asia advocated by, among others, v. Wissmann (1959) and Hormann (1974). Rather, they confirm the evidence of glaciations and equilibrium line depressions of 1300 m and more in these high mountain regions reported by Kuhle (e.g., 1982, 1989, 1994, 1996b). The crux of these contradictory opinions on Quaternary glaciation in the high mountains of Asia (cf. Kick 1996; Röthlisberger, 1984) lies, among other factors, in the differing identifications of morainic material and debris of slope provenance. The age classification of debris accumulations is based on the glacier stages in High Asia proposed by Kuhle (1994, p. 260).

In principle, it should be noted that especially talus cones and talus slopes are better able to develop in glacial valleys than in fluvial V-shaped valleys for purely geometrical reasons connected with the concave shape at the base of the trough valley side. Pressure release and loss of support owing to melting ice lead to diverse collapse features on oversteepened valley sides. As though suddenly released from a mould, parts of the valley sides collapse after deglaciation and leave debris accumulations of catastrophic origin. There is a *direct link between glacier retreat and the formation of true talus accumulations*, as almost every historical glacier front vividly demonstrates.

The pattern of debris accumulation distribution is closely related to the extent of modern glaciers. Despite high aridity, the debris accumulations accompanying the glacier stretch

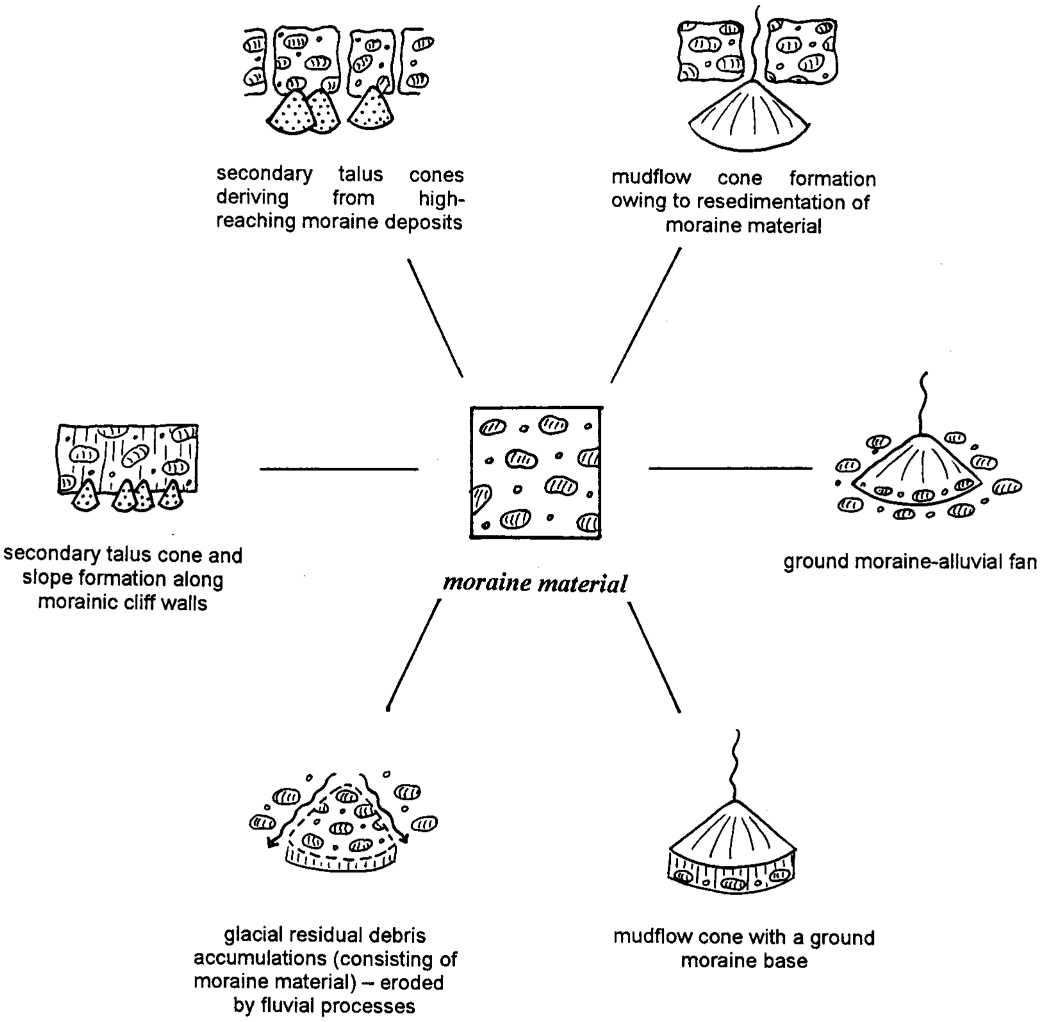


Figure 2. Some examples of transitional glacial debris accumulations deriving from moraine material.

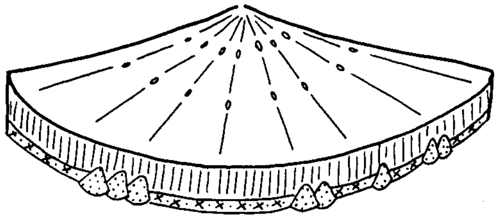
more than 1000 m lower (down to about 2500 m) in the northwestern Karakoram than on the southern slopes of the Himalayas. Depending on the type of glacier and the location of the glacier snout in the valley, specific ice-marginal debris accumulations are formed. Particularly in the Kumaon and Garwhal Himalayas, the apex areas of talus cones have been modified by steep hanging glaciers during Postglacial times. A festooned pattern of moraines is visible in the upper to middle parts (the Alkanada, Nilkanth and Hathi Parbat valleys).

The shift of the altitudinal zones of debris accumulation during the ice ages and its effect on the build-up of debris accumulations

In contrast to the present-day distribution of glaciers, the tributary catchments were also ice-filled during the Last Glacial Maximum, sealing off both potential debris-supply areas and potential accumulation areas, so that the formation of mudflow and alluvial cones was greatly impeded at this time.[2] Only smaller glaciers, like those at the end of the Late Glacial – ensure an exposed relief and the production of sufficient debris by the ice-free valley sides to enable debris accumulations to form along the glacier (Figure 4). These Late Glacial debris accumulations, which were modified by slope processes in Postglacial times, characterize the mountain environment today. Consequently, when inland ice covers the entire relief, debris accumulations – apart from ground moraine – tend not to form owing to the lack of source areas. This example demonstrates that in the laws of geomorphology there are no linear increases in the chains of cause and effect, but that from a certain stage of development onwards it is ‘leaps’ and ‘points of reversal’ that control landscape processes and accumulations when a factor – in this case, glaciation – is amplified.

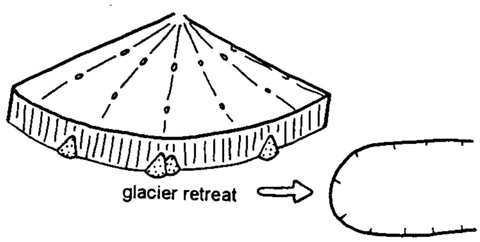
In general, both the periglacial region and the altitudinal zone of fluvial activity were greatly limited by the extensive glacier cover in humid areas during the Last Glacial Maximum, and the conditions necessary for debris accumulation were not promising. Present conditions are very favourable

[2] A most impressive recent analogy to debris accumulation conditions during the Last Glacial Maximum is the Baltoro – and in places also the Biafo – glacier in the Muztagh–Karakoram, where we observed a conspicuous paucity of debris on the valley sides along the glaciers. The glaciers themselves almost resemble Ice Age glaciers in size.



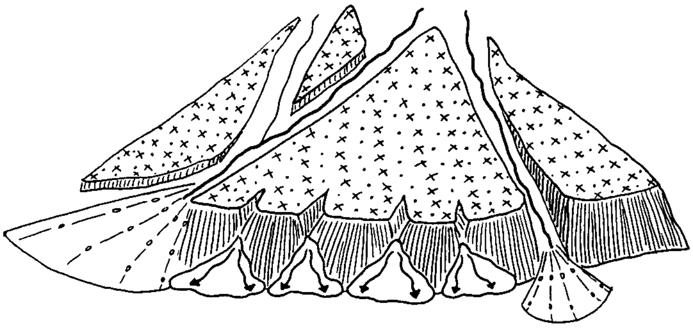
A

Dual debris accumulation structure of a Late Glacial ground moraine base overlain by fluvial debris deposited during Postglacial time.



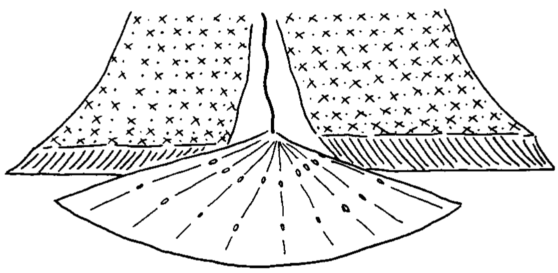
B

In former times the debris accumulation was deposited against the glacier as kames. The distal cliff walls can be maintained after glacier retreat.



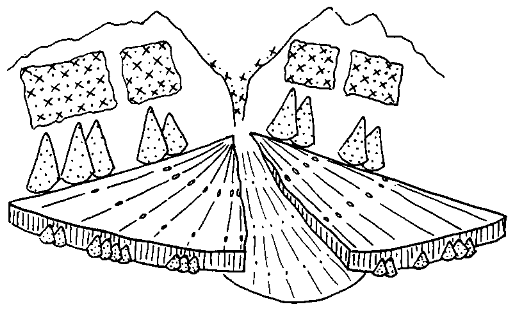
C

Residual debris accumulation consisting of ground moraine, which covers the valley flanks up to several hundred metres above the valley bottom line and which is gradually transformed into a fluvial debris accumulation. The conical apex which begins at the mountain spur – and not below a gully - is subsequently eroded out of the ground moraine material by fluvial processes, therefore it resembles a purely fluvial debris accumulation. The tributary gully rivers deposit mudflow-like debris accumulations consisting mainly of resedimented moraine material.



D

The ground moraine covering the main valley flanks is incised by tributary rivers. The fluvial deposits are composed to a great extent of resedimented moraine material.



E

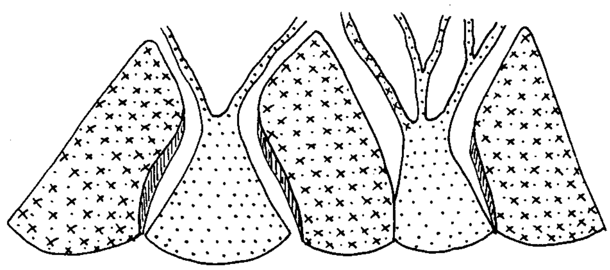
Compound, primary fluvial debris accumulation: The debris accumulation receives a high debris supply from the lateral valley flanks. These debris accumulations often derive from displaced high-level moraines. Also the tributary valley is filled up with moraines. The distal cliff part of the sediment cone may be lined by secondary talus slopes and heaps.

morainic material fluvial debris accumulation talus cones and slopes distal cliff edges

Figure 3. Selected examples of typical transitional glacial debris accumulations in the Hindu Kush and Karakoram.

F

Secondary talus cones and talus slope formation deriving from high-level moraines. Their surfaces are often reworked by mudflows, indicating their high fine material content.



G

Residual cone-shaped debris accumulations in ground moraine: These are the remnants of a formerly closed moraine mantle, which is eroded by Postglacial slope processes in a cone-shape. They are in their present shape erosion not accumulation forms.

Figure 3. Continued.

for debris deposition, the lower limit of glaciation of the side valleys being comparatively high.

How to trace the course of deglaciation in a longitudinal valley profile by means of debris accumulations, and do typical sequences of debris accumulation exist?

After deglaciation, debris accumulations were bound to build up *successively from the former to the recent glacier location*, so that older debris accumulations are found downvalley and the youngest talus cones near the glacier termini. Following the *principle of correlating debris accumulations with glacier stages* one might assume that the thickness or the size of the debris accumulations would increase downvalley, the formation period having been longer. However, *the progressive filling of the valleys with debris after deglaciation cannot be proved by means of the size of the debris accumulations* over a lengthy longitudinal valley profile, since in this relationship the *type of catchment* of the side valleys is *more important* for the formation of debris accumulations and the catchments vary greatly along the longitudinal valley profile. Furthermore, debris accumulations develop intermittently, preferentially at relief instabilities, and therefore *not in a homogeneous manner*.

In the direct vicinity of the glacier, however, where the catchment areas and the conditions of deposition are more uniform, the experimental setup is more appropriate. And here observations show that debris accumulations increase in size with increasing distance from the recent glacier terminus and must be older downvalley. In qualification, however, it must be said that the size differences of the debris accumulations will level off as they continue to develop, and a sort of 'climax stage of debris accumulation development' will be reached (debris accumulations in the Momhil valley downvalley from the end of the Momhil glacier tongue to the confluence with the Shimshal valley: using glacial history to obtain a chronology of debris accumulations photo 20).

Further, it should be taken into account that debris accumulations have been deposited in the shape of kames by slope processes on Late Glacial glaciers and in their lateral moraine valleys, and that many of the debris accumulations present today are 'subsidence debris accumulations' consisting of a mixture of slope-derived and morainic materials that lost their support and collapsed after glacier retreat. That means, on the one hand, that *the material* of these polygenetic debris accumulations *may be considerably older than the original form* that developed during Postglacial time. On the other, the post-deglaciation situation was by no means a *tabula rasa*; rather, the dimensions and mode of deposition of morainic material substantially influence the Postglacial build-up of debris accumulations.

Transitional glacial debris accumulations and passive formation of debris accumulations

In the study areas a variety of secondary debris accumulations have evolved out of primary debris accumulations, and among such 'mothers and daughters' those debris accumulations that are similar in form and origin should be distinguished from those that differ. Another term for the former is 'regenerated debris accumulations' (e.g., stacked ice avalanche cones, Photo 30). The latter are much more frequent and occur especially when morainic deposits shift (e.g., talus cones formed beneath higher-level morainic deposits), they are also found in fluvial debris accumulations (basal talus cone formation at the cliff faces of mudflow-alluvial cones). Secondary formation of debris accumulations is particularly evident in dry areas. Particularly at elevations between 1500 and 3500 m, the decisive factor for debris supply is not bedrock but the type and distribution of the moraine lining of the valley flanks.

In their genetic evolution, many of the debris accumulations are in a transitional phase between originally glacial depositional processes and nival, fluvial and purely gravitational processes of deposition and denudation. Such debris accumulations are termed 'transitional glacial debris accumulations' and should be subdivided into 'secondary debris accumulations' and 'residual debris accumulations'. Whereas the former may consist of slope-derived and glacial material, the latter term refers to the relicts of glacial de-

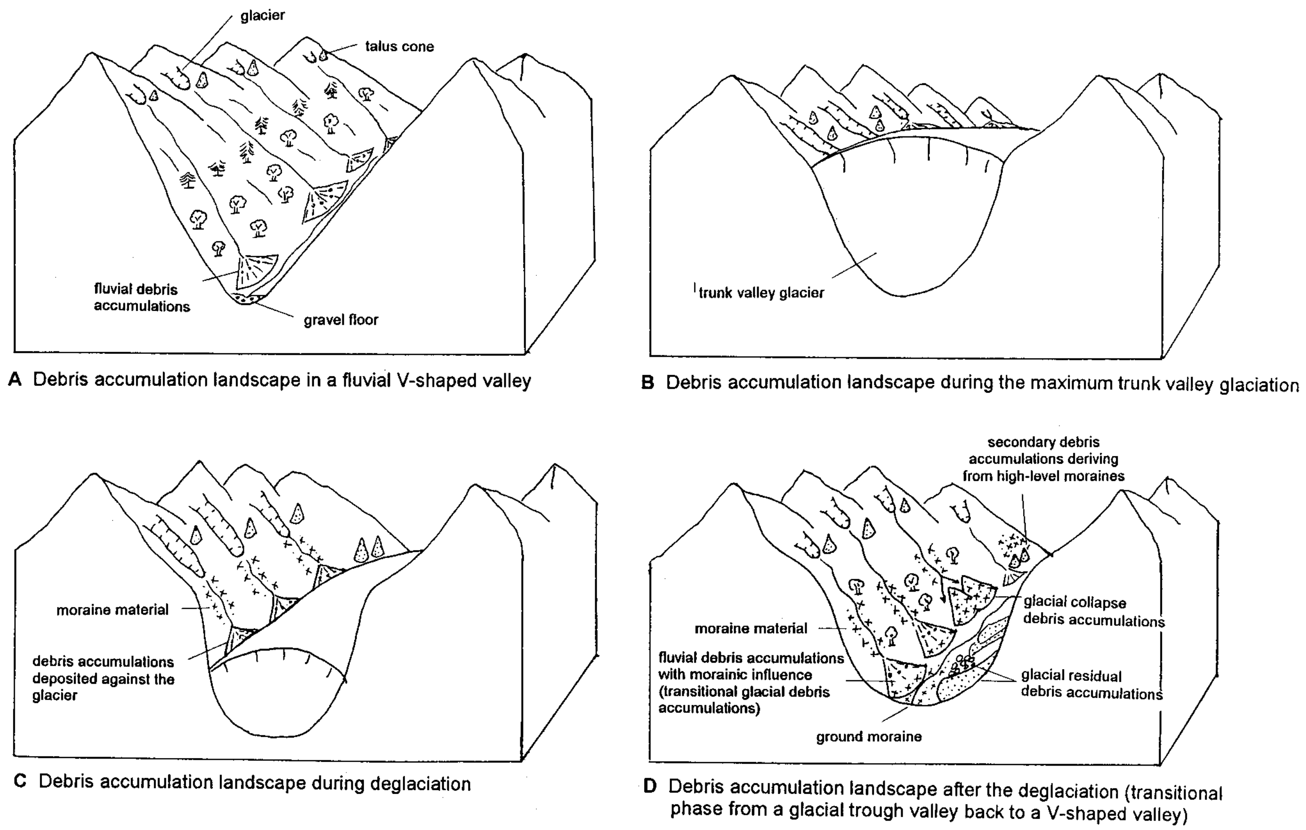


Figure 4. Debris accumulation landscape during the transformation of a fluvial V-shaped valley into a glacial trough valley.

bris accumulations that were carved out by Postglacial slope processes. This is a *passive debris accumulation formation*, i.e., the conical debris accumulations are erosional remnants of a formerly continuous morainic cover on the valley sides. The most conspicuous feature of this passive formation of debris accumulations is that the cone tips do not connect with a feeder channel, but are carved out of the loose material by lateral gullies; in a manner of speaking, the cone tip is 'dead'. At the proximal area of the cone, where the ground moraine clings to the valley side, these moraine-derived debris accumulations have considerably steeper inclinations than purely fluvial debris accumulations of similar appearance.

The *dual debris-accumulation structure* – ground moraine base and fluvial debris from the side valleys – is easily recognizable at the exposed outcrops of the fluvial debris accumulations in the dry high mountain areas. The moraine relicts are being gradually destroyed by Postglacial slope processes and covered by slope-derived and fluvial debris, so that these debris accumulations possess a *morainic core* that is no longer recognizable today.

In addition, the debris accumulations that were deposited against the glacier may be subdivided into *direct* and *indirect ice-contact debris accumulations*. In the former case, the debris accumulation was deposited directly against the glacier, in the latter it may have been built up against a lateral moraine. Although the distinct conical shape of many debris accumulations has the advantage of offering an easy description of these features, it also has a disadvantage when it comes to identifying their origin. *Convergent evolution* often meant that cones that had later been carved out of the loose material were not recognized as such, i.e., an erosional accumulation was *mistaken for* a depositional form.

The following categories of typical 'transitional glacial debris accumulations' were identified in the study area (Figures 2 and 3):

(a) Dual debris accumulation structure of a Late Glacial ground moraine base overlain by fluvial debris deposited during Postglacial time.
(b) Conical residual debris accumulation carved out of Late Glacial ground moraine by fluvial processes during Postglacial time. Situated at the mouth of a steep juvenile tributary valley. Similar in form to a fluvially deposited debris accumulation.
(c) Further development of type b) towards dominantly fluvial deposits. An alluvial or mudflow cone (partly resedimented from morainic material), laterally framed by residual moraines on the valley sides.
(d) Composite fluvial debris accumulations: the mudflow-alluvial cones may have been formed by the resedimentation of moraine-filled side valleys. They receive lateral debris from talus and mudflow cones that may also have been formed out of redeposited morainic material attached to the valley sides. The cliff faces of these composite debris accumulations are often reworked into secondary talus slopes.
(e) Secondary formation of talus slopes beneath high-reaching morainic deposits on the valley sides.
(f) Moraine mantle covering the valley side. In the process of steady redeposition into a secondary talus slope.

(g) Residual conical debris accumulations, similar in shape to primary true talus cones but carved out of a ground moraine mantle adhering to the valley side.

It should be emphasized that the majority of debris accumulations are diverse transitional or composite forms. In the final analysis it is the dominant geomorphological processes that govern the type of debris accumulation. This means that it is of great importance to take into account the *evolutional element*, expressed in the form of *genetic series of debris accumulations*. A rigid classification system is less of a help than a hindrance in attempting to understand the formation of debris accumulations. In principle, composite forms of debris accumulation are more typical than a debris accumulation due to one process only. The mere fact that debris transport often passes through various altitudinal zones explains the existence of many composite forms of debris accumulation. In particular, the transition from an 'oversteepened ice-age debris accumulation landscape' to a Postglacial 'adjustment debris accumulation landscape' results in polygenetic debris accumulation forms.

Regional–empirical section

The debris-rich, arid to semi-arid high-mountain areas of mainly moderate to extreme relief energy: the eastern Hindu Kush

The study area in the eastern Hindu Kush (35°30′–36°30′ N/71°30′ E–73°30′ E) is crossed by the main Hindu Kush chain from NW to SE, of which the highest catchments are Tirich Mir (7706 m) and Noshag (7485 m). Directly to the south and oriented parallel to the Higher Hindu Kush is the Lesser Hindu Kush, with elevations of only 6550 m. The maximum vertical distance, 6000 m, is reached at the eastern flank of Tirich Mir towards the Tirich valley (Gruber, 1977, p. 102). The equilibrium line runs between 4800 m in the SE and 5300 m in the NW of Chitral (Haserodt, 1989, p. 71). The Hindu Kush has a central crystalline zone with strong granite intrusions, which build up Tirich Mir and Buni Zom (Photo 1). In valley locations slate is the main rock (Chitral and Lun slate), continuing the Karakoram slate series occurring further to the east (Searle, 1991, p. 86). Being particularly prone to weathering, it provides favourable conditions for the formation of debris accumulations. Generously dimensioned valley receptacles with broad debris accumulations like those of Drosh (1440 m) and Chitral (1475 m) alternate with confined stretches like those downvalley from Buni (1900 m). The debris accumulation landscape in the valley systems of the Hindu Kush is chiefly characterized by glacial debris deposits. High morainic deposits blanketing the valley slopes safeguard the bedrock from atmospheric influences and protect the slopes from retreat and from the formation of autochthonous debris accumulations. The structure of fluvial debris accumulations is also substantially influenced by the resedimentation of morainic deposits.

Purely slope-derived talus cones and slopes and resedimented residual glacial debris accumulations

This semi-arid mountain landscape is dominated by bare debris accumulations, i.e. debris accumulations that are almost devoid of vegetation and in places only slightly consolidated.[3] Talus cones and slopes are among the commonest depositional accumulations in the landscape of the eastern Hindu Kush. Indeed, they dominate the landscape between 2000 and 4500 m (Photo 1). These bedrock-derived debris accumulations should be distinguished from the secondary debris accumulations later evolving from unconsolidated deposits. The widespread distribution of the bare debris accumulations ranging from high elevations to valley sites, i.e. over a vertical distance of up to 4000 m and more, already implies that *one climatic characteristic alone cannot be responsible for debris production*. The true talus slopes caused by frost weathering at high elevations interlock with the talus slopes of medium elevations, whose formation may also be due to temperature and chemical weathering and especially to the redeposition of morainic material.

Example 1: The moraine-influenced true talus cone on the orogr. right-hand side of the Mastuj valley. The base of the true talus cone with its fluvial catchment area on the orogr. right-hand side of the Mastuj valley, downvalley from Mastuj, is located at an altitude of 2100 m (Photo 2). The vertical height of the talus cone measures some 400 m, and it consists chiefly of plate-size rocks. In summer the approximately 3000 m high ridges are snow-free. The talus cone shows minimal traces of reworking so that we are apparently dealing with a pure form of talus cone. The rock fragments are homogeneously distributed as to size, which is also true of the nearby talus cones in the Mastuj valley. The linear erosional forms on the talus cone surface are mostly due to resedimentation of the debris. The product of the mass movements resembles that of a mudflow with the typical lateral debris ridges and terminal debris lobe. Since, however, no allogenic material is transported from a potential catchment area, an essential mudflow condition is missing in the strict sense. Hence these accumulations are termed 'mudflow-like debris flows'.

The isolated talus cone is embedded in a cavity of the metamorphic rock. The face of the outcrop is 10 to 30 m high and is reminiscent of a rockslide event that could have been triggered by glacial reworking of the bedrock.[4] The debris accumulation rests on a glaciofluvial terrace. The proximal section of the talus cone is already close to the line of the mountain ridge, so the slope section is approaching the stage of a complete frost debris slope. The valley slope already

[3]A distinction should be made between the bare talus slopes whose lack of vegetation is due to climatic reasons only and those on which trees are unable to find a hold because of active debris deposition from the catchment area. The talus slopes in the Hindu Kush and Karakoram are often strongly cemented owing to ascending solutions – especially in limestone areas – and thus attain a high degree of stability.

[4]Such collapse structures were often sighted during fieldwork in the Braldu valley (Muztagh–Karakoram) in 1997. They always occurred in combination with other glacial indicators (moraines, erratics at high elevations) at the mouths of side valleys, so that the collapses cannot be solely due to structural weaknesses of the bedrock.

has such a considerable debris cover that a specific catchment area is no longer present. The point of reversal from a catchment to an area of accumulation is missing.

Immediately up- and downvalley, Late Glacial morainic deposits adhere to the valley sides. In contrast to the talus cone, these deposits show strong gullying. In addition, fluvial redeposition is causing the slope moraines to turn into cone-shaped secondary debris accumulations.

Owing to the high clay content of the morainic material, saturation turns the base into a viscous flow. These secondary debris accumulations already represent the initial transitional form between glacial debris accumulations and debris accumulations that are later identifiable only as slope-derived. Only the high fine material content of the features termed 'moraine-influenced debris accumulations' or 'transitional glacial debris accumulations' serves to indicate their glacigenic origin.

Taking into account the lateral morainic material and the glacially polished rockflank that tends to collapse after deglaciation owing to pressure release, this *apparently solely slope-derived talus cone turns out to be a glacier-induced debris accumulation*.

Example 2: Moraine-influenced talus cones on the orogr. left-hand side of the Ghizer valley: residual and secondary debris accumulations. Now let us turn our attention to a debris accumulation on the orogr. left-hand side of the Ghizer valley, east of Shandur pass, at an altitude of 2915 m (Photo 3). The fluvial catchment area of the valley side reaches some 500–700 m above the valley floor. What is remarkable about this craggy slope is that some of the gullies are filled with light-coloured debris. The main gullies supply darker debris, similar in colour to the bedrock and breach the lighter-coloured moraine cover. This debris cover, only relicts of which have been preserved, is a moraine blanket that is being modified by slope processes. This results in, first, slope-related depositional forms, partly consisting of resedimented morainic material, and second, purely morainic debris accumulations carved out by slope processes. That is, residual morainic, approximately conical debris accumulations remain beyond the slope gullies. A characteristic feature of these composite forms of debris accumulation is that the proximal part of the cone does not lie directly beneath the feeder gully but much further downslope. This downslope displacement of the cone apex is due to channelling of the debris by morainic material. In this way the composite true talus cone assumes a waisted shape in front view.

Example 3: Glacially induced collapse debris accumulations in the Laspur valley. On the orogr. left-hand side of the Laspur valley we find a good example of glacially induced collapse debris accumulations (Photo 4). On the inner slope of a valley bend at 3200 m, composite true talus slopes have formed at the foot of a clearly glacially polished rock flank. They are graded according to rock size. The glacially oversteepened rock flank became unstable after deglaciation, and collapse processes were the result. Upslope, the proximal parts of the cones are still adjoined by strongly oversteepened slope sections in metamorphic rock.

Fluvially influenced debris accumulations: mudflow cones, alluvial cones, and transitional glacial debris accumulations

In the study area of the Hindu Kush mudflow and alluvial cones and related debris accumulations tend to occur at elevations between 1400 and 3600 m (Photos 1, 5 and 6). The spatial distribution of true talus cones, alluvial cones and mudflow cones displays an almost *axial symmetry in the altitude range*. The *optimal distribution area* of both debris accumulation forms lies at *intermediate altitudes between about 2000 and 3000 m*. Above this zone true talus cones are in the majority, their formation being chiefly due to weathering processes and avalanches. They mostly cover the slopes and thus require a small depositional area. With increasing elevation, the fluvially influenced debris accumulations slowly decrease, and their upper limit of distribution is higher than about 3700 m. This is where the shallow, nivally influenced mudflow cones of the periglacial region occur, being able to develop freely in pass locations. Below 2000–3000 m the distribution of true talus cones decreases. The altitudinal distribution of the modification of slope-derived debris accumulations by morainic material or secondary forms evolving from them, is related to the extent of glaciation and the depositional conditions of the morainic material. Only *below the equilibrium line can morainic material be released* by the glacier. In the lower Chitral valley, kames were observed up to a base level of 1600 m. Moraine-influenced debris accumulations occur between altitudes of 1400 m and at most 4500–5000 m, with a distribution maximum of 2000–3000 m. In the case of formerly *unglaciated mountains* these broad mudflow and talus cones may be considered to be *allogenic with regard to this altitudinal zone*.

Example 1: The complementarity of catchment size and the size of moraine-influenced debris accumulation types in the Yarkhun, Mastuj and Laspur valleys. The Yarkhun, Mastuj and Laspur valleys are dominated by broad sediment cones, sometimes more than 100 m deep, and more than 1 km in radius (Photo 7). Huge mudflow cones have built up, chiefly in confined stretches of valley. What is remarkable is their small-scale, fluvially influenced catchments which, at 4500 m, do not even extend above the present-day equilibrium line. In many places it is almost impossible to comprehend where the enormous quantities of debris required to build these huge accumulations came from. The solution would appear to be that these are either ancient forms or the products of resedimentation and the present removal of morainic material. The further one proceeds up the Mastuj valley and its continuation, the Yarkhun valley, the shallower the alluvial and mudflow cones become (Photo 5). Since the debris accumulations are different in size but have similar catchments, their decreasing depth can theoretically be correlated with progressive deglaciation.

The catchment areas of the large alluvial and mudflow cones are surrounded by elevations of up to 5000 m at their valley heads. Depending on aspect, they are located either just below the equilibrium line or just touching the snowline border zone. Hence the high elevations are mostly unglaciated or exhibit relics of rock glaciers at the present time. During the Last Glacial Maximim and Late Glacial, however, these catchments were located up to 1000 m below the equilibrium line. Some of these tributary valleys contained short, steep hanging glaciers. The steep headwalls of the catchments suggest that these could have been avalanche-fed glaciers, which are characterized by a high debris supply.

During the Late Glacial glaciation the tributary valleys were hermetically sealed off by the trunk valley glacier, as long as they were not themselves glaciated and had a glacial link with the main trunk glacier. The debris masses produced by the tributary valleys were deposited up against the glacier (direct ice-contact debris accumulations) or against the outer slope of the lateral moraine (indirect ice-contact debris accumulations), unless the glacier was accompanied by a lateral moraine valley where the debris accumulations could develop in fan-like or conical shapes. Because of the glacier barriers at the valley mouths the debris accumulations were very dense and very high. If the supply of debris is higher than the height of the glacier flank, debris begins to accumulate on the glacier surface. This occurs especially in the short steep tributary valleys whose volume is rapidly exhausted when debris production is high.

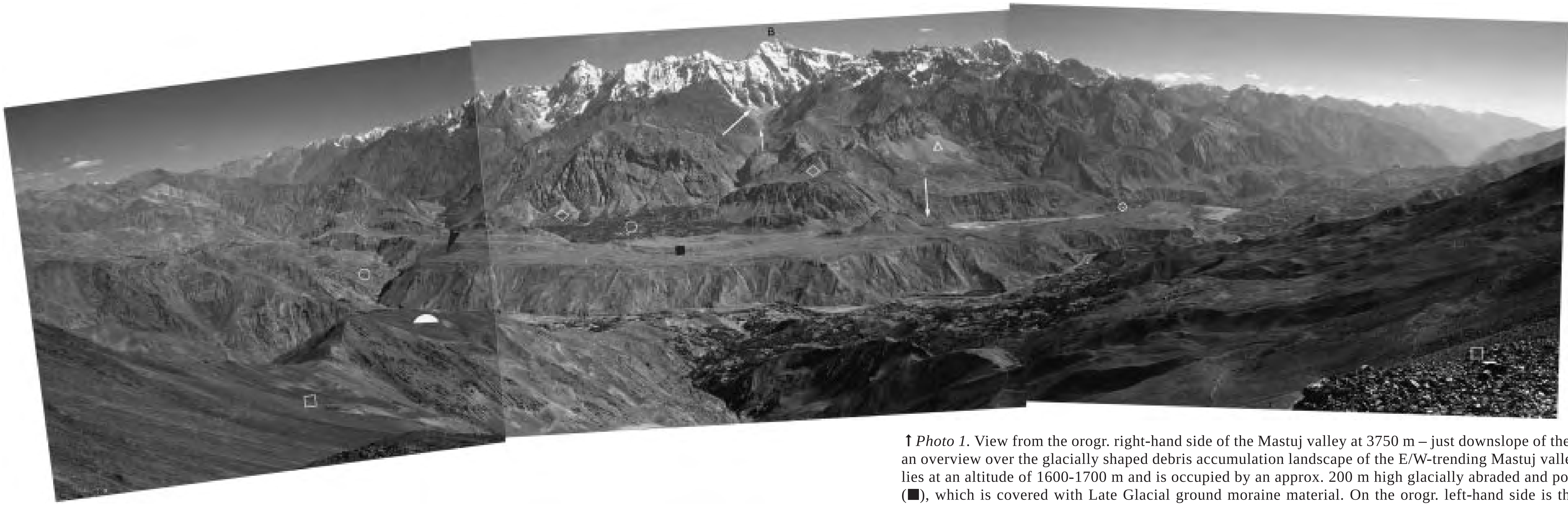
In the course of deglaciation these ice-supported glacial debris accumulations were gradually released, like a cake from a baking tin. After the supporting wall of the glacier is removed, the debris accumulation is able to preserve its shape and its steep walls, but eventually it will collapse. At present fluvial undercutting is helping to keep the walls steep. Thus the present-day alluvial cones and mudflow cones should be considered to be multiphase landforms. They are being both incised and built up by fluvial processes. Here, *accumulation and erosion* are *synchronous processes*. The original shape, the ancient accumulation, is being permanently modified.

At 2450 m in the lower Yarkhun valley, the fluvial debris accumulations have low side walls so they merge almost accordantly into the debris-covered floor of the trunk valley (Photo 5). The debris accumulations are alluvial cones containing morainic debris. The cone surface is very regular and almost elongate. At the orogr. right-hand side of the Yarkhun valley several hundreds of metres high, strongly gullied morainic deposits are notable (Photos 5 and 6). Their remobilization by mudflows, rockfalls and slides contributes to the build-up of the alluvial cone. In places, the moraines clinging to the valley walls are already disintegrating into debris accumulations resembling mudflow cones. Elsewhere, the morainic deposits are being displaced, forming secondary dry alluvial cones. The disintegration of the morainic deposits occurs in the interference zone of the neighbouring mudflow-alluvial cones – in the blind corner, so to speak, of the primary accumulation of adjacent cones – so that the mudflow-alluvial cones are increasingly coalescing into compound mudflow-alluvial cones (Photo 5). At the present time, secondary formation of debris accumulations in the interference zone is almost more active than that of the mudflow-alluvial cone itself.

Example 2: The dual structure of ground moraine base and overlying fluvial debris in the confined valley between Mastuj and Buni and in the lower Laspur valley. Like the Hunza valley in the northwestern Karakoram, the wider stretches of the Mastuj valley below Mastuj (2279 m) contain a complex, extensive depositional landscape of glaciofluvial terraces, alluvial cones and mudflow cones with a morainic influence. Many of these debris accumulations have ground moraine bases. The adjacent valley sides also used to be covered by morainic deposits which slope processes have resedimented until their origin is no longer recognizable. Downvalley from Mastuj a conical deposit built up from the orogr. right-hand side of the Mastuj valley with a cliff face some 60–80 m high occupies almost the entire main valley floor (Photo 7). Its base consists of ground moraine, the younger upper part of the debris accumulation comprises fluvial deposits from a small catchment that reaches an elevation of only 4000 m. Here too, the mudflow alluvial cone is laterally framed by talus cones and talus slopes. The dual structure of the fluvially modified debris accumulation of the tributary valley mouths of ground moraine and fluvial sediment layers may be regarded as a highly typical geomorphological phenomenon in the eastern Hindu Kush and northwestern Karakoram.

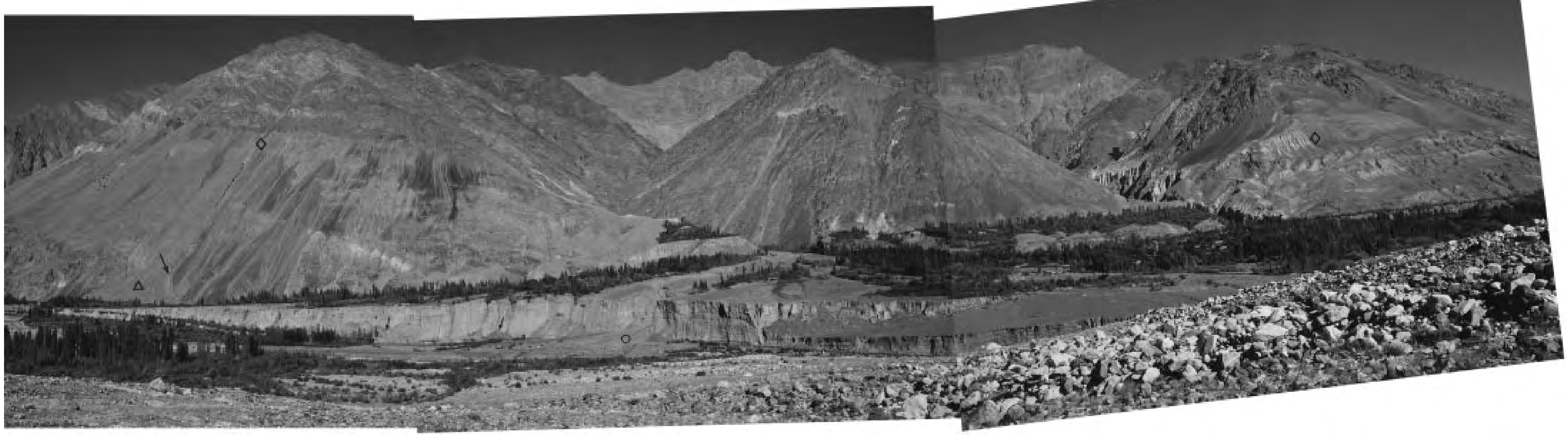
Example 3: Moraine-derived debris accumulations in the valley section of Drosh in the lower Chitral valley. In the valley section of Drosh (1400–1500 m) in the lower Chitral valley, up to 300-m-high, kame-like moraines edge the valley flanks (Photo 8). Their reddish colour distinguishes them clearly from the bedrock. That these are allochthonous debris accumulations is evident from the fact that their tips begin in the bedrock *next to the upslope gullies.* The valley side is scarcely higher than 3000 m asl. The moraines are being dissected into conical shapes by fluvial processes. At the base, lacustrine sediments up to several metres deep are interbedded in these glacial deposits. In places, the valley floor is covered by ground moraine. Thus the debris accumulation landscape is dominated by glacial deposits. Purely slope-derived debris accumulations are few. At this altitude, contemporary debris supply is very low, mainly resulting from the resedimentation of glacial deposits. Especially the alluvial cones that breach the moraines formerly sealing off the tributary valleys, consist mainly of glacigenic debris.

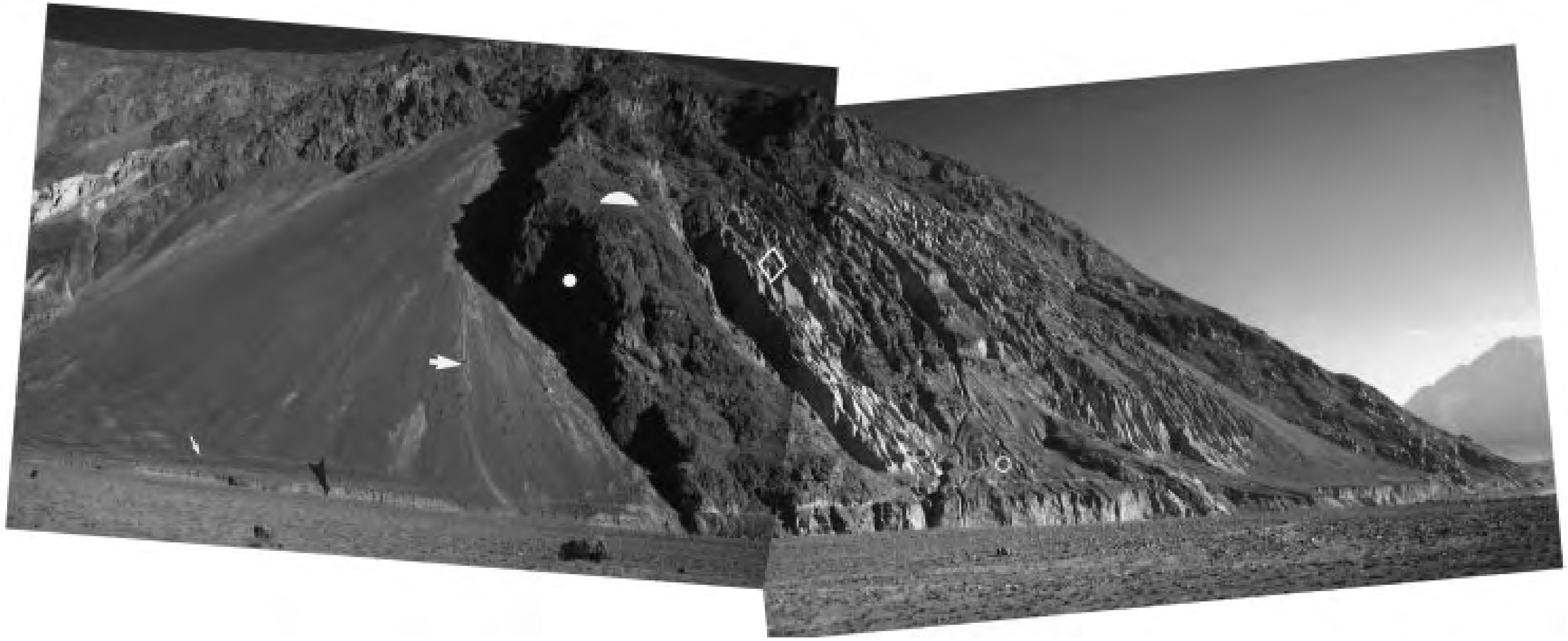
When assessing debris accumulations today, we should remember that the *catchment areas* may *have changed their characteristics*, e.g., *from glacial to nival*, within the fluctuation range of the equilibrium line shift during the Last Glacial Maximum and Late Glacial period. Assuming a Late Glacial equilibrium line depression of 1100 m, the equilibrium line in Hindu Kush was located at about 4000 m or lower. That means that the catchment regimes of the peaks,



↑*Photo 1*. View from the orogr. right-hand side of the Mastuj valley at 3750 m – just downslope of the Sani pass – giving an overview over the glacially shaped debris accumulation landscape of the E/W-trending Mastuj valley. The valley floor lies at an altitude of 1600-1700 m and is occupied by an approx. 200 m high glacially abraded and polished rock plateau (■), which is covered with Late Glacial ground moraine material. On the orogr. left-hand side is the NW-facing Buni Zoom massif (B), at 6500 m the highest catchment area. Only a small part of the summit region rises above the equilibrium line at about 5000 m, so that in view of the semi-arid climate conditions are favourable for debris production and deposition. Avalanche talus cones (↗) nourish a gradually starving rock glacier (↑). At the valley flanks autochthonous, unconsolidated true talus slopes (△) alternate with glacial, kame-like sediments (◇). Large mudflow-alluvial cones (○) derive from the catchment areas, which are connected with the lower valley regions over relatively short distances. All the cones are now under cultivation. The mud flow-alluvial cones dictate to a large extent the course of the main valley river, which is pushed aside to the opposite valley flank of the central rock plateau. At these locations the rock plateau is cut back in a semi-circle (↙). A thin debris mantle (□) with slight soil development, which is at this altitude already governed by periglacial processes, covers the glacially polished valley flanks in the foreground (◓). (→) shows the locality of a slate flow (Schieferfliessung). (Photo L. Iturrizaga, 23 September 1995.)

↓*Photo 6*. Further downvalley a further fluvially deposited debris accumulation is present. In the central part the mudflow-alluvial cone is deeply incised by a discharge channel, which accumulates a secondary alluvial fan (○) at the Mastuj gravel floor. The distal escarpment, which is several decametres high, is divided into various earth pillars and is lined by secondary debris heaps (↓). The sickle-shaped incisions in the distal cone section may be caused by the unregulated runoff of surplus irrigation water of the oasis settlement. However, they occur also on sediment cones, on which no settlements have been built. At the sides the mudflow-alluvial cone is surrounded by talus slopes (△), part of which have been strongly reworked by mudflows (↘). Therefore the mudflow-alluvial cone also receives a small supply of debris from the adjacent slopes. The talus slopes represent a remnant of moraine deposits (◇) that formerly covered the valley flanks. The nearby catchment areas are at present glacier free, but moraine deposits (↓) in the V-shaped section, which have been subject to resedimentation in the Postglacial period, are evidence of a former side valley glaciation. (Photo L. Iturrizaga, 23 September 1995.)

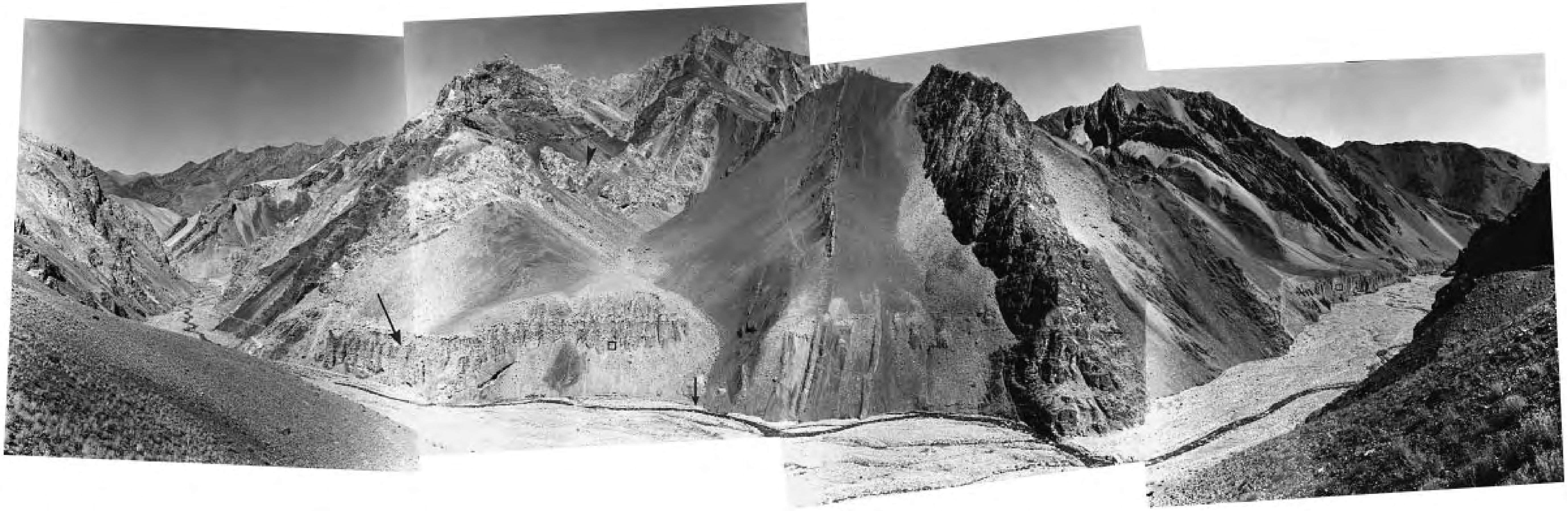




↓ *Photo 3.* The debris accumulation located in the Ghizer valley at 2915 m demonstrates very clearly the transformation of a former closed moraine mantle into residual debris accumulations (◆) in combination with the supply of pure slope material (↙) from the higher catchment area, which leads to a composite debris accumulation (△) of pure slope debris and glacial debris. Subordinate gullies alongside the main direction of free fall are still filled with moraine material (◇), whereas the main supply channels are already occupied by slope debris (▽). The conical debris accumulation (△) is composed of dark, coarse slope debris and fine, light-coloured moraine material. Owing to the latter, mudflow-like debris flows are able to develop on the cone surface. The "passive debris accumulation" created by slope processes is shaped like a sand-glass. The apex of the debris accumulation has been shifted downslope (←) by the channelling of the moraine material. In the foreground is a valley floor (○), which was flooded by a landslide-dammed lake several years ago. (Photo L. Iturrizaga, 24 September 1995.)

← *Photo 2.* The talus cone at the orogr. right-hand side of the Mastuj valley, opposite the Laspur valley mouth at an altitude of 2100 m is embedded into a landslide scar (●). The smooth and straight cone surface has been only slightly reworked by debris flows (→). In the neighbourhood of the talus cone – separated by glacially polished debris-free rock sections-gullied moraines (◇) have been deposited. They are already transformed into conical secondary debris accumulations (○). The talus cone is developed along a glacially polished, formerly closed rock surface. At 4000 m, the catchment area of the debris accumulations lies far below the equilibrium line. The bareness of the debris accumulations is caused primarily by climatic conditions and secondly by morphodynamic processes. In the foreground the Mastuj river is incised into the terrace (↓). The horizontal line at the base of the talus cone is a footpath (↘). (Photo L. Iturrizaga, 23 September 1995.)

↓ *Photo 4.* In the Laspur valley, at a side valley mouth, typical composite glacially induced collapse talus slopes (*Nachbruchschutthalden*) (△) have developed at 3200 m. The valley flank is clearly glacially polished (◓). During and after deglaciation the oversteepened valley flanks lost their support due to the melting of the glacier. It is also possible that part of the collapse accumulations has been removed by the retreating glacier. (Photo L. Iturrizaga, 23 September 1995.)

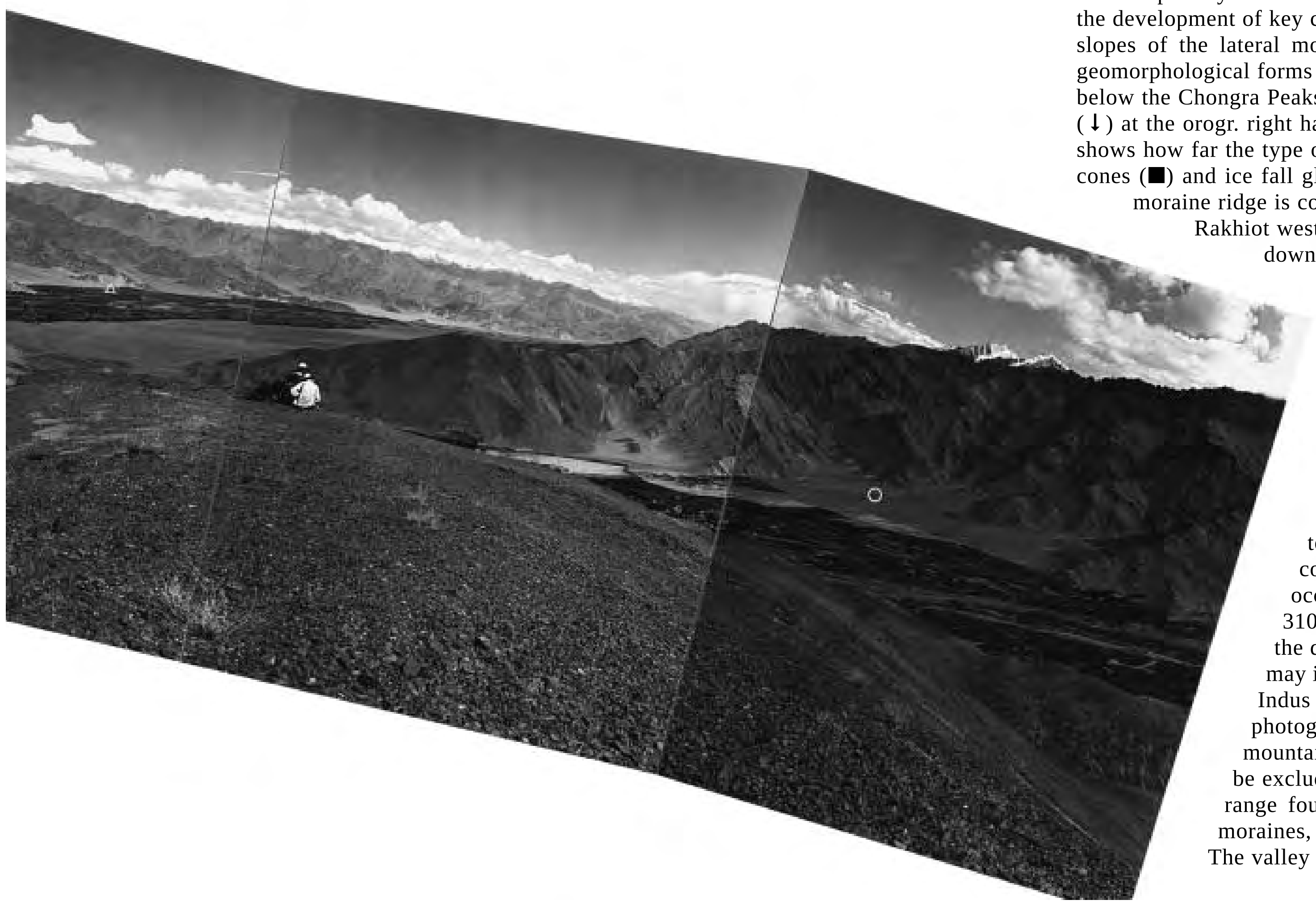


↖ *Photo 26.* Talus cones and talus slopes (▲) dominate this section of the Martselang valley between 3600 and 3700 m. The vertical outcrop escarpments of the geological strata are heavily mantled with debris, thus inhibiting weathering processes. Looking at the distal cliff walls (↘) of some debris accumulations, it becomes evident that this is moraine material (□). It is also obvious that fluvial debris accumulations are missing at the true valley mouth. On the one hand debris is transported away by the Martselang river (↓), on the other hand the lateral incision of the debris accumulation, plugging the valley mouth, indicates that the debris accumulation does not originate from the short side valley, but is of glacigenic origin. The transversal rock threshold (↙), as yet only slightly incised by the tributary river, shows that it is a relatively young side valley. (Photo L. Iturrizaga, 9 August 1993.)

← *Photo 28.* View at 4400 m from an Ice Age-transfluence pass from the Parkachik valley into the middle Suru valley loop towards NW. The tributary valleys at the orogr. left hand valley side lead across a confluence step into the main valley (⇩). The right part of the panorama shows the continuation of the glacially polished mountain ridge (◓) shown in photo 29 (see KUHLE et al. 1997). Especially at the orogr. left hand side, the flanks of the Suru valley side are covered by moraine material (◆), but a shallow moraine cover (◇) is recognizable at the orogr. right hand valley side. The side valley glaciers are lined by avalanche cones (↘). The lateral moraines (○) belonging to a historic to Neoglacial glacier stage are relatively intact and are unaffected by erosion processes. The end moraines of the Sentik glacier located further upvalley are well preserved (□). (Photo: L. Iturrizaga 31 July 1993.)


Bk
R

↖ *Photo 23.* The photo panorama covers a relief amplitude of 7000 m: On the right-hand side the Nanga Parbat massif (main peak not visible) rises up to 8125 m, whereas to the left-hand side the Rakhiot valley drops down to 1200 m at the confluence with the Indus valley over a horizontal distance of 30 km. This rapid relief gradient results in a characteristic sequence of debris accumulations. The upper third of the valley is almost completely glaciated und does not allow the deposition of large debris accumulations. The avalanche-produced debris does not contribute to the development of slope debris forms. Farther downvalley the tributary valleys are occupied by talus cones and talus slopes (△) of the periglacial region, some of which are greatly influenced by avalanches. The steepness of the relief prevents the development of key cryogenic forms, such as patterned ground. Various types of talus slopes mantle the slopes, e.g. basally coalesced talus slopes (←) or talus slopes of the lateral moraine valleys with a moraine base (▲). The talus cones produced by freeze-thaw action can be considered as supra-regional, key geomorphological forms of the periglacial zone. Secondary debris accumulations are found at the base of 250 m high moraine ledges. This moraine-talus complex below the Chongra Peaks (6830 m) (Ch) is in the transformation phase to a debris accumulation completely reshaped by slope processes. The large landslide scar (↓) at the orogr. right hand Rakhiot valley side existed in a similar form in 1936 already (cf. photographs by Finsterwalder 1936). Moreover, the Ganalo valley shows how far the type of debris accumlation is dependent on the elevation of the catchment area: While the orogr. right-hand valley side displays ice avalanche cones (■) and ice fall glaciers (□), the orogr. left hand side with lower catchment areas is occupied only by talus slopes. At its upvalley beginning, the lateral moraine ridge is covered by talus cones (↘). The 'Great Moraine' (◆), an isolated glacial debris accumulation, is surrounded by the Rakhiot glacier and the Rakhiot western glacier, which undercut the moraine and lead to the formation of secondary talus slopes. In the photograph a huge ice avalanche runs down to the moraine. Considering the high amount of debris supplied by ice avalanches, the Rakhiot glacier has only a slight debris cover. The upper forest line running at 3800-3900 m is formed by birches, which are exposed to numerous avalanches and mud flows. The middle and lower part of the Rakhiot glacier is accompanied by lateral moraine valleys at both sides, which are filled with highly dynamic mudflow-avalanche cones (○). The lateral moraine valleys peter out at moraine terraces up to 200 m high (□). The mudflow-avalanche cones receive debris from talus slopes (↘) und moraine material located at their lateral margins. The Rakhiot gorge (↓) is almost debris-free. Localities: Nanga Parbat-massif (N), Ganalo peak (G), Rakhiot peak (R), Chongra peaks (Ch), Buldar peak (Bk), Buldar ridge (b), Rakhiot glacier (r), Ganalo glacier (g). (Photo L. Iturrizaga, 9 October 1995.)



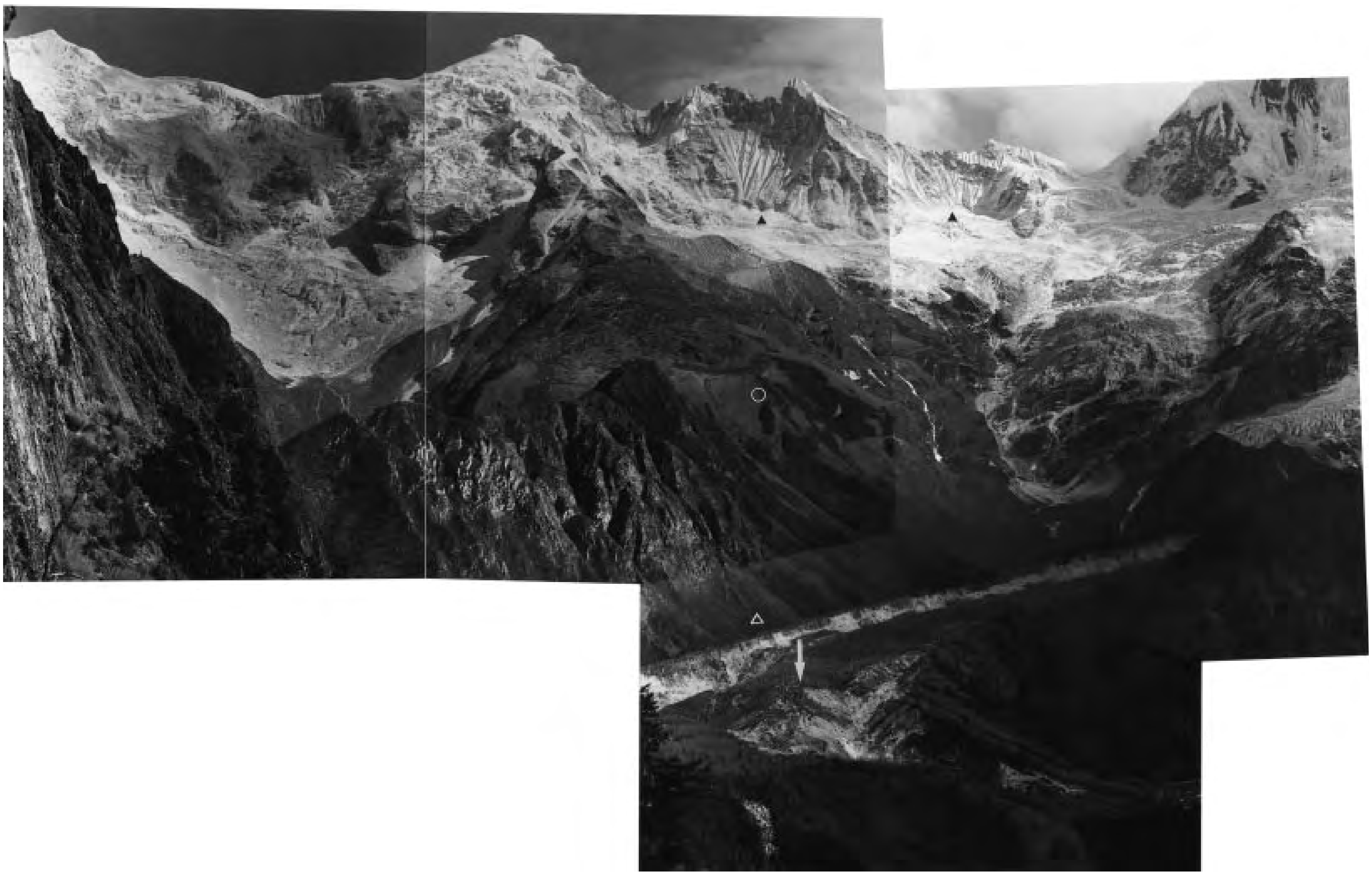
← *Photo 25.* View over the wide Indus valley, photographed at 3880 m from the orogr. left-hand side of the Indus valley towards N to the Ladakh Range. The very homogeneous relief configuration is composed of short valley courses. They lie one behind the other over several tens of kilometres and are occupied by very similar debris accumulations in the form of isolated and compound mudflow fans which largely consist of remobilized moraine material. The catchment areas at 5000–6000 m reach only the nival zone, at some places glacier patches occur. The relief amplitudes are moderate, ranging between 2000–2500 m over very long horizontal distances. The Indus river which runs at 3100 m erodes only low cliff walls from the distal parts of the debris accumulations. Considering precipitation averages about 100–150 mm/yr the debris accumulations are sparsely covered by vegetation. Furthermore the instability of the substratum due to freeze-thaw cycles higher up may inhibit plant growth. The limited extent of the oasis settlement reflects the scanty amounts of river discharge. While at the orogr. right hand Indus valley side the mudflow-alluvial fans are completely framed by mountain spurs, the mudflow-alluvial fans, located at the side where the photograph was taken, are only partly framed by mountain spurs. At their sides subordinate mudflow cones (○) supply further debris. The lower mountain spurs are partly weathered into talus slopes and debris covers (△) up to the ridges. A glacigenic origin of the debris accumulations cannot be excluded. The spatial extent of the debris accumulations exceeds the proportion of free rock walls. Glacial sediments exist, but not in the wide range found in other valley sections of the Karakoram. Therefore the transitional glacial debris accumulations play a minor role. High-level moraines, like those downvalley of Skardu (2200 m) in the Indus valley, are not preserved. A classical terminal basin is visible upvalley of Leh (↓). The valley flanks in the upper catchment areas often show kame formations. (Photo L. Iturrizaga, 24 July 1993.)

← *Photo 31.* Panorama from N to S over the heavily debris-covered Barmai glacier looking at the orogr. right, W-facing Hathi Parbat valley side. In the lower valley basin (left margin) the predominance of the debris supply of this valley side becomes evident. The Hathi Parbat river is pushed aside to the opposite valley flank (↙). The upper part of the Barmai glacier is accompanied by ice and snow avalanche cones (▲). Just downvalley of two hanging glaciers talus cones (△) are deposited into the narrow lateral moraine valley, which is confined by a lateral moraine wall (○). The upvalley talus cone shows a moraine pedestal (◇) covered with vegetation. At present the moraine material is being incised by meltwater furrows (↘↘). Only a rock bastion (□) separates the two talus cones. Note the gorge-like rock incisions (→), which become wider upslope. (Photo L. Iturrizaga, 3 October 1993.)

← *Photo 32.* The photograph was taken from the Lata Peak (3700 m) towards N. In the background the Nanda Devi rises up to 7816 m. The Rishi valley lies at about 2800 m. Frost-talus cones (△) reworked by avalanches occur above the forest line. Large debris accumulations are found neither at the valley bottom nor at the valley flanks. (Photo L. Iturrizaga, 7 October 1993.)

↑*Photo 37.* View westward from Larkya La (5104 m) to the upper glacier basin, which is bordered by the Nemjungaon Himal and Peri Himal with heights of over 7000 m. Three heavily debris-covered glacier streams, composed of several icefall glaciers, occupy the broad valley basin. The glaciers are lined by true talus cones, which are strongly reworked by ice-avalanches (▲). They have been deposited into a small lateral moraine valley lying between 4000–4200 m. The supply funnels are filled with debris, which is partly underlain by permafrost. Ice avalanches create broadly shaped supply gullies (○). The avalanche-mudflow cones are very active at present. The cone surfaces are furrowed by meltwater discharges. Debris deposits are found at the inner slopes of the lateral moraine, where the glacier or the glacier meltwater broke through the lateral moraine (↖). Structurally-controlled debris accumulations (△) are well developed at the rock bars in the middle of the valley basin. The talus cones are consolidated (▽) below the outcrops of the geologic stratum. (Photo L. Iturrizaga, 4 January 1995.)

↓*Photo 38.* View from 3800 m into the western Manaslu valley basin. A striking pedestal-moraine arc (○) at a transfluence pass is visible in the middle of the photograph. Ice avalanche slopes (▲) are deposited just below a lower mountain ridge, while the ice avalanches of the higher catchment areas directly coalesce forming glaciers. The fossil talus cones of the lateral moraine valleys (△) at the orogr. right hand side of the western Manaslu glacier are consolidated and covered by forest (↓). Even the tongue of the Manaslu-W-glacier, which terminates at 3300 m, is occupied by forest. The valley basin resembles that of the Rakhiot valley (Nanga Parbat massif), but the western side of the Manaslu is so steep that no sufficient snow accumulation area is available to provide a larger glacier cover. (Photo L. Iturrizaga, 6 January 1995.)



↑*Photo 5.* In the middle part of the Mastuj valley, near to Brep (2450 m), we find a broad U-shaped main valley, in which the fluvial debris accumulations of the tributary valleys can expand freely. Thinning-out mudflow-alluvial cones coalesce and are not undercut by the Mastuj river, because they lie in its inner slope section. In the interference zone between the mudflow-alluvial cones a considerable debris aggradation (↙) due to the resedimentation of high-level moraines (○) can be observed. The morainic accumulations dominate on this valley flank. The higher catchment areas are at present free of glaciers. The vegetation patches are limited to the oasis settlement. (Photo L. Iturrizaga, 23 September 1995.)

↑*Photo 7.* Downvalley from Mastuj (2280 m) a broad mudflow-alluvial cone occupies over 2/3 of the valley floor. If the cone were to expand fully, it would dam the Mastuj river. The Mastuj river has carved out up to 60–80 m high cliff walls at the distal part of the sediment accumulation, which is mantled by a closed talus slope veil (●) at its base. Considering the relatively small catchment area, which reaches only some kilometres into the mountain chain up to 4000 m, the debris accumulation is remarkably large. The debris accumulation shows a dual composition of ground moraine material (□) at the base, overlain by fluvial deposits of the tributary valley. In this example too, glacial sediment accumulations, resedimented from the upper valley sections, contribute to cone formation. The lateral debris supply by adjacent slope debris accumulations (△) is clearly recognizable in this photograph. The present moderate activity of the debris accumulations is indicated by the shallow drainage channels on the cone surface. In the left cone section is the main incision (↓), where the oasis settlements are found. (Photo L. Iturrizaga, 23 September 1995.)

↑ *Photo 8*. The reddish kame formations (□) stand out clearly against the slope in the transitional zone from the valley flank to the valley floor at the orogr. right-hand side of the Chitral valley, near Drosh (1450 m). That they are actually allochthonous debris accumulations, becomes evident from the fact that their proximal sections start beside the catchment area (↙). The cone apexes are 'dead'. They terminate at the mountain spur. Not until the Postglacial epoch did fluvial dissection (↓) of the kame formations begin. Undissected alluvial cones (●) are deposited at the valley mouth of relatively small catchment areas, which reach up to 3500 m. The cones partly consist of moraine material. In the foreground the over-500-m broad Chitral gravel floor is visible. Huge lacustrine sediments are accumulated in this valley chamber. (Photo L. Iturrizaga, 22 September 1995.)

↑ *Photo 9.* View from 1935 m towards the orogr. left-hand side of the Ghizer valley close to the settlement of Singal. The debris accumulation shown here resembles a fluvially accumulated debris landform, such as a mudflow cone. Closer examination reveals that the cone apex does not end in the potential supply valley, but peters out in a concave shape along the valley flank (↙). However, the tributary river (↓) laterally dissects the debris accumulation and deposits a comparatively large alluvial cone (●), which contains resedimented debris from the main debris accumulation. A look at the adjacent valley flanks shows that they are covered with debris material of glacigenic origin (◇). They are also in the transformation phase between a mantle-like covering and cone-shaped residual debris accumulations. The debris accumulations might be kame formations, however, both the internal structure and the uniform and only slightly dissected moraine deposits (– –), reaching up to over 700 m above the valley floor, indicate a remnant of ground moraine, which is being fluvially reworked in the Postglacial period. This means that fluvial processes erode a cone-shaped debris accumulation out of the moraine material, so that it represents a residual form of a glacial debris accumulation. The distal part shows two levels (1 and 2) and does not possess a cliff wall owing to its high fine material content. (Photo L. Iturrizaga, 25 September 1995.)

↑ *Photo 10.* Just upvalley of the locality shown in photo 9 a further moraine-derived debris accumulation is deposited. The valley flank is covered by a thin blanket of ground moraine (◇), whose viscous consistency traces the surface structure of the bedrock. The main supply gully (⇩) of the small catchment area is amply filled with debris. The development of the strongly dissected, accordion-shaped distal cliff wall (↓) can be attributed to the surplus drainage of the irrigation-water from the oasis settlement. The relation between the size of the catchment area and the debris accumulation shows very clearly that the small-sized and at present unglaciated catchment areas possess apparently disproportionately large debris accumulations at their valley mouths. This suggests a high share of allochthonous debris, i.e., moraine material. (Photo L. Iturrizaga, 25 September 1995.)

↑ *Photo 11.* A mudflow cone (3450 m) (□) is undercut by the Yazghil glacier (●) at its outer slope, so that it shows a nearly vertical distal cliff wall. Also this kame-like formation is composed of resedimented moraine material (↘). Further upvalley talus cones with an angle of 30° blanket the valley flank and partly cover the kame formation (▽). In the background the moraine-covered valley flanks (◇) of the Shimshal valley are visible. They reach up to 700 m above the valley floor. (Photo L. Iturrizaga, 18 August 1992.)

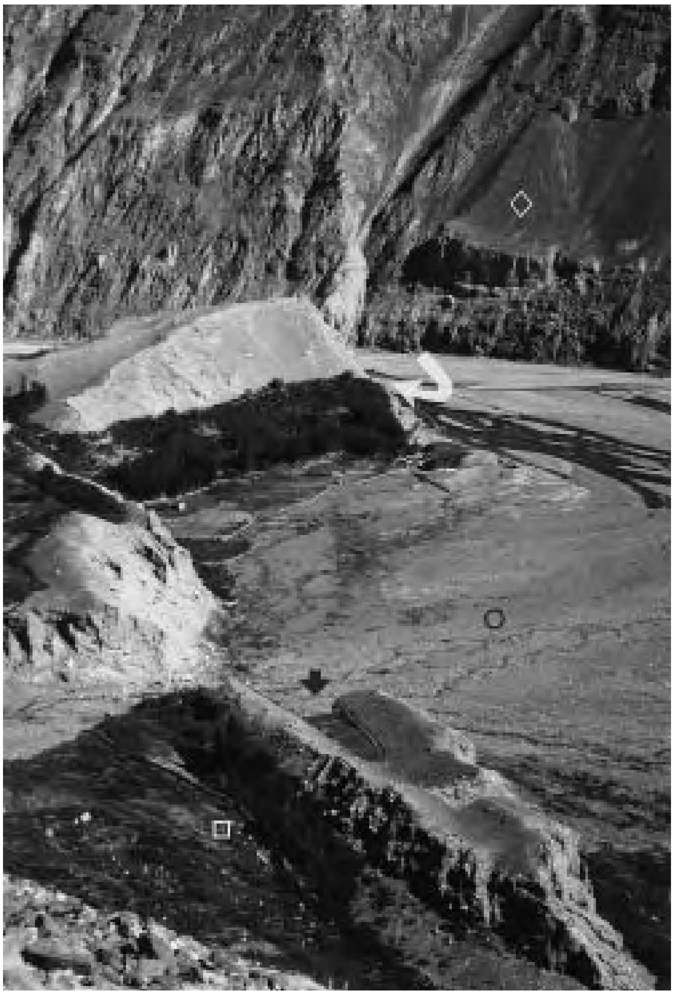
↑*Photo 12.* Settlement elements can serve as a good indicator for the aggradation and degradation of debris accumulations. In the course of this century the permanent settlement of Shimshal (3080 m) – located between two end moraine arcs (●) – has lost a considerable part of its cultivated land owing to glacier lake outbursts. This is documented by the curved shape of the sediment terrace (⇨). The ground beneath of the old Khan settlement (↘), which showed an intact core zone at the beginning of this century, was destroyed by extreme flood events. Therefore it is mainly the threshing places (▶) that are located at the distal cliff walls (→), whereas the individual houses are scattered about the field area. The valley flanks are covered with thick ground moraines (□) up to 700 m above the valley floors. At many places they have been resedimented into secondary talus slopes (△). Mudflows and earth slides (○) deriving from displaced morainic material destroy the field area. (Photo L. Iturrizaga, 7 August 1992.)

↑*Photo 13.* The S-facing Zadgurbin valley is being extended by headward erosion into the Ghujerab mountains. Ground moraine (□) coats the narrow V-shaped valley, transforming it into a ravine-shaped valley. Talus cones (▷) are deposited on the moraines. The cliff walls of the moraines (←) are dissected into the shape of organ-pipes. These glacial sediment relicts provide the source material for mudflows. The left middle ground of the photograph shows a light-grey gravel floor (○) of the Shimshal valley, lined by talus slopes (△). (Photo L. Iturrizaga, 25 August 1992.)

↑*Photo 14*. View from 3050 m from the Shimshal gravel floor to the orogr. right-hand valley flank into the Zadgurbin valley. The mudflow-alluvial cone, which is seasonally undercut by the Shimshal river, was deposited against the Shimshal glacier in the Late Glacial period, maybe also during Neoglacial time. The central incision of the cone took place after deglaciation when the base-level of erosion was lower. Talus slopes (△), which are nourished by high-level moraines (◇), are accumulated on the mudflow-alluvial cone. The remains of an end moraine (↓) have also been incorporated in this cone. Nowadays, the glacially induced cliff walls, which are 60–80 m high, are cut back by gravity processes and fluvial undercutting, as attested by the series of talus heaps (– –). A young "daughter alluvial cone" (○) spreads over the Shimshal gravel floor. The valley flanks are glacially polished and collapse at the convex parts of the trough valley shoulder. (Photo L. Iturrizaga, 14 August 1992.)

↑*Photo 15*. View towards SW from the Winian Sar pass (4250 m) towards the Maidur high-mountain valley floor, which provides the upper connection to the Zadgurbin ravine, and towards the southern Ghujerab Range with the NW-facing side of the Kuksar summit (5578 m) (↙). The dark mountain spurs (↓), visible in the foreground, consist of soft, poorly resistant slates in contrast to the widespread limestone ridges. Here, at a valley floor altitude between 3800 and about 4200 m, primary talus slopes dominate the valley flanks, rather than the secondary talus slopes found farther downvalley. The fluvial reworking of the talus slopes is very limited at the arid lee-side of the Ghujerab Range. The talus slopes are deposited on a glaciofluvial terrace (○), so that they are not undercut by fluvial processes. Further downvalley the talus cones gradually cloak a moraine accumulation (◇). (Photo L. Iturrizaga, 26 August 1992.)

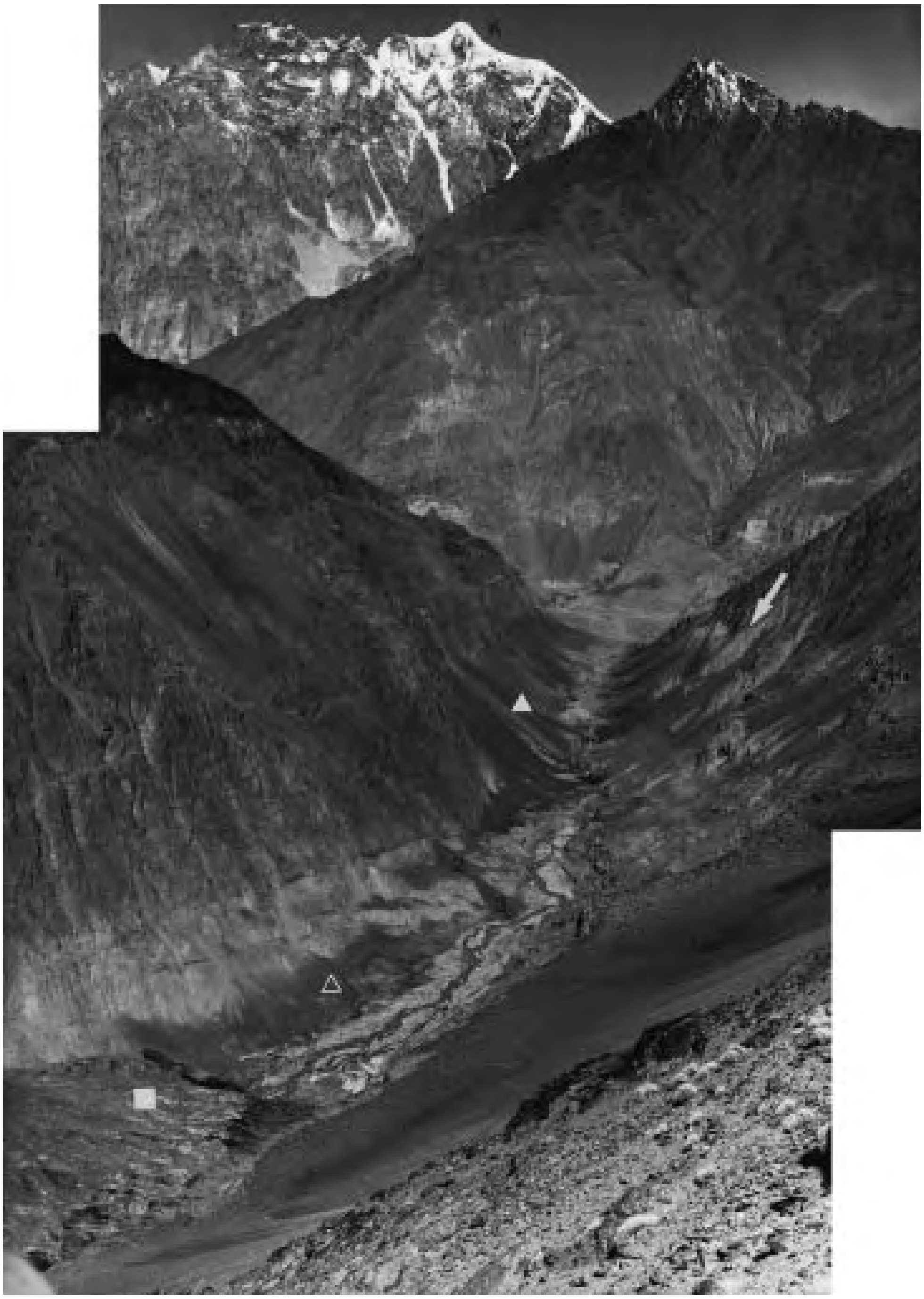
↑ *Photo 16.* Remnants (□) of the end moraine (◇) of the former Shimshal glacier continue at the orogr. left-hand Shimshal valley flank. They are masked by true (△) and moraine-derived talus slopes (▲). At some places, the moraine material (◆) is still easily recognizable. The older surface of the mudflow-alluvial cone of Chukurdas is undercut by the present "daughter cone formation" (○), yet, on the other hand, it has been partly incorporated by the young debris accumulation. (Photo L. Iturrizaga, 14 August 1992.)



← *Photo 17.* View of the quadrant-shaped end moraine from the former Shimshal glacier in front of the Churkurdas valley. It separates the mudflow-alluvial cone into an inactive and an active part. At its distal terminus the end moraine has been truncated by the Shimshal river (∪). The former terminal basin is now occupied by a mudflow-alluvial cone (○). The peripheral fan segments are only episodically reached by flood events. The inactivity there is confirmed by the presence of the settlement (←). In the foreground the boulders (□) lying in the *Hippophae rhamnoides*-bushes indicate the high rockfall activity. In the background, kames (◇) have been deposited on the orogr. right hand Shimshal valley side. Some irrigation plots (↓) occur in the right end moraine section. This combination of end moraine and fluvial debris accumulation exists in various transitional stages in the Karakoram. (Photo: L. Iturrizaga 13 August 1992.)

← *Photo 18.* This talus cone is located directly below the Yazghil glacier tongue at 3100 m on the orogr. left-hand Shimshal valley side. This cone has a height of about 350 m, the supply gully reaches another 500 m upslope to a nival catchment area. The debris-filled supply channels (▽) are a characteristic feature of the low-transport, dry high mountain regions. The middle parts of the valley flanks are coated with moraine material (◇), which is dissected into stable pillars. The true talus cone is undercut by a small tributary branch of the Shimshal river. The exposure (↗) shows a layered profile and indicates the high fine material content. The various colours of the surface of the talus cone demonstrate the different ages of the rock patinas, and also distinguish the light-yellow displaced morainic material (○) from the reddish-brown slope debris (●). (Photo L. Iturrizaga, 12 August 1992.)

→ *Photo 19.* View of the lower catchment area and the path of a mudflow. Pillar-shaped remnants of morainic material (◆) tower above the upper slope section. They are interrupted by a mudflow-talus cone. Sudden melt water discharges as well as heavy precipitation events lead frequently to seasonal resedimentation of talus material and moraine debris. (Photo L. Iturrizaga, 8 August 1992.)



↑ *Photo 20.* The Momhil valley mouth has many talus slopes (△▲), especially at the bottom of its trough valley. An end moraine position (▼) – belonging to a historic period of the Little Ice Age according to Meiners (1996, pp. 144–145) – marks the sudden change from the younger, lower talus slopes (▲) to the older, higher talus slopes (△). The talus slopes are partly recruited from Late Glacial moraine remnants (↙). Directly upvalley of the end moraine position there is a regenerated talus cone sequence which consists of three segments (1,2,3). Supposing that the Momhil glacier tongue (■), which terminates nowadays at 2840 m, does not advance any more, the height of the young talus slopes will probably adjust to the higher talus slopes, which lie farther downvalley. In a "fresh" condition the glacier stages can be parallelized with the corresponding extent of the debris accumulation formation. The Karun Koh (K) rises from the Shimshal valley floor, which lies at 2750–2800 m, up to 7164 m over a horizontal distance of only 8.75 km. At the Karakoram northern slope, the valley of Shimshal is so arid that the moisture supply is not even sufficient to support a forest zone in the upper slope areas and in the ridge areas at the convection level of the slope winds. Therefore bare debris accumulations find their optimal distribution area in this region. Owing to scarce cloud cover during the whole year in the Karakoram, maximal insolation amounts are recorded, which are conducive to insolation weathering processes. (Photo M. Kuhle, 15 August 1992.)

↑ *Photo 21*. The Hassanabad valley photographed from the 1929 end moraine, 2.5 km upvalley of its junction with the Hunza valley. The lower steep-sided trough valley is mantled with young, light-grey, slightly weathered moraine material (○), providing the source material for the formation of talus slopes. A chaotic melt-out landscape occupies the valley floor. The branches of the Hassanabad Nala are lined by Hippophae rhamnoides (↙). (Photo L. Iturrizaga, 23 September 1992.)

↑ *Photo 22*. Large-sized rockfall event in gneiss bedrock close to Sarat (2300 m) in the Hunza valley. The boulder with a diameter of 2 m left the roadway of the Karakoram Highway almost intact. The adjacent stone wall has been destroyed by debris slides (↙). The roadway shows a hole (▼) which was caused by the boulder at the back. (Photo L. Iturrizaga, 16 September 1992.)

← *Photo 24.* In the middle part of the Rakhiot valley, near to Tato (2300 m), the valley flanks are covered by Late Glacial, 250 m high moraine ledges (□), on which talus cones (▲) are deposited. Morphodynamic activity at the slope is relatively low, so that moraines are well preserved. The exposure profile is heavily gullied and shows isolated secondary mudflow cones (↘) at the base. Towards the lower xeric forest line the forest becomes very sparse. (Photo L. Iturrizaga, 12 October 1995.)

↓ *Photo 27.* At the Moray Plateau the alluvial fans can expand freely at an altitude between 4400 and 4600 m. These alluvial fans are deposited on ground moraine material and represent a further variant of the dual development of debris accumulations, which can be termed ‘compound ground moraine-alluvial fans’ (○). Since the catchment areas have a maximum height of 5500 m, the upper limit of debris deposition is not reached. Only at some locations do perennial snow patches survive in this dry and cold high mountain region. The glacially polished mountain ridges (◓) are covered by a thin debris blanket. (Photo L. Iturrizaga, 16 August 1993.)

↑ *Photo 29*. View from the orogr. left Suru valley side at 4200 m towards N, giving an overview of the valley section between Parkachik (3490 m) and Tongul (3290 m) with a roches moutonnées-landscape: Not only the great mountain ridge (○) at the back but also both mountain humps (□) at the valley bottom are glacially abraded and polished. At present the round shape is being destroyed by weathering processes. The debris has accumulated as talus cones, talus slopes and debris covers (△). Only the upper rock plateau (◇) gives evidence of the former intact rock surface. (Photo L. Iturrizaga, 1 August 1993.)

↑ Photo 30: View from 4200 m in the Nandakini valley northward to the pass between Nanda Ghunti (6309 m) and Trisul (7120 m). In the foreground, the Shilasamudras glacier (■) flows westwards. The Nandakini valley shows, on the cataclinal orographic right-hand side, smooth slopes (▲) without talus cone formation, whereas on the paraclinal orographic left-hand side talus and mudflow cones (△), which are deposited on ground moraine material (◇), cover the valley flanks. The deeply incised gullies (↘) supply the talus cones with avalanches, even in September. In the middle ground, talus cones (▽) underlain with ice appear at a height between 4300 and 4800 m. A multi-storey ice avalanche cone (1,2), adjacent to an undercut sediment cone (◆), feeds the Shilasamudras glacier. (Photo L. Iturrizaga, 20 September 1993.)

← *Photo 34*. Mudflow cone with a nival catchment area at the orogr. right-hand side of Thulo Bheri Khola downvalley from Dunai (2150 m). The slope is overlain by Late Glacial moraine accumulations (○), which are being removed by mudflows. The mudflow cone in the foreground shows two generations (1, 2), which are both undercut by the river. (Photo L. Iturrizaga, 16 February 1995.)

↑ *Photo 33.* The precipitous orogr. right-hand valley flank of the Barbung Khola side – photographed at 2100 m - is still covered with a Late Glacial moraine mantle (◇) in places. Convex-shaped talus cones (△), which bear a sparse vegetation cover and are reworked by mudflows (▽), line the valley flank up to a height of 50 m. An alluvial cone (○) expands fully at the valley bottom of the Thulo Bheri Khola. The nival catchment areas reach up to max. 5900 m. At the orogr. left valley side slate flows (↙) can be observed. (Photo L. Iturrizaga, 6 February 1995.)

↑ *Photo 35.* In the lower Barbung Khola between 2900 and 2700 m huge Late Glacial moraine deposits are preserved. In the Postglacial period they were transformed into residual talus cones (△). The inactive cone surface is covered by conifers (↖), while the debris flows undercut (↘) the conical moraine accumulations at their sides. (Photo L. Iturrizaga, 19 February 1995.)

← *Photo 36.* View from Siklis (1900 m) towards Annapurna IV (7525 m) (AIV) and Annapurna (II) (7937 m) (AII) as well as the Lamjung massif (L). The Madi Khola drains the southern declivity. The photograph shows an ice avalanche (↙), passing about 2000 m of vertical distance and running out on an avalanche-cone glacier. The glacier tongue (→) terminates at 2300 m. It represents one of the lowest ice margin positions at the south side of the Himalayas. The altitude zone of debris accumulations of the high mountain regions between 4000 and 5000 m is missing owing to the steepness of relief. Considering the almost debris-free valley flanks, it is astonishing where all the debris produced by ice avalanches has been deposited. Even the avalanche cone glacier shows only a slight debris cover. (Photo L. Iturrizaga, 30 January 1995.)

↑ *Photo 39.* View from about 4300 m into the Barun valley, which shows a well shaped Ice Age-trough profile. The valley floor is carpeted with ground moraine (□). The moraine base is overlain by autochthonous consolidated debris accumulations (△) from the adjacent slopes. These compound debris accumulations, which almost plug the valley floor, are incised by the Barun river. Young collapse processes (↙) destroy the older trough valley profile. Hanging glaciers (●) with end moraine formations (○) are found above the steep trough valley flanks. Mixed debris accumulations (▲) formed by rockfall, mudflows and avalanches follow downslope. (Photo L. Iturrizaga, 28 November 1994.)

↑ *Photo 40*. View from the upper Barun glacier (5300 m) towards the orogr. right-hand valley flank. The gullied lateral moraine (●) is gradually reworked by glacial undercutting processes and mass movements. Nowadays these transitional glacial debris accumulations are easily recognizable, but their prehistoric reconstruction proves to be very difficult in lower unglacierized mountain areas. (Photo L. Iturrizaga, 6 December 1994.)

which rise only slightly above 3000 m here in the Drosh area, were transformed from nival to fluvial during Postglacial time. Only the catchments above 4000 m have experienced the change from a glacial to a nival catchment, as in the case of the alluvial fans of the Chitral, Mastuj and Yarkhun valleys further upvalley.

Residual cone-shaped moraine accumulations and mudflow-alluvial cones as quasi-convergent forms, with an example from the Ghizer valley. At the orogr. left-hand side of the Ghizer valley, opposite Singal, there is a debris accumulation with a base elevation of 1800 m, which at first glance resembles a fluvially deposited mudflow-alluvial cone (Photo 9). The fluvial catchment of this debris accumulation scarcely extends above 3000 m. Close observation shows that the bifurcate cone tip does not derive directly from the very steep valley directly upstream, but clings concavely to the craggy zone. This type of landscape is reminiscent of the moraine-influenced debris accumulations of Drosh, however in that case the moraine cover was breached and a fluvial alluvial cone was built up at the tributary mouth. This cone was bordered by the remains of terrace- to cone-like moraines. This type of debris accumulation is, so to speak, a preliminary stage of the debris accumulation at Drosh. Here, the debris accumulation that was carved in a cone shape out of the morainic material seems to have been built up by the tributary. In fact , it is what is left of a *ground moraine mantle that covered the valley side up to more than 700 m above the valley floor* and is *dissected by mass movements* from the very steep valleys and gullies that are now free of morainic material. At the end of these gullies, juvenile alluvial fans form, mainly consisting of resedimented morainic material. The residual moraine still clearly dominates the landscape at this tributary mouth. In the course of time, however, this moraine will be further undercut by the catchment's streams and will retreat. As at Drosh, the alluvial fans directly associated with the main feeder gully will dominate the very steep valley. Morphodynamics being low at these slopes, the morainic deposits will continue to be preserved. As yet, they are neither strongly gullied nor do they show signs of being redeposited in secondary debris slopes. The distal part of the debris accumulation does not exhibit the cliff faces that are otherwise so characteristic of large fluvial debris accumulations, but disintegrates into secondary aggradational heaps. This in turn points to the high fine-material content of the debris accumulation, which is typical of ground moraine.

This example, too, shows that the debris accumulation is *disproportionately large in relation to its small catchment area*, suggesting a glacial origin.

The debris-rich, arid to semi-arid high mountain areas with an extreme relief energy and high glaciation: the northwestern Karakoram

In terms of the development of debris accumulation types, the transition from the eastern Hindu Kush to the northwestern Karakoram is unremarkable. The unconsolidated debris accumulations of the arid to semi-arid valley locations continues unchanged. As part of the Young Palaeozoic–Mesozoic geosyncline of Eurasia, the sediment zone of the Tethys Karakoram runs north of the Main Karakoram Ridge. Thick, slightly metamorphic limestone and dolomite series with interbedded slates are typical of this zone (Schneider, 1957) and provide the talus slope belts commonly found in the study area. Precipitation in the valley locations of the northwestern Karakoram scarcely exceeds 130 mm/yr, whereas it rises continuously to about 2000 mm at high elevations (Flohn, 1969, p. 211, Hewitt, 1989, p. 14), giving an extremely steep precipitation gradient. In the vertical altitudinal zonation, two entirely complementary precipitation regimes are reflected in the distribution of debris accumulations. Significant, probably monsoon-controlled bad weather – of uncertain origin (see Paffen et al., 1956; Reimers, 1994; Weiers, 1998, among others) – during the summer months is the most important factor in the geomorphological processes governing debris production and transport in the Karakoram, which has been designated a region of winter precipitation (Goudie, 1984, p. 371; Iturrizaga, 1996, p. 216). The landscape is dominated by up-to-1000-m broad debris accumulations generated by catastrophic rainstorm events. This means that *deviations on the statistical climate scale are the major triggers of geomorphological processes* in the formation of debris accumulations. Freeze-thaw cycles occur at changing elevations in the Karakoram at all seasons (Hewitt, 1989, p. 14), having most impact at elevations between 4000 and 6000 m in the time span from May to October. Precipitation levels between 500 and 1000 m and temperatures around freezing supply the necessary moisture and freeze-thaw conditions required for frost action. The climate resembles that of the Hindu Kush, but greater vertical relief distances and a larger ice cover distinguish the northwestern Karakoram from the mountains to the west. Relief differences of up to 6000 m over horizontal distances of only 10 km, for example between Rakaposhi (7785 m) and the Hunza river (1850 m), illustrate the steepness of the relief. Among the study areas, the northwestern Karakoram is unique for its volume of debris and the variety of its debris accumulations.

In the Karakoram, high-lying valley floors between 4500 and 2500 m in combination with high catchment areas of up to 8000 m favour the formation of an expansive valley glaciation, the largest glaciation outside the Antarctic.

The Hunza river's annual denudation rate of 1800 m^3 km^{-2} corresponds to a surface erosion of 1.8 mm/yr (Ferguson, 1984, p. 587). The loss of settlement land during the last hundred years is an obvious and impressive indicator of the rapid undercutting and erosion of debris accumulations (Iturrizaga, 1997 a, b).

Many of the valleys are in a transitional phase between a glacially oversteepened – and hence unstable – trough valley and the more stable fluvial, V-shaped valley (Figure 4). The talus slopes often disguise the glacial valley form and wrongly suggest a narrow V-shaped valley.

Talus slopes cannot serve as a criterion to distinguish the periglacial zone or to mark the transition to the nival or periglacial zone. The site of deposition may be at a considerably lower elevation than the debris source. On account of the extreme relief in the study area, the over-1000-m-high talus slopes of the periglacial zone stretch down as far as 1500 m asl, although this is not the lower limit of the periglacial zone, which is at about 3000 m. The debris accumulations of the arid high mountains, with their warm summers and insolation weathering, merge gradually into the debris accumulation zone of the cold-humid glacier regions.

The *centre-to-periphery change in debris accumulation types* along the valleys is primarily dependent on relief conditions and on the configuration of main and tributary valleys. It is especially noteworthy in the Karakoram that the occurrence of *high-level morainic deposits decreases towards the modern glacier terminus*, i.e. into the valley, and the secondary talus cones are succeeded by primary ones upvalley. Hence, starting at the middle section of valley, a lessening transformation of debris accumulation towards the mountain interior is visible. One of the reasons for this is that the raising of the glacier surface, accompanied by a lowering of the equilibrium line, decreases towards the mountain interior and towards the accumulation area of the glacier, and the moraine mantle lining the valley is less high. In addition, glacial deposits are removed very rapidly by frequent freeze-thaw action and the resulting mass movements, and by avalanches at high elevations.

Debris accumulations in the Shimshal valley

In purely quantitative terms, most of the talus slopes in the northwestern Karakoram are located in the Shimshal valley and its tributaries. A large proportion of these are secondary debris accumulations deriving from Late Glacial morainic material. Secondary talus slopes do not always evolve out of moraines. Sometimes they are reworked into earth pyramids or dissected into gullies, depending on their composition. Like in the Hindu Kush, we find a dual structure of a ground moraine base overlain by fluvial material. Debris accumulations parallel to the glacier are much more widespread on the northern Karakoram slope than in the Hindu Kush.

The Shimshal valley is 60 km long and runs from east to west, parallel with the Karakoram Main Ridge, whose highest catchment area reaches a peak of 7885 m at the Destighil Sar. The elevation of the valley floor ranges from 2600 to 3200 m. The valley starts with a gorge, which is not conducive to debris deposition. Further on, the valley has long steep slopes which narrow into a subglacial ravine towards the valley bottom. Here the steep valley walls are bordered by a series of homogeneous talus slopes of limestones and slates. In many places the slopes are covered by high-level morainic deposits, later resedimented as secondary talus slopes. A variety of debris accumulations – talus cones, alluvial cones and mudflow cones, end moraines and kames – have been deposited in the upper Shimshal valley. Here too is the only permanent settlement in the Shimshal valley system (3080 m, 36°26′ N/75°17′ E) (Iturrizaga 1996, 1997b).

Glacier lake outbursts truncate the fluvial debris accumulations

Glacier lake outbursts have a major impact on the shape of debris accumulations in the Karakoram. From its northern slopes six large glaciers flow into the Shimshal valley, of which the 23-km-long Malangutti, the 31-km-long Yazghil and the 47-km-long Khurdopin glaciers are building potential glacier dams (Iturrizaga, 1997a). These catastrophic glacier lake outbursts have an average recurrence interval of 10 years and their direct impact is visible in the undercutting of the valley floor sediments. Truncation of the debris accumulations is most easily recognizable at the settlement area of Shimshal (Photo 12). In the course of this century it was moved back by at least 100 m. Another settlement, Pasu (2650 m) in the Hunza valley, below the confluence with the Shimshal valley, has suffered a similar loss of land.

Special features of the topographic pattern of the end moraine and fluvial debris accumulations in the Shimshal valley

An end moraine deposited by the Neoglacial Shimshal valley glacier is located at 3100 m in front of the tributary valleys of Bandasar on the orogr. right-hand side of the Shimshal valley (Photo 14) and Chukurdas on its orogr. left-hand side (Photos 16 and 17). The end moraine segments have been almost completely embedded in alluvial or mudflow material. There is an interesting interlocking of 'dead' debris accumulation – i.e., the end moraine detached from its depositional agent, the Shimshal glacier – and the still-growing alluvial fan. An apparently similar location pattern of end moraine and alluvial fan has been reported from the Hunza valley near Yal (2000 m, 36°14′ N/74°29′ E) (see photo in Schneider, 1957, p. 470). However, here the end moraine derives from the northern Rakaposhi slope, i.e. it is a tributary valley moraine, whereas in the Shimshal valley it is a trunk valley moraine. By contrast, in the case of the interlocking debris accumulation at the junction between the Shimshal and Hunza valleys, we are dealing with a very indistinct mixture of morainic material from the opposite Batura glacier and the Shimshal alluvial fan. The interlocking of end moraine from a trunk valley and fluvial debris accumulation from a tributary valley is not a regular phenomenon; rather, it is a *fortuitous but frequent combination of glacial, fluvial and slope-derived debris*. It is uncertain to what extent causalities exist between the location of the ice margin and the support of the sediments.[5]

The Bandasar mudflow cone: the truncated mudflow and alluvial cones as an indicator of glacial genesis and the formation of mudflow cones by resedimentation of morainic material

The Zadgurbin valley mouth on the orogr. right-hand side of the Shimshal valley is bordered at an altitude of 3050 m by a mudflow cone with a diameter of about 1 km and a cliff height of 60 m (Photo 14). It is linked to a glacial catchment, that of the over-6000-m high Boesam Pir. In the lower part of the valley, the extremely steep Zadgurbin valley is completely covered by Late Glacial morainic deposits, providing

[5] The glacier tongue of the Baltoro glacier ends at 3300 m and is now also framed by two mudflow cones. It would be interesting to observe the interaction between end moraine and mudflow cone if the glacier were to advance.

the source material for large-scale mudflows (Photo 13). The Bandasar mudflow cone is divided into two by a central flow channel. In the orogr. left-hand segment the continuation of the Shimshal glacier end moraine, which is integrated in the Chukurdas alluvial fan, is embedded in the mudflow cone. However, there is very little evidence here of the end moraine, as only a small whaleback-shaped remnant peeps out at the surface of the mudflow cone.

The almost perpendicular cliff faces of the Bandasar mudflow cone raise the question of their origin and of the genesis of the entire mudflow cone. Basically the cliff faces may have been formed in one of two ways: (1) by fluvial undercutting (2) by glacial erosion, i.e., the mudflow cone would then be a kame. It seems likely that the distal parts of the mudflow cone have been undercut in modern times by fluvial processes mainly during the summer months, keeping them continuously steep. However, it should be noted that the central formation of a 'daughter' alluvial fan actually prevents undercutting of the cliff faces and also that the secondary talus cones from mudflow material at the base of the cliffs have not been washed away, so that we are dealing with old cliffs, now being reworked. Furthermore, the secondary talus cones at the cliff faces are evidence that the mudflow cone is disintegrating and no longer subject to the same processes as when it was being formed. Contemporary mudflow processes would destroy the cliff profile. These indicators support the hypothesis of glacial formation. Strong evidence in its favour is supplied by the preservation of kames on the valley sides directly downvalley from the mudflow cone (Photo 17). They are some tens of metres high. These debris accumulations adhere to the slope – they have no connexion with the valley floor and have lost all support; they crop out into the air. It therefore follows that the mudflow cone cannot be older than the above-mentioned kames, or else that the mudflow cone itself must have been deposited against an earlier glacier. Granite erratics on the 4350 m high Chatmerk pass are evidence of a Last Glacial Maximum ice thickness of more than 1300 m in the Shimshal valley (Kuhle, 1996b, p. 156). It also follows that the mudflow cone can only have formed after the Last Glacial Maximum, i.e., it was deposited against the glacier when the ice was less thick during the Late Glacial. Only after deglaciation could the mudflow cone develop in a semi-circular shape. In Postglacial time the mudflow cone continued to build up slightly owing to talus-supplying processes and to secondary cone formation in the frontal area. The mudflow cone was formed in a few catastrophic events by resedimentation of the morainic material available in the catchment area. Steep tributary-valley gradients combined with sometimes high meltwater rates provided favourable conditions for displacement of the morainic material.

High-level morainic deposits as source material for secondary talus slopes

The vertical distribution range of talus slopes in the Karakoram is remarkable. They occur not only in the zone of maximum debris production bordering the equilibrium line, but also in the zone between 1000 and 5000 m, occasionally lower or higher. Depending on altitude, they are formed by a variety of weathering processes. In all cases, debris production in the mountains is facilitated by the enhanced exposure to insolation, very frequent freeze-thaw cycles and sporadic plant cover. The Shimshal valley sides are bordered by talus slopes up to 1200 m high and several kilometres long with inclinations of up to 40°.

Especially in the broad valley sections, for example at Sost (2850 m), Garkuch (1800 m), Gilgit (1450 m) and Skardu (2200 m), ground moraine with occasional interbedded lake sediments mantles the valley sides up to several hundreds of metres above the valley floor. In the Shimshal valley too, morainic mantles cover extensive areas of the up to 5000 m high, glacially polished valley sides. These high morainic deposits supply the source material for secondary talus slopes and mudflow cones (Photo 19).

The Shimshal talus slopes have undergone considerable reworking by elongate mudflows with dam-like boundaries and debris lobes at their bases (Photo 19). The susceptibility of talus slopes to mudflows is due to their *high content of fine clays and silts.* The fine material of high-level morainic deposits is gradually transported downslope. Snowmelt is the time when high morainic deposits on the valley sides are mobilized, creating mudflows that flow over the talus slopes. In extreme cases the best material for mudflows is supplied by morainic talus cones, i.e., cones deriving directly from the redeposition of morainic material. Saturation causes the clay components to swell, leading to plastic flow. Because their individual elements interlock rather like building blocks, cones consisting solely of talus are more stable and tend to produce rockfalls in reaction to precipitation events. Rounded rock fragments from the morainic material are also found in places on the talus slopes.

Depression of the lower limit of nivation and the origin of rockfall gullies

Given the dry climate of the northwestern Karakoram, the question is how to account for the origin of the rockfall gullies, which are responsible for the formation of single large talus cones. For the development of rockfall gullies is due not only to repeated, purely gravitational falls of rock fragments – as the name suggests – but also to a considerable degree to fluvial processes, that is, meltwater flow from small cirque glaciers and snow patches. In other cases, ice avalanches have shaped them out of the bedrock. Rockfalls *later* took over from fluvial processes as primary users of the gullies. The lowering of the equilibrium line during the preceding LGM and Late Glacial was of necessity linked to a drop in the lower boundary of nivation. The talus cone has small supply funnels that are linked to low catchments extending to about 4500 m. At the present time they are free of ice and snow or contain only seasonal snow patches. The lowering of the nivation limit meant that the funne ls stored ice and snow and supplied abundant meltwater in the summer, in time causing the gullies to develop. Hence, the gullies were primarily of fluvial origin with some rockfalls during their initial development phase, and were later deepened by further rockfalls.

A valley mouth with no debris accumulations: the Pamir Tang valley and the thick morainic deposits in the Shimshal valley opposite the Yazghil glacier tongue

The segment of the up-to-2 km broad Shimshal valley between Shimshal and the Pamir Tang valley further upstream is the terminal basin of the former Shimshal valley glacier. In this segment, no tributaries join the trunk valley and so it seems strangely devoid of debris accumulations. Linked to catchments at elevations up to 6500 m, the Pamir Tang valley displays no large fluvial deposits at its confluence. Its middle section is steeply V-shaped near the valley floor and contains an abundance of talus slopes and morainic deposits that are several hundreds of metres high. So it is all the more surprising that there is no alluvial fan at the mouth of the valley. This absence is due to local glacial history. During Late Glacial time the valley mouth was almost entirely blocked by the advance of the Shimshal glacier. Evidence of this is provided by the up-to-700-m high and several tens-of-metres thick morainic deposits on the orogr. right-hand side of the Shimshal valley (Photo 11), on either side of the mouth of the Pamir Tang valley (Iturrizaga, 1997b). After the ice melted, the Pamir Tang river had to make its way through this morainic material before it could join the receiving stream. These Late Glacial moraines are remarkably well preserved, which, in view of the morphodynamic activity in the northwestern Karakoram, suggests they are young deposits. The glacial sediments covering the slope prevent debris accumulations being formed solely by slope processes. During Postglacial times the morainic deposits were – and still are – fluvially dissected into triangular segments several hundreds of metres in width.

Debris accumulations in the Momhil valley downvalley from the end of the Momhil glacier tongue to the confluence with the Shimshal valley: using glacial history to obtain a chronology of debris accumulations

The debris accumulations downvalley of the Momhil glacier tongue illustrate very clearly the linkage between debris accumulation formation and glacier stages (Photo 20). The 26 km long, NNW-facing Momhil glacier (36°17′–20′ N/75°04′ E) ends at an elevation of 2840 m, 5 km away from the confluence of the Momhil and Shimshal valleys (Meiners, 1996, pp. 139–146). This glacier-free section of the valley is marked by a historical and a much higher Late Glacial glacier level. The historical stage is terminated at 2790 m by an end moraine 2 km away from the modern glacier tongue. The elevation of this end moraine marks a distinct break in the height of the talus slopes. Whereas the upvalley talus slopes are about 50 m high, the height of those downvalley rises abruptly to a maximum of 300 m. Even without the presence of an end moraine – in case it has already been eroded – this distinct change in talus slope height should be sufficient evidence of an ice margin.

By dating the end moraine location using the classification of glacier stages proposed by Kuhle (1994, p. 260) it is possible to establish the time span of talus slope formation. The 50 m high talus slopes upvalley from the historical end moraine location must be younger than 400–180 years because the valley was previously occupied by the Momhil glacier. The talus slopes below the end moraines are much older. They started to form several thousand years after the retreat of the Neoglacial and Late Glacial glaciers. The Postglacial talus slopes are connected to the basal trough formed in the V-shaped valley. The concave U-shaped profile is conducive to the formation of talus slopes because accumulation naturally occurs here rather than on a steep slope. This basal, trough-valley-linked talus slope formation is also found at the mouth of the Lupghar valley and at the confluence with the Shimshal valley. Furthermore, the example of the Momhil glacier shows that talus slope formation occurs immediately after deglaciation – whereby displaced moraine and slope material may be involved in building the debris accumulations – and the glacial legacy may be destroyed very rapidly.

Debris accumulations in the Hassanabad valley (Batura-Muztagh/south Karakoram slope): A young glacier forefield and its debris accumulations, and the Postglacial collapse dynamics of glacially formed trough valleys

The north-south oriented Hassanabad valley (36°17′–28° N/74°36′ E) joins the Hunza valley downstream from Aliabad (2250 m) on the orogr. right-hand side of the Hunza valley. More than 100 m high glaciofluvial terraces have been deposited at the Hassanabad valley mouth, so the Hassanabad river has cut into them but has not built a large alluvial fan there. The Hassanabad valley has very steep, narrow trough-valley sides, owing to the highly resistant gneiss bedrock (Photo 21). The highest point of the catchment is Shispare Sar at 7611 m. The 15 km long Hassanabad glacier is an avalanche caldron glacier with correspondingly abundant supraglacial debris. Over a horizontal distance of only 2 km in the middle section of the trough valley, both flanks rise vertically by the same amount: from 3000 m to 5060 m on the orogr. right-hand side, from 3500 m to 5725 m on the left. At the valley head too, the south-facing steep face falls from 7295 m (Pasu II) to 4000 m over a horizontal distance of 3.5 km. In this narrow valley, only 150 m high Late Glacial moraine terraces occur on the orogr. left-hand side. Downvalley of the modern glacier tongue, at an altitude of 2400 m, the lower parts of the valley flanks are lined with a thin mortar-like layer. A 30 m high end moraine rampart bars the Hassanabad valley floor at an altitude of 2150 m and a distance of some 3 km from the valley mouth. It obviously marks a glacial advance in historical time[6]. The debris accumulation landscape in front of the Hassanabad glacier is characterized by recent short-term glacier oscillations: the lower flanks are decorated with fresh but already strongly gullied and shallow morainic deposits. The valley floor is carpeted with ground moraine. Talus accumulations immediately overlie the valley floor and hence cannot have developed fully before the glacier retreated in 1925. They stretch down from the slopes and cover the ground moraine. These talus slopes show a classic sorting of large blocks at

[6] With its spectacular oscillations of several kilometres in a few months around the turn of the century, the Hassanabad glacier counts as a textbook example of a surging glacier.

the foot of the slope and smaller fragments towards the apex. Furrowed by numerous closely spaced gullies, the young morainic material is undergoing rapid erosion, chiefly as a result of rainstorms.

The steep and smooth trough sides of the Hassanabad valley do not provide a suitable surface for the morainic material to accumulate. The area between the end moraine and the recent glacier tongue impressively demonstrates how much debris can accumulate over short periods. On the orogr. left-hand side of the Hassanabad valley, more than half the valley floor is taken up by a true talus cone with man-high boulders at its base, illustrating the active collapse dynamics of the oversteepened, glacially formed trough-valley sides after deglaciation (Kuhle et al. 1998).[7]

About 100 m high, the talus cone was built up after the ice melted in the first half of the 20th century and so – the end moraine having been dated to 1925 – it cannot be more than 60 or 70 years old. The Hassanabad valley was visited in mid-September 1992, shortly after the heavy precipitation of 7–9 September 1992. At this time the cone experienced many rockfalls, including boulders up to 1 m in diameter. It is not possible to deduce the age of debris accumulations from their size and thickness, or from sedimentation rates derived from these data. Extreme events that build up a large proportion of the debris accumulations in only a few hours, days or months, alternate with lengthy phases of non-activity or gradual debris accumulation.

Mass movements triggered by the rainstorm event of September 1992 also destroyed most of the main route across the Karakoram, the Karakoram Highway (Hewitt, 1993; Reimers, 1994; Iturrizaga, 1996, 1997b). Most heavily affected was the 25 km stretch of road through the Hunza gorge between the settlements of Bulchi Das and Muhammadabad (2300 m). The destruction of the Karakoram Highway shows how slope failure can result when human activity and glacially predetermined factors overlap. The bedrock consists of gneisses and granodiorite, which are both highly resistant and massive rocks. This makes the large number of landslides and rockfalls (Photo 22) even more remarkable. It is important to note that *recent mass movements do not create the now dominant slope forms but primarily destroy an older form*, namely the glacial relief dating from the Last Glacial Maximum to Late Glacial time.

A contribution to the discussion on recent debris production: the relationship between primary and secondary debris supply

The high proportion of resedimented and residual glacial debris accumulations in recent debris accumulations raises the question of how much contemporary primary debris is being produced from solid bedrock. Evidently, the diverse *secondary debris accumulations* redeposited from glacial sediments give a cursory observer the *impression that recent or autochthonous debris supply is much greater than it actually is*.

[7] Here reference should be made to Gardner and Hewitt (1990; p. 159), who present evidence showing how recent landslides were triggered by the surge of the Bualtar glacier in the Karakoram.

A talus cone with a slant height of 35 m, a height of 20 m, a radius of 30 m, and therefore an angle of slope of 33°, has a volume of 924.77 m^3 and comprises 1 178 097 square rocks whose sides are 20 cm long. Talus cones of such dimensions belong to the smaller examples of their kind, but are common in the Karakoram. If we estimate a time span of 10 000 years for the Postglacial period, a rock must have fallen every three days for such a cone to form. If we halve the cone volume for shallower talus slopes, a rockfall event had to occur every 6 days. Larger talus cones – which can reach lengths of 1000 m in the Karakoram – would need to average 10 to 20 times as many rockfalls.

Rapp (1960a, pp. 91–92) studied the recent morphodynamics of talus slopes in Spitsbergen over the period 1882–1954 and concluded that contemporary debris accumulations build up very slowly, although the talus slopes are very large and the study area is subject to strong frost weathering. This disproportion between supply and size of the talus slopes cannot be explained by hypothesizing that the supply surfaces are already exhausted by weathering processes, for there are high walls immediately adjacent to the talus slopes. Rapp assumes that debris production during the 10 000 year long Postglacial period was once much higher.

Field observations in the mountains of High Asia suggest that similar conditions also prevail: primary debris production is already past its peak, even though this is a high-mountain area with very intensive weathering processes. *Present-day debris production does not explain the immense debris accumulations*. They are a relict of the last glaciation phases.

The contradiction repeatedly observed in the field that *disproportionately large debris accumulations* occur beneath small catchments and vice versa, can be explained by the close connexion between debris accumulations and former glacial phases. ‘Disproportionately large’ debris accumulations are due to the redeposition of glacial sediments in the catchment, whereas ‘small debris accumulations’ show that little debris is produced on moraine-free valley flanks with less glacial influence.

Another argument supporting low debris production – considering the abundant availability of unconsolidated rock – is that, in comparison with intermediate elevations, few talus cones can be found in the snowline border zone where the highest number of freeze-thaw cycles are recorded. The number of talus cones increases with decreasing elevation, although in the case of primary talus cones we might expect to find the opposite: namely that most talus cone occur at high altitudes with intensive frost weathering. This underlines the fact that the talus cones of the intermediate elevations are subject to ‘outside influences’, i.e., induced by glacial processes. Hence, at intermediate elevations of the study areas in High Asia purely autochthonous, non-glacially influenced talus slopes are very rare. Glacially induced collapse talus slopes are frequent, even when they are not secondary talus slopes. In this case the bedrock subsides owing to the relief of pressure on the rock after ice-melt. Maximum debris supply occurred just after deglaciation when the oversteepened trough-valley sides and the unstable glacial sediments simply collapsed when the supporting ice melted.

Settlement and agricultural areas at the foot of rockfall slopes are good indicators of the extent of modern mass movements. In Shimshal boulders fell on the fields after slight rain in early August 1992. They did not come from the talus slope nor from the bedrock, but from the high-level morainic deposits above the talus slopes. The fact that it is at all possible for many settlements to occupy areas at the foot of 100-m-high, unstabilized rockfall slopes suggests that the talus slopes are not very active at present. The failure of the inhabitants' efforts to stabilize the slopes by planting *Hippophaë rhamnoides* bushes and laying the necessary irrigation canals into the talus slopes, may be due to the undercutting of the talus slopes by the irrigation canals themselves. On the other hand, the canals are destroyed by fluid mass movements such as mud- and debris flows and not by primary rockfall events.

The bareness of the debris accumulations in the dry high mountain regions suggests enormous recent activity there. Compared with other high-mountain regions, this area of debris accumulation is indeed very active; however the absence of vegetation is primarily due to lack of water and not to extreme activity. The fact that the debris surfaces are not stabilized is often due to fluvial undercutting of the talus slope base and not to recent active debris delivery from the catchment. In the case of the study areas in the Hindu Kush and Karakoram, contemporary *resedimentation of glacial debris is several times greater than the production of new debris*. In the long term, the present high redeposition rate of high-level morainic deposits means that the erosional regime in these mountains is gradually shifting back towards primary debris processes. When no morainic material is left, there will be no secondary debris deliveries worth the name. At the same time the lack of moraine cover will again expose the bedrock to weathering agents. In principle, it should be emphasized that at the end of the great phases of glaciation, such as the terminal Late Glacial, the debris that was collected by the ice was released on a large scale and became available for further formation by slope processes.

The distribution of debris accumulations in the transition zone from the Karakoram to the Himalayas: The Rakhiot valley, Nanga Parbat north side

The Nanga Parbat (8125 m), on whose northern slope the Rakhiot valley (35°14′–35°29′ N/74°30′–74°40′ E) runs down in a north-south direction, forms the western cornerstone of the Himalaya chain, which runs in close correlation with the Karakoram in this section of the mountain region. The Rakhiot valley falls by just under 7000 m over a horizontal distance of 28.5 km from the highest catchment area of the Nanga Parbat to the lowest level where the Rakhiot valley joins the river Indus at 1194 m (photo 23). The extreme relief of the Nanga Parbat already implies that the debris accumulations may be characterised by ice and snow avalanches into very low regions. The Rakhiot valley has no pronounced side valleys, so that for topographic reasons the formation of mud and alluvial cones can only occur on a limited scale. For the most part the side valleys are short steep branch valleys, at whose exits consolidated and unconsolidated talus cones as well as steep-sided mudflow-avalanche cones are deposited. In the Rakhiot valley gneisses as well as crystalline schists outcrop (Searle, 1991, pp. 291–295). The central-peripheral distribution of the debris accumulations from the mountain centre to the valley exit observed here is typical of many of the short longitudinal valleys among those valleys with catchment areas over 7000 m. Glacial residual debris accumulations develop in particular along the valley centre through the transformation of Late Glacial morainic deposits (Iturrizaga, 1998b).

The upper catchment area of the Rakhiot valley above 5000 m – Debris production induced by ice avalanches, and corresponding debris accumulations

Steep valley sides with ice balconies surround the Nanga Parbat basin, which is bounded by the Ganalo Peak (6601 m) and the Chongra Peak (6830 m). While ice avalanches 'heal' to glaciers below the very high catchment areas, beneath the lower ridges only ice avalanche cones are found. The ice avalanche cones successively block the supply funnels with their proximal cone sections, so that here glacier growth begins from the base. Beneath the Jiliper Peak (5206 m) are merely talus cones, which are overformed by avalanches. The current enormous debris supply via the erosive and planing activity of the ice avalanches on the valley sides has little effect on the debris accumulations of the valley sides. The debris is transported and deposited in and on the glacier and in its lateral surroundings. Only where the ice avalanches open into funnels connecting with talus or mud flow cones do the debris accumulations immediately benefit from debris supply. The small steep hanging glaciers as well as the ice avalanches prepare the potential supply funnels of the talus cones in the case of glacier retreat.

On the Rakhiot glacier the widely distributed fresh boulder masses bear witness to large mountain slip and landslide events. Bearing in mind the considerable avalanche activity and associated debris production, the sparse debris cover of the Rakhiot glacier is surprising. It appears in large extents as a blank ice glacier, whereby the tongue end is as usual for the ablation area heavily covered with debris.

Debris accumulations between 5000 and 3000 m with particular reference to the lateral moraine valley as debris accumulation areas

Lateral moraine valleys are a widely distributed feature in the Asian high mountain regions (Oestreich, 1911/12; Visser, 1938, p. 37). In particular the great width of the floors of the lateral moraine valleys with only little outward transport of the debris material by means of the receiving stream predestines them as favourable locations for debris accumulations. Glaciation of the valleys does not rule out the development of debris accumulations because of the presence of the broad lateral valleys.

The Rakhiot glacier is accompanied by lateral moraine valleys on both sides from an altitude of 3800 m downwards.

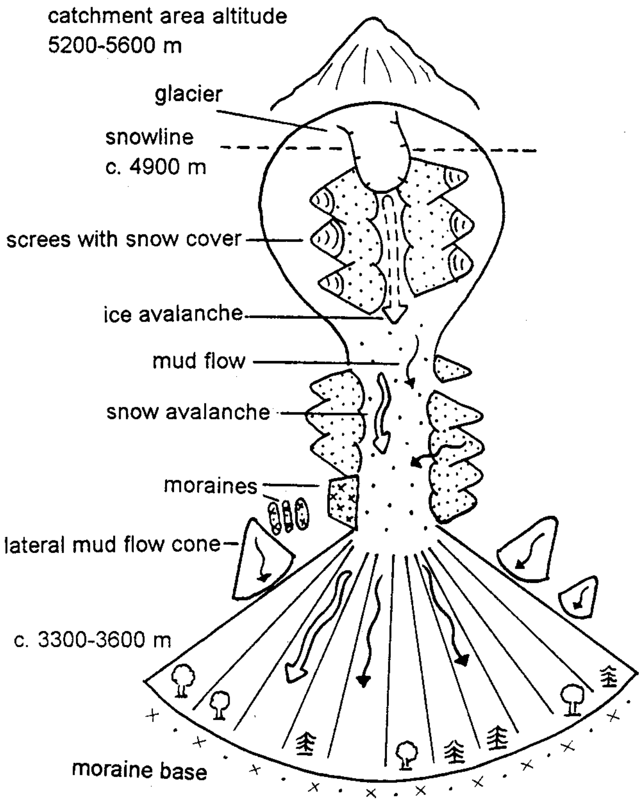


Figure 5. Highly active compound debris accumulation type (formed by avalanches, mudflows and rockfall) in lateral moraine valleys with a glacial catchment area.

At the beginning of the lateral moraine, that is at the conjunction between lateral moraine and adjacent valley flank, the talus cones cover the lateral moraines like a veil and assimilate these successively. Further downvalley the distance between lateral moraine and valley flank extends to 1 km near Fairy Meadows (3300 m). These two deposit forms, i.e., glacial and slope-dependent, tend in opposite directions in their deposit orientation, so that inevitably a system of competition between both deposit forms develops. The lateral moraine valleys are a product of high debris supply, which is produced in the upper catchment areas, and this oversupply of debris means that the glacier does not bound immediately on the valley flank, but rather a new morainic deposit bed is formed.

Above the lateral moraine valleys from an altitude of 4200 m, the Rakhiot glacier is accompanied on its orographic right-hand side by a Late Glacial lateral moraine about 300 m high, below the Buldar Peak (5602) and the Chongra Peak (6830 m). The good preservation of this lateral moraine in the high zone of intensive weathering and erosion processes supports its young age. Talus cones which collapse downwards at narrow points of the lateral moraine are to be found on the moraine terrace. It can clearly be seen how through these 'talus collapses', the debris cover, originally readily identifiable as a moraine, rapidly loses its facility to be easily diagnosed as a glacial deposit through resedimentation. In the course of time these ample lateral moraines will successively break through the Rakhiot glacier as a result of basal undercutting, and avalanches and rainfall will break up the surface of the terrace. These transitional debris accumulations are preserved in a similar manner further downvalley.

It can furthermore be observed that although the uppermost catchment areas demonstrate the most active debris production, in the long term we are dealing here with the genetically *most stable debris accumulations,* and interregionally, i.e. both in the arid and in the humid mountain regions of High Asia, the *most homogenous debris accumulations* are to be found at this altitude zone. For the most part these are talus cones overworked by avalanches (Figure 6).

The altitude of the catchment area of the lateral moraine valley debris accumulations extends to a maximum of 5600 m. Thus steep, short hanging glaciers, which release ice avalanches of broken-off ice, flow down from the crest areas reaching *just above the snow line.* At the valley exits of these short side valleys *highly active mudflow avalanche cones* are deposited (Figure 5). Many of these side valleys are funnel-shaped at their end and entirely covered with talus cones. This talus belt extends to an altitude of between about 4800 and 5400 m. These large unconsolidated debris collection basins with a narrow, steeply dropping valley bottom provide ideal conditions for debris flows and mudflows, with precipitation events, ice and snow avalanches as well as meltwater streams. Moraines are not preserved at this level, they are for the most part to be found in the lower levels of the branch valleys. In the variable range of the snow line, high levels of snow deposition overlap with temporary high levels of meltwater, so that the debris accumulations of the lateral moraine valleys show a very fresh surface, conditioned by wet mass movements. These mudflow cones have a high density of table-sized blocks with rounded corners. Erosion channels up to 2 m deep traverse the mudflow cones. The debris accumulations of the lateral moraine valleys coincide with the upper timber line, so that the distal parts of the debris accumulations are covered with vegetation (birch, pine, juniper). The forests are much broken by avalanches. Frequently one finds composite mudflow cones, i.e., the mudflow-avalanche cone receives debris from the resedimentation of the adjacent lateral talus slopes and small mudflow cones.

The debris accumulations of the lateral moraine valleys differ from the normal cone-shaped deposits of unglaciated valleys in that they are usually not undercut by the receiving stream and also do not have a central incision canyon. The distal base of the debris accumulations is formed from ground or lateral moraine material. Undercutting of the debris accumulations usually occurs by means of the glacier and not the lateral moraine valley stream.

Debris accumulations in the middle section of the Rakhiot valley (3000–2000 m) and the Rakhiot Gorge (2000–1200 m)

The degree of transformation of moraine terraces by mass movements in the central section of the Rakhiot valley between 3000 and 2000 m is still relatively low in comparison to other valleys at this altitude. Disintegration of the moraine outcrops into pyramidal columns and residual talus slopes

Altitudinal Zone	Type of debris accumulation
1200 – 1700 m	Gorge section with negligible debris accumulations, in the upper section resedimentation of moraine material
1700 – 3000 m	Transformation of moraine deposits by erosion processes in residual debris accumulations, the lower xeric timber line begins at ca. 2300 m and thus also the transition from consolidated to unconsolidated debris accumulations
3000 – 4000 m	Lateral moraine valley debris accumulations in the form of avalanche-, mudflow- and talus-cones, partially overworked by ice avalanches (from glaciers); in the distal cone areas the debris accumulations are vegetated; the tree cover is much reduced by avalanches, talus creep by means of periglacial processes
4000 – 5500 m	Avalanche debris accumulations, composite accumulations of ice, snow and debris, talus cones (sometimes with ice inserts), talus creep by means of periglacial processes
5500 – 8125 m	Flanks free of debris accumulations, ice avalanche debris accumulations

Figure 6. The altitudinal zones of debris accumulations in the Rakhiot valley.

takes place (Photo 24). In isolated cases, mudflow cones overformed by avalanches emerge from the steep branch valley downvalley from the moraine terraces. At the valley shoulder of Bezar Gali (3800 m) above Tato (2300 m) on the orographic left-hand side of the Rakhiot valley no debris slopes are to be found, but rather a cover of ground moraine overlies the valley flank. The erratics at an altitude of 3800 m as well as a 1400 m high ice fill of the Rakhiot valley, characterise the confluence of the Rakhiot glacier with the High Glacial Indus glacier (Kuhle, 1996a, pp. 148–149). The gorge section initiating the Rakhiot valley for the first 5 km is for the most part debris-free. At the upper end of the gorge isolated moraine remnants, which today are being resedimented, cling to the valley flanks up to 1700 m (photo 23).

Age classification of the debris accumulations

By means of correlation of the locational relationship of the debris accumulations with the glacial deposits, the debris accumulations can be placed in a relative time scale. A detailed age classification of the glacial sediments, made by Kuhle (1996a), is available for the Nanga Parbat area, which facilitates a corresponding classification of the debris accumulations. The debris accumulations above the High Glacial glacier surface may be much older than 17 000 years. As debris production and ice and snow avalanches are however very active at this altitude, the material on the surfaces of the debris accumulations can be very young, while the cone cores in contrast may contain debris materials of greater age. At altitudes above 4900 m no more debris accumulations characterised by or underlaid by moraines are to be found. Slope sections between the maximum High Glacial ice level and the Late Glacial glacier surface – i.e., between 4500 and 1800 m downvalley – were freed of ice in the late High Glacial and thus were available for debris supply and in some cases as sedimentation surfaces. The debris accumulations of the lateral moraine valleys could have been created as early as the early to middle Late Glacial and could have developed synchronously with the Late Glacial glaciation. The retreat of the Late Glacial Rakhiot glacier only slightly affects the debris accumulations deposited in the lateral valleys up to several hundred metres wide, and on the moraine terraces. Only in the area below the moraine terrace of Fairy Meadows up to a Late Glacial glacier terminus at 1700 m does a rapid backward erosion of the glacial sediments occur, due to the absence of ice and the resulting absence of a counterbalance of the moraine deposits clinging to the valley flanks. The Postglacial development of debris accumulations could take place from 13 000 B.P. onwards.

Debris-rich arid high-mountain areas of moderate to low relief energy and predominantly periglacial-nival influence: the Ladakh and Zanskar ranges

In the Ladakh and Zanskar ranges (33°30′–34°30′ N/75°50′–79°50′ E) similar climatic conditions prevail to those in the Karakoram; however the pattern of debris accumulation distribution is completely different owing to slighter variations in relief amplitude and therefore less glacial cover. Leh (3522 m, 34°09′ N/77°36′ E) receives an annual precipitation of 115 mm, of which 58 mm usually fall in just less than 7 days between May and September (Dronia, 1979, p. 464). The lowest local erosion level at Ladakh lies at 3000 m. At maximum catchment elevations of 6000 m relief energy is on the moderate side. The study area is devoid of forest. The catchments of the debris accumulations are chiefly fluvial or periglacial/nival. The Ladakh and Zanskar mountains give the impression of a mountain landscape drowning in debris (Photo 25). The contrast seen in the northwestern Karakoram between high, debris-free walls and an excess of debris in the valleys is not found here, where the entire mountain range is covered by debris of slope and glacial origin. In general, slopes covered by small-sized debris predominate; in fact they are characteristic of the entire altitude range between 3000 m and the firn line. Because of the lack of vegetation, solifluction processes are largely of the free type. Basically, slide movements dominate over fall movements in building up the dry debris accumulations.

Compound geomorphological accumulations – a typical sign of mountains with high relief amplitude – decrease as a result of the wider valleys and the low relief energy. In the non-glacierized mountain ridges the upper limit of debris accumulations is often not reached, and the high regions up to the mostly rounded peaks are covered with a thin debris mantle that is sorted by freeze-thaw action according to slope inclination.

The broad Indus valley, which is several kilometres wide near Leh, puts few restrictions on the development of the debris accumulations from the tributary valleys of the Ladakh and Zanskar ranges (Photo 25). The debris accumulation landscape is homogeneous, being characterized by the regularity of the coalescing mudflow- and alluvial fans on both sides of the valley. The fans have 3–4 km long slant heights and continue to spread over tens of kilometres into the Indus valley. It seems appropriate to distinguish between those debris accumulations (here termed '*exposed debris accumulations*') that emerge from their valley 'receptacle' and those that are deposited within the frame of the mountain ridges ('*partly surrounded by mountain ridges*' and '*debris accumulations surrounded by mountain ridges*'). The sides of the main fans are bounded by small subordinate alluvial or mudflow cones emerging from the lateral mountain spurs. These cones have an inclination of 8–15° and help to build up the alluvial fans. The steep, several hundreds of metres high, true talus cones that frame the fans in the northwestern Karakoram rarely occur in such dimensions here because of the lack of relief. Rare too are moraines located high on the valley flanks. The mountains surrounding the alluvial fans display local kame terraces bearing slope-derived debris accumulations. On the orogr. left-hand side of the Indus valley, glaciofluvial terraces from the trunk valley often lie in front of the fans. A well-developed glacial terminal basin above Leh indicates that the Ladakh catchments have experienced a fundamental change from glacial to fluvial or nival processes between Late- and Postglacial times. Because of their location in the snowline border zone, the mountains of Ladakh are especially prone to such transformations. For example, directly beneath the terminal basin above Leh there is a glaciofluvial mudflow-alluvial cone which is presently being aggraded or eroded by fluvial and nival processes only.

A transitional area from the eastern Karakoram and the Ladakh/Zanskar ranges to the western Himalayas: the northern Nun Kun slope – the cleared, debris-poor, glaciated valley heads

The Nun Kun massif (7135 m/7087 m, 33°55′–34°05′ N–75°50′–76°15′ E) in the western part of the Zanskar range, just under 200 km to the east of Nanga Parbat (8125 m) forms a transition between the eastern Karakoram and the Main Himalayan Ridge. Following the debris-rich massifs of the Hindu Kush, Karakoram and Ladakh mountains, the northern slope of the Nun Kun massif displays a very mixed range of debris accumulations in the middle segment of the Suru valley, with a paucity of debris in the upper catchment areas and diverse debris accumulations in the valleys. In the Nun Kun massif there is a glacial zone with several glaciers, up to 60 km long, that are chiefly characterized by ice wastage and remain within the bounds of their lateral moraines. At a maximum vertical span of 3500 m over long horizontal distances, the absolute relief amplitudes are moderate in the context of High Asia. The tributary valleys on the orogr. left-hand side of the Suru valley start at an elevation between 4800 and 4600 m and cross a confluence step to join the Suru valley at about 4000 m. In comparison with the desert-like aridity of Kargil (2800 m), the part of the Suru valley near the confluence with the Indus already enjoys more favourable conditions, with occasional rainfalls from the monsoonal fringes blowing from the south. The annual precipitation of this dry-alpine environment is estimated at 400–700 m.

The Suru valley has a classic trough shape (Photo 28). Especially on the orogr. left-hand side, between Parkachik (3490 m) and Tongul (3290 m), the Suru valley is mantled by relatively shallow morainic deposits that are several hundreds of metres high, the legacy of a Late Glacial valley glacier. At the mouths of the tributary valleys well-preserved end moraines and pedestal moraines occupy the valley floor.

The 10 km long Parkachik glacier ends as a potential valley-blocking glacier in the Suru valley. Only a few tens of metres are still open. In comparing the Parkachik glacier with the paraglacial debris accumulation forms of the Karakoram glaciers, it is most appropriate to proceed using negative criteria. The Parkachik glacier has neither lateral moraine valleys nor large paraglacial debris accumulations. Moraine ridges of former glacier highstands are no longer preserved, so that secondary glacial talus cones are absent. On the floor of the Suru valley there is a lenticular roche moutonnée, several hundreds of metres long and about 150–200 m high which is presently being gradually destroyed by rockfalls and collapse processes (Photo 29). It is covered by a thin veil of debris. *Current processes are destroying the ancient glacially moulded rock mound*. The orogr. right-hand side of the Suru valley consists of a similarly glacier-overridden mountain spur, only 800–1000 m high, and looks like a larger copy of the roche moutonnée on the valley floor (Photo 28). Its catchment area lies below the equilibrium line. Here too, large areas are occupied by unconsolidated talus cones and occasional mudflow cones. The Suru valley exhibits an inverse altitudinal distribution of dry talus slopes that is otherwise only found in semi-arid glaciated mountains, i.e., the proportion of unconsolidated debris accumulations increases with decreasing elevation.

A remarkable feature in the Suru valley is that the distal parts of the debris accumulations all end in a conspicuous convex curvature rather than the usual elongated or concave cone foot. These features are not true talus deposits but moraine accumulations, as is recognizable from the fact that they are being dissected into cone shapes by their catchments. Typical characteristics of the lateral boundaries of these moraine cones are the rows of erosion notches.

The Suru river is undercutting the distal moraine cones, and the soil profile shows rounded boulders embedded in a fine matrix, a characteristic feature of moraines. The Suru valley and the northern Nun Kun slope in the western Zanskar range exhibit few purely slope-derived debris accumulations in their upper glacial catchments. Owing to the thick flank glaciation of the pyramidal peaks, the area lacks the relief energy and ice-free rock areas necessary for a productive supply of debris. The bedrock of the northern Nun Kun slope consists of highly resistant metamorphic rocks (marble, amphibolite, hornfels, quartzite, and gneiss) that produce very little debris in the present climate. Most of the debris accumulations in the Nun Kun massif possess nival and fluvial catchments. Debris production by avalanches is probably negligible because of the low relief amplitudes, especially in the Suru valley.

Transition to the Kumaon-/Garhwal Himalayas: the broad pass regions and high plateaux as extra-local debris accumulation sites, with special reference to the More Plains (4600 m)

The broad high-mountain passes and high plateaux may be distinguished as special landscape zones with regard to their debris accumulations. Here, the development of the individual debris accumulation is controlled by the relief situation and the characteristics of the hydrographic network, as well as by climatic conditions. In particular, the low discharge rates of the small catchments facilitate the unimpeded development of the debris accumulations. Within the narrower pass area the relief amplitude is often reduced to a minimum. Gently sloping, often periglacially and glacially rounded accumulations characterize the landscape. For example, the Shimshal transfluence pass in the Karakoram has extremely rounded accumulations and the bedrock is covered with ground moraine. Slow downslope movements of the periglacial region dominate, rather than rapid fall processes.

Fifty km SE of Upshi (Zanskar) lies Taglang La (5328 m), where the Tibetan type of landscape begins, with broad rounded mountain chains. Here the bedrock – mostly limestones – is completely covered by solifluction debris with the stone stripes typical of freeze-thaw processes. Firn caps and perennial snow patches are only visible above 5500 m. This is one of the few study areas where the upper limit of debris accumulation is not reached locally. Non-glacierized mountain ridges are in parts covered with debris right up to the summit region, which is only possible because of the low relief and in particular because of the lack of summit walls. The high equilibrium line at about 5800–5900 m means that the relief is freely available for debris accumulations. Immediately south of the Taglang La the More Plains, a 54 km wide high plateau, start at an elevation of 4500–4600 m. Here we find optimal and unrestricted conditions for alluvial fan formation in a 3–7 km wide, flat-bottomed high-altitude valley. An interesting aspect of the high plateaux is that, when the equilibrium line drops to the elevation of the plateaux, they become either fully glacierized or develop into an accumulation zone. Accordingly the glacial deposits differ from those in the valleys of greater relief. On the high plateau, ground moraine deposits dominate the valley floor (cf. the comments by Kuhle, 1994, 1996b, about the Tibetan plateau). The alluvial fans of the adjoining mountain groups with radii of several kilometres and angles of inclination of about 1° in the distal parts merge gradually into the High to Late Glacial ground morainic deposits. This type of debris accumulation dominates the high plateaux and may be termed a ‘compound ground moraine-alluvial fan.’ These fans coalesce with the laterally adjacent alluvial fans and with those on the other side of the valley. Kames were observed at some valley mouths. The mountains surrounding the high valley floors reach altitudes between 5800 and 6000 m. The maximum differences in altitude are about 1500 m over a horizontal distance of several tens of kilometres.

The moderately debris-covered high mountains of the humid Kumaon-/Garhwal Himalayas (Trisul/Nanda Devi and Kamet massifs) with locally extreme relief energy

In this section of the Himalayas (30°10′ N–31°00′ N/79°10′–80°00′ E) – the Kumaon-/Garhwal Himalayas at the transition between the West and East Himalayas – the study area comprises the Alaknanda trunk valley and four tributaries, the Nilkanth, Hathi Parbat, Nandakini and Rishi valleys. Mountains like Nanda Devi (7816 m) (Photo 32), Trisul (7120 m) and Kamet (7756 m) are among the highest catchment areas. The western side of the Kamet slope drops from 7756 m over a horizontal distance of 12 km to 3996 m at Ghastoli. Among the highest relief amplitudes are those at the west side of Dunagiri. From the 7066 m high Dunagiri the Tolma Gad valley drops down to an elevation of 2161 m at Surajthota, over a horizontal distance of only 11 km. In contrast to the broad and clearly structured long valleys in the western Karakoram – such as the Hispar or Shimshal valley which runs more than 60 km in a straight line – we find a closely meshed valley network here. Short side valleys cluster around the transverse gorge of the Alaknanda and Dhauli Ganga valleys. Modern glaciers are between 3 and 15 km long.[8] Perfectly preserved trough valleys with gorge-like bottoms down to an elevation of 1400 m control the topography of the main valleys and thus also the development of debris accumulations in the form of basal talus slope ramps. The narrowness of the valleys impedes the formation of alluvial fans and mudflow fans in many valley sections. Only inner slope locations permit narrow terrace deposits, on top of which talus cones and slopes have accumulated. Closed, largely ungullied valley walls chiefly composed of gneisses and granites (Gansser, 1964, pp. 108–115) are typical of the valley sections between 1500 and 3000 m.

[8] Nand et al. (1989, pp. 22–30) postulate an extensive Pleistocene glaciation in the Kumaon Himalayas, with end moraines occurring down to a valley floor elevation of 1000 m. Erratic boulders are found near Joshimath (1800 m) for example. Large areas of the lower Himalaya chains are covered by morainic material. Recent fieldwork by Kuhle (1995) has also found evidence of an LGM ice margin at an altitude of 1100 m in the Alaknanda valley near Pipalkoti (30°26′15′′ N/79°26′16′′ E).

Abundant precipitation from the summer monsoon and moderate temperatures tend to hinder frost shattering. Debris production is lower in the humid-tropical mountain regions than in the continental mountain areas of the Karakoram. So the actual zone of less well-consolidated talus cones begins only above the treeline at 3600–3700 m.

The Alaknanda, Nilkanth and Hathi Parbat valleys

From 3100 m onwards the Alaknanda valley starts to widen after the 18 km long stretch of gorge beginnning at Josimath. The valley floor is occupied by broad mudflow and alluvial cones on which settlements have mostly been built. At the approach to Badrinath (3020 m, 30°44′12″ N/79°29′27″ E) a debris landscape of glacial origin opens up, characterized by a marked U-profile, a valley floor covered by ground moraine, glaciofluvial deposits and lacustrine sediments. Purely slope-derived debris accumulations take second place to polygenetic debris accumulations interfingered with morainic deposits. The debris accumulation structure is controlled by glacially induced collapse dynamics. The debris accumulation morphology of the valley sides exhibits similar forms to those in the Hindu Kush and the Karakoram, where the dissected morainic deposits covering the slopes have been carved into a triangular shape. Here too, the talus cones contain remobilized morainic material previously covering the slopes. On this valley flank there are also cone-like accumulations several hundreds of metres high alongside the gullies of the mudflow-alluvial cone. They rise abruptly, *without a feeder gully*, up from the evenly shaped, upslope part of the slope. The sides of these debris accumulations display sharp erosion-induced edges. So the full-form of this '*pseudo talus cone*' resembles a piece of pie rather than the usual cone segment. Initially the ground moraine mantled the valley sides completely. The triangular outline was *subsequently carved out of the glacial debris mantle* by lateral erosion by the slope channels. The terrace-shaped incision at the distal cone ends is due to the fact that the base is composed of ground moraine. After deglaciation the slope-derived debris accumulations built up on top of the ground moraine (Figure 7). In their initial phase, the cones of the orogr. right- and left-hand sides of the Alaknanda valley were connected by the morainic base, which was later dissected by fluvial processes. In the upper Alaknanda valley, collapse debris accumulations (rockfall slopes) near Mana are slowly beginning to cover a 100 m high ground moraine terrace. The *morainic core* is now *concealed*.

A compound accumulation of slope and glacial sediments is common in the upper catchment areas of the Kumaon Himalayas: the end moraine ramparts lying on the talus cones (Photo 31). They were deposited on the talus accumulation by short, steeply flowing hanging glaciers. The end moraine loops are being dissected by the meltwater channels of the retreated glaciers and are gradually being incorporated into the talus cones. They can be seen mainly in the Nilkanth and Hathi Parbat valleys. Other conspicuous features in these valleys are the feeder gullies of the permanent and discontinuous avalanche cones that are already assuming a gorge-like shape and may be designated as *glacially induced V-shaped gullies* (Photo 31). What is remarkable about these gorges is that they become broader upslope, i.e., they are notched into the rock in a narrow V-shape. This *upslope widening* does not correspond directly to fluvial development but can be attributed to the existence of a glacier that formerly covered the valley wall. Near the summit the gully had the longest time to develop. Only when the glacier level sank did gullying continue further downslope (Kuhle, 1982).

Debris accumulations in the Nandakini valley (Trisul-S/SW side)

Upwards of 3500 m, the Nandakini valley, whose highest catchment reaches its peak at the Trisul (7120 m), contains numerous glacial debris deposits of former glacier termini of Postglacial age (Photo 30). The bases of the slope debris accumulations are truncated mainly by lateral moraines left behind by the glaciers. It is remarkable that this deep circular valley contains no high-level morainic deposits. Hence there are almost no secondary debris accumulations of morainic material, and the transitional glacial debris accumulations play a background role. Compound accumulations due to avalanche, rockfall and mudflow processes occur frequently, but the last-named process is never dominant.

The shape of the Nandakini valley shows a structurally controlled asymmetry of the valley sides in terms of outcropping beds and bedding planes (Photo 30). The paraclinal orogr. left-hand side is formed by outcropping beds and is therefore very steep, with different types of debris accumulations everywhere. By contrast, at the altitude zone of the valley floor between 3500 m and 4200 m, the cataclinal orogr. right-hand side of the Nandakini valley has more gently inclined bedding planes giving a homogeneous slope with only a thin moraine cover.

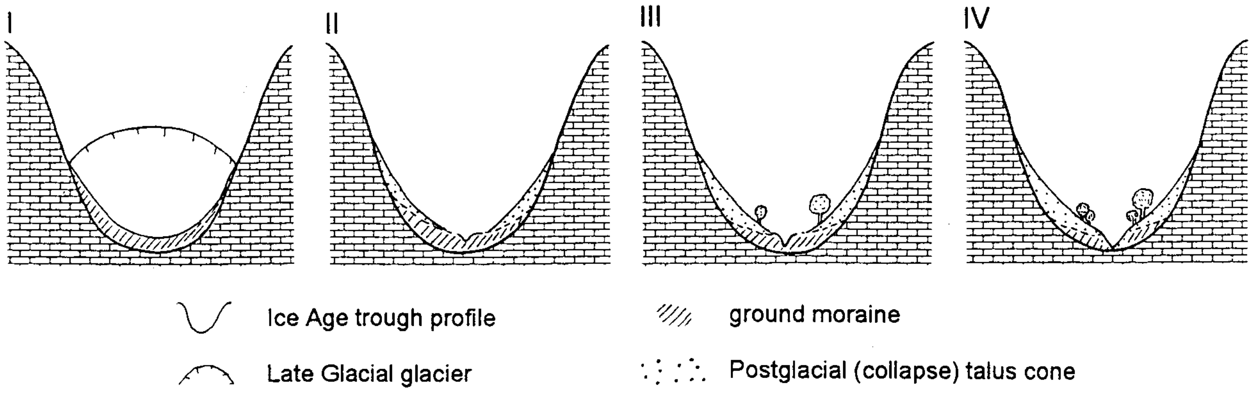
The following hypsometric sequence of debris accumulations can be seen on the paraclinal, orogr. left-hand side of the Nandakini valley:

(1a) Between 3500 and 4000 m: vegetation-covered talus cones with central flow channels generated by avalanches or meltwater. The cone slopes undergo only slight reworking by rockfall or fluvial processes.

(1b) Between 3500 and 4000 m: vegetation-covered talus cones without central flow channels, but with high debris transport from the rockfall gullies on the rock slopes. The debris accumulations listed in (1) and (2) contain ground moraine at their bases.

(2) Between 4000 and 4500 m: Mostly vegetation-free true talus cones: The abundant falling debris covers a kame terrace at the base of the talus cones. Avalanches modify the cone surfaces. The cones consist largely of fresh, hand- to table-sized blocks of granite and gneiss. The individual components are stacked with almost no matrix material, so the blocks are stably interlocked owing to the high friction of the angular fragments.

(3) Between 4500 and 5000 m: Discontinuous and permanent avalanche talus deposits, occasionally ice avalanches modify the cones.



I Late Glacial glacier in the Ice Age trough valley

II After deglaciation the valley floor is carpeted with ground moraine, on which are sucessively deposited slope-derived collapse debris accumulations.

III The debris supply of the valley flanks decreases. The surfaces of the debris accumulations begin to consolidate. The ground moraine material is still visible on distal exposures.

IV (Collapse) talus cones mantle the morainic base.

Figure 7. Development of the debris accumulation landscape following the Late Glacial deglaciation.

(4) From 5500 m onwards ice avalanche cones are formed, which are now feeding the glaciers.

The moderately inclined slope sections on the orogr. right-hand, cataclinal side of the Nandakini valley are blanketed by thin, frost-shattered debris in the slate between 4000 and 48 000 m. There are very marked creeping debris movements in the periglacial zone.

Just as glaciers tend to lose ice after overcoming a steep rock step and then regenerate downslope, so a similar phenomenon of *accumulation-regeneration* occurs in the formation of debris accumulations. Two stacked ice avalanche talus cones are connected by a gully whose channelling effect guarantees renewed lower cone formation. This coalescing proves to be a very typical feature of the steep Himalayan flanks. It extends over several levels and can only occur because of the great relief amplitude of more than 3000 m and the alternation between cliff walls and steep rock ledges that permits debris to accumulate.

Cirque-like trough-shaped depressions occur in the cliff wall between 3900 and 4200 m. They measure as much as 100 m in diameter. Their formation is due to former glacial processes when glacier termini extended down to lower elevations and ice avalanches occurred during ice retreat, gouging out the valley sides at the steeply truncated snouts. Today these depressions are undergoing fluvially induced linear erosion by periodic thread-like waterfalls.

Areas with a moderate to low number of debris accumulations in the semi-arid Lower Dolpo area with largely moderate relief energy

The Lower Dolpo area (29°00′–29°20′ N/82°30′-83°15 E) lies between the Kanjiroba Himal in the N/NW and the Dhaulagiri Himal in the SW. With regard to debris accumulations it represents an interesting transitional area between the arid to semi-arid areas of the Karakoram and the extremely humid southern Himalayan slope. The Kanajiroba Main Peak (North) attains 6861 m, the Putha Hiunchuli in the south of the study area reaches 7246 m. Precipitation at Jumla (2424 m, 29°18′N/82°12′ E) amounts to merely 696 mm/yr (Kleinert, 1983, p. 47). The mountain environment displays a sparse steppe vegetation (e.g., juniper, deodar). The xeric lower forest line practically coincides with the lower boundary of solifluction. This close proximity stands in sharp contrast to the situation in the Alps where the solifluction zone ends above the forest line. In this study area too, the presence of a discontinuous xeric lower forest line results in a bilateral distribution of the bare and sometimes unconsolidated deb ris accumulations in the altitudinal profile. A detailed geomorphological description of the Dhaulagiri Himal was given by Kuhle (1982). According to Kuhle (1995) a 550 m thick outlet glacier of the Tibetan Plateau still filled the Thulo Beri Khola at 1900 m during the Last Glacial Maximum.

The transitional glacial debris accumulations in the Barbung Khola and Thulo Bheri valleys (Photos 33–35): in the lower reach of the Barbung Khola, at an elevation between 2000 and 2900 m, we find numerous transitional glacial debris accumulations consisting primarily of morainic material. Downvalley from Kakkotgaun (3000 m) up to 150 m high moraines were deposited by a Late Glacial glacier, especially on the orogr. right-hand side of the Barbung Khola valley. They bear a gappy conifer vegetation and the river undercuts parts of their bases. The cliff faces are disintegrating into conical secondary debris accumulations and residual debris accumulations several tens of metres high. This conical shape is not a product of aggradation, but is due to subsequent dissection of a fossil debris accumulation. The moraines stand out clearly in the slope profile. Because of their thickness, a very lengthy transformation process will be necessary before linear erosion integrates them into slope-related debris accumulation processes.

Apart from lake sediments upvalley from this moraine site, this Barbung Khola valley section seems to have few purely slope-derived debris accumulations. The valley system consists of very steep-walled U- to V-shaped valleys. Further downvalley, between 2600 and 2300 m, the Barbung Khola takes on an narrow V-shaped form. The valley walls have a thin moraine cover and occasional furrows due to mudflows. Again and again, structure-related true talus cones and slopes, not higher than 100 m, are interbedded in the rock outcrops.

On the orogr. left-hand side of the Thulo Beri valley, at 2100 m, echelons of landslides are visible in the schists. These were not pluvially triggered saturation flows; local outflow has caused saturation of the bedrock and its debris cover. In comparison with the nearby southern side of the Himalayas, both the slides and the resulting slope retreat make a negligible contribution to debris accumulation.

Recent debris production is nowhere near as great in this semi-arid part of the mountains as in the Karakoram. The talus cones range between a few metres to mostly not more than 10–20 m in height, so that only the basal slope zone is covered by these debris accumulations. Generally the radii of the mudflow cones measure a few tens of metres. The cones often consist of medium to small blocks and are of structural origin. Generally, the morainic material forms an almost intact blanket overlying the bedrock; only in places is it conspicuously dissected by erosional furrows. The surface of the moraine cover is semi-consolidated.

Debris accumulations in selected study areas of the Central Himalayas: Extreme relief energy on the southern side of the Himalayas – debris accumulations on the south side of the Annapurna with special reference to the Modi, Mardi, Seti and Madi Kholas

Debris accumulations and factors of relief, climate and lithology

The study focuses on the debris accumulations of the southern slope of the Himalayas (27°30′–29°00′ N/82°30′–88°00′ E). The distribution of debris accumulations in the high mountains is primarily a function of relief conditions. Hence, regardless of climate, the *debris accumulation zone* may *be reduced to a very narrow altitudinal belt owing to high relief energy*; in some places it may even disappear, as a result of extremely steep relief over long vertical distances. This is the case at the southern slope of the Annapurna-Lamjung massif where no frost-weathered true talus cones have formed because of the steep relief (Photo 36). Here, the ice-avalanche altitudinal zone merges into the debris accumulation region of the fluvial zone. Some 30 km away from the Annapurna basin – Annapurna I (8091 m), Annapurna South (7219 m), Hiunchuli (6441 m), Machhapuchhare (6993 m) – the erosion level of the Himalayan forelands is located as much as 7000 m lower (e.g., Kusma at 1000 m). The valleys of the Modi, Seti and Madi Khola are correspondingly gorge-like. In complete contrast to this are the relief conditions at the northern Annapurna slope whose local erosion level is the Tibetan Plateau at an elevation between 4000 and 5000 m.

Extreme relief conditions are also the reason why catchments may span various climate zones. A high percentage of the debris accumulations may be described as *allochthonous*, i.e., the *elevation of the deposition* site is considerably *lower than the climatic zone where the debris originated.* The *catchment's transformation from 'glacial' to 'fluvial'* generally takes place more quickly along the length of the cross valleys of the Himalayas than in the Karakoram. In the Himalayas the main ridge is adjoined in the south by the Himalayan foothills which scarcely exceed 4000 m, so that the catchments are purely fluvial. In the Himalayas, debris-free walls with heights of several thousand metres alternate with wide glaciofluvial terrace landscapes at low altitudes from about 1500 m downvalley. The formation of alluvial cones and mudflow cones by the side valleys cannot prevail against the trunk valley deposits, which are sometimes as much as 200 m deep. In the transverse gorges many collapse debris accumulations, moraine debris accumulations, and less thick glaciofluvial terraces form a link with the mountain foreland. The transitional glacial debris accumulations are fewer in the Himalayas compared with the Karakoram, there are fewer high-level moraines and therefore secondary debris accumulations are less important.

Whereas the Karakoram is largely divided by longitudinal valleys, the main valley system on the south side of the Himalayas consists of *transverse valleys*. This directly affects the distribution of debris accumulations. Longitudinal valleys have more space and therefore more favourable depositional conditions than the cross valleys with their gorge-like sections.

The debris-producing freeze-thaw regime was considerably less active on the humid and cloudy windward side of the Himalayas than on their lee side. The forest zone is a continuous belt up to elevations of 3600 m. So it is not surprising that consolidated debris accumulations are dominant. The precipitation values for the southern slope of the Annapurna Himal are among the highest in the Himalayas. Kleinert (1983, p. 91) gives an annual precipitation of 6170 mm for Lumle (28°17′ N/83°48′ E). Whereas debris transport over short distances is dominant in dry areas, through-transport over long distances is characteristic for the southern slope of the Himalayas. The lower boundary of solifluction lies at about 3000 m in the study area, i.e., freeze-thaw-influenced debris layers are still found up to 600–800 m below the forest line (Kuhle, 1987, p. 30). In the Himalayan foothills lateritic weathering reaches up to 2000 m on the southern slope of the Himalayas (Boesch, 1974; Kalvoda, 1992, p. 46) and produces several metres of regolith.

In both the Himalayas and the Karakoram mainly massive rock such as granite is found in the central parts, and metamorphic rocks and sediments such as slate and limestone occur in the foothills. The highest peaks do not always consist of magmatic rock, as one might expect, but may also be built up of sediments, like for example the Nilkanth, Annapurna or Mount Everest. Not only the type of rock but also its bedding has a decisive influence on the amount of debris produced. The summit flanks of the Annapurna massif have heavily jointed southern walls (Kuhle and Roesrath, 1990, p. 17). The rock structure predetermines the directions of the debris feeder channels and the accumulation sites.

The outcropping beds turn out to be more productive suppliers of debris than the bedding planes – a phenomenon here termed '*systematic talus cone formation resulting from the erosion of outcropping beds*'. The dependence on structure of relief formation and the corresponding debris accumulations is easily recognizable in the vertical range of a few metres up to several thousand metres at the great summits.

The high-energy ice avalanches also carve out the structural shape of the mountain at high altitudes and their tracks follow structural irregularities in the rock. When the equilibrium line is higher, the gullies carved out by the ice avalanches continue to be deepened by rockfall and avalanche processes. That is, today's true talus cones with nival catchment areas are then located beneath gullies that are of glacial origin.

The foothills of the Himalayas are characterized by landslide deposits; however, permanent saturation has disguised the severe geometry of the debris accumulations and *amorphous debris accumulations* are now dominant.

In spite of the greater maximum elevations of the catchments, the ice cover is much less on the southern slope of the Himalayas than in the Karakoram. So the paraglacial debris accumulations only extend as far as about 3600 m at most. The avalanche cone glaciers that stretch down as far as 2300 m at the farthest, benefit with regard to their lower elevations from the steep relief conditions that cause through-transport rather than providing accumulation areas. Hence the valley flanks are also largely devoid of debris and the usual transitional debris deposits from the accumulation area to the glacier tongue are absent.

At medium elevations, the gradually developed rockfall slopes tend to be rare; collapse debris accumulations dominate especially in the narrow stretches of valley. Moraines covering the valley sides are not as typical in the humid zones of the Himalayas. They have either already been destroyed by precipitation or stabilized by a plant cover. By contrast, large 'morainic plugs' are more frequent in the wider valley sections, for example in the middle Barun, Buri Gandaki and in the lower Barbung Khola valleys (Photos 33–35).

The Modi Khola

The Modi Khola is just under 45 km long and originates in the Annapurna basin. It joins the Kali Gandaki at 686 m. Between the Hinko gorge (3000 m) and Chandrakot small mudflow cones and alluvial cones occur only very sporadically. Most of the mudflow-alluvial cones have a central, deeply incised canyon. They are generally single cones, with a simple, non-interlocking structure. The slopes are marked by many small-scale landslides (Ives and Messerli, 1989), however they generally do not develop into large debris accumulations. On the orogr. left-hand side of the Modi Khola valley, typical slate flows are visible in mid-slope locations at 1700 m. Owing to the high humidity, *sediment through-transport is much greater in the Himalayas* than in the arid areas. The zone of high slide frequency lies between 700 and 2000 m. Redeposited morainic material was discovered up to an elevation of 1400 m.

At Hinko Cave (3030 m) the Hiunchuli and the Machhapuchhare are connected with the valley bottom line at 3000–3500 m over a horizontal distance of only 9.6 km. The valley shape varies between gorges and narrow troughs, which are lined and shaped by snow- and ice avalanches. Remnants of snow avalanches were observed up to an elevation of 2000 m in January 1995. To the south of the Machhapuchhare and Hiunchuli there is a distinct break in the processes of debris supply. Whereas ice avalanches are responsible for debris production and slope formation at high-level catchment areas, further downvalley, in catchments at 4500 m, it is snow avalanches that modify the slopes and debris accumulations but do not shape them. Even farther downvalley we enter the area in which ancient, partly glacial, debris is redeposited below the forest line. Young debris is chiefly produced by landslides. One such may be seen at the confluence of the Modi Khola and the Chomrong Khola near Chomrong (2155 m) (28°25′56″ N/83°49′42″ E).

The Seti Khola: fluvial side-valley debris accumulations compete with trunk valley terraces

Upvalley from the confluence of the Mardi Khola and the Seti Khola, a gigantic glaciofluvial terrace landscape has formed at an elevation of 1100 to 1400 m in the Seti Khola valley.[9] The Seti Khola originates between Annapurna III (7855 m) and Annapurna IV (7525 m). In the Seti Khola we find a clear dominance of trunk valley debris accumulations in the shape of a 150–200 m high terrace fill of the valley. The tributaries are scarcely able to deposit cone-shaped debris accumulations, rather they cut gradually into the terraces, so that there are two competing systems: the conical debris accumulations of the side valleys and the terraces of the trunk valleys. The terraces consist of up to 7 major levels, sometimes with minor sub-terraces in between.

The Madi Khola: Paucity of debris in the upper catchment areas resulting from extreme relief energy

The Madi Khola originates between Annapurna IV and Annapurna II. In combination with the Lamjung (6931 m) in the east, its southern walls form an impressive steep face (Photo 36). Over a horizontal distance of just under 10 km the massif drops from just under 8000 m to 2500 m, a difference in altitude of some 5500 m. The valley head lies in a very narrow valley basin, a few hundred metres wide. A 2 km long avalanche cone glacier runs southward from the foot of the wall. Its lobe ends at 2300 m, *an unusually low elevation for a modern ice margin* in the Himalayas. The southern flank is practically devoid of debris. Flat parts of

[9] According to Fort (1987) the sediment deposits in the Seti Khola valley and further downvalley in the Pokhara Basin are due to an earthquake 500 years ago.

the wall are occupied by small ledge glaciers. The ice load on the narrow ledges often causes ice to break off. A main avalanche track runs between Annapurna II and Lamjung Himal. Either these funnel-shaped depressions are a sort of initial stage in the process of juvenile valley formation or else they are supply channels for future true talus cones should the equilibrium line rise. A talus slope belt – otherwise so typical of frost debris zones – is absent here because of the steep relief. The foot of the wall is bordered by ice avalanche cones and not by true talus cones. If we remember that the lower boundary of ice avalanches of the other 8000 m peaks is at 4000 m on average – possibly even higher in places – in the Himalayas, it becomes clear that the debris accumulation pattern plays a special role at the southern Annapurna slope.

Debris accumulations in the Manaslu region with special reference to the transverse valleys of the Buri Gandaki and the Marsyandi Khola

The Manaslu massif is bounded by two of the large Himalayan transverse valleys, the Buri Gandaki and the Marsyandi Khola (28°00′–28°40′ N/84°15′–85°00′ E). Both these trunk valleys are largely cut into gneisses, which being highly resistant have retained their steep-sided trough-valley glacial profile. The valleys of the Himalaya forelands cut into the weakly resistant slates of the Navakot nappes that are highly prone to slides and mudflows when saturated. The rock distribution largely controls the type of debris accumulation. In the altitudinal zone below 800 m where the Navakot nappes control rock structure, broad slope failures due to saturation are the dominant process of slope retreat. Debris accumulations ranging in shape from bulbous to irregularly conical have built up below the scars. Sometimes distinct depositional accumulations are absent altogether since the debris is immediately removed by receiving streams as a result of the high saturation rates. The catchments of these debris accumulations are mostly only a few hundred metres higher in elevation than the area of debris accumulation, so we are dealing with an autochthonous process. Isolated mudflow-alluvial cones with radii of several tens of metres have built up in the narrow valley sections of the Buri Gandaki. The debris accumulations contain many coarse blocks.

The catchment areas rise abruptly to more than 5000 m towards the Himalayan interior. This rise is accompanied by the transition from the slides that dominate in the slatey rocks of the foothills to the linear mass movement processes where there is a great horizontal distance between the source area and the depositional site and the debris accumulations are often allochthonous. In Postglacial time, the glacially rounded gneiss walls have been destroyed well below the thalweg by fluvial undercutting and also by collapses controlled by release joints. In the transverse valleys, landslide and rockfall debris are the most conspicuous debris accumulations (including those downvalley from Jagat (1235 m), cf. Jacobsen, 1990, pp. 31–32). Secondary glacial debris accumulations are less well-developed here. Even large ground moraine outcrops at 2200 m on both sides of the Buri Gandaki produce strongly cemented, even steep walls without any notable basal secondary debris accumulations. On the other hand, the few wider stretches of valley like that at Philam (1595 m) are characterized by thick, up to 150 m high glacial accumulations (kames) that are now undergoing fluvial incision and at whose bases mudflow-alluvial cones with a radius of 300 to 400 m are being deposited. In the central section they are presently being incised by mudflow pressure.

In the middle Buri Gandaki the gorge shape is even more pronounced than in the lower course. Over a horizontal distance of 10 km, the Shringi Khola from Shringi (7177 m) in the Thaple Himal connects with the confluence with the Buri Gandaki at an elevation of about 1500 m, i.e., over a relief difference of 5677 m. Glaciofluvial terraces are frequent, shaped into a conical or semi-circular form by the meandering Buri Gandaki river.

The altitudinal zone between 3400 and 3900 m is characterized by the more frequent occurrence of various types of transitional forms between mudflow-, rockfall- and avalanche cones with different recent activity and with periglacial and glacial catchment areas. Special types of debris accumulation are the mudflow-alluvial cones directly adjoining the recent glacier termini in front of which lie thick, Late Glacial, sometimes Neoglacial, fluvially divided end moraine loops.

One example of this is the glacier forefield of the north-eastern Manaslu glacier which also has a small proglacial lake. Downvalley there is a glaciofluvial transitional cone with a length of some 700 m. It consists largely of resedimented morainic material. These outwash-plain-like accumulations are typical forms of debris accumulation between 3500 m and 4600 m in the upper unglaciated reaches of the Himalaya valleys (in contrast to the Karakoram where these valley sections are generally glaciated).

The forest line is located at 3700 m in the Buri Gandaki and the transition from the clearly activity-controlled bare debris accumulations to the vegetation-poor or bare debris accumulations that are also climate-controlled begins upslope. From 3800 m onwards, occasional true talus cones can be observed. Farther upvalley they dominate the valley flanks in the side valleys of the Buri Gandaki as paraglacial talus cones.

The Jarkya Himal on the orogr. left-hand side of the Buri Gandaki, opposite the Manaslu massif, already forms a transition to the Tibetan-type landscape with rounded accumulations undergoing bound and free solifluction. True talus cones are rare here, and morainic debris covers the gentle slopes. The view westward from Larkya La (5213 m) gives a good overview of the accumulations of the upper Dudha Khola in the Peri Himal (photo 37). The highest summits are the Himlung (7125 m) and Panwal (6885 m). Here too, there are many paraglacial debris accumulations in the form of diverse types of talus cones and talus slopes, as there are in the other study areas, in both arid and humid mountain regions. Generally speaking, *the various forms of debris accumulation become more similar with increasing altitude in mountain regions although the climates are* *fundamentally different*. On the one hand, conditions of debris production become more uniform because freeze-thaw patterns in arid and humid mountain regions become more similar with increasing altitude; on the other, similar depositional conditions prevail in the upper glaciated catchments of the climatically different mountain regions.

The orogr. left-hand side lateral moraine valley of the Dudh glacier starts in a narrow V-shape at an altitude of about 4500 m and widens downvalley to 3700 m, becoming increasingly trough-shaped (Photo 38). Small mudflow cones and collapse features can be recognized only occasionally on the valley floor. These inactive lateral moraine valleys are very typical of the Himayalas. The environment here shows that the lateral moraine valleys are chiefly a product of excess debris in the upper catchment areas – i.e., they are built up by glacially transported debris – rather than resulting from active debris delivery on the immediately adjacent slopes.

The debris accumulations in the Marsyandi Khola are similar to those in the Buri Gandaki, with some local modifications (Figure 8). Downvalley from Thonje (1810 m), gorge-type debris accumulations can also be observed (collapse talus slopes consisting of coarse blocks, sometimes resting on glaciofluvial terraces, landslide accumulations, fluvial side-valley debris accumulations, strongly truncated by the receiving stream). At the confluence of the Musi Khola (flowing down from the Himalchuli western slope) and the Marsyandi Khola at 1100 m there is an extensive kame terrace landscape that impedes recent autochthonous debris accumulation at the slope bottoms.

Jacobsen (1990) has described the glacial history of the Manaslu Himalayas. The ice margins of the Last Maximum Glaciation postulated by Jacobsen (1990, p. 70) at about 1000 m in the main valleys have been called into question by moraines recently found at 450 m near Dumre in the Marsyandi Khola (Kuhle, 1995). With regard to the age of debris accumulations, this would mean that debris accumulations older than the ‘LGM’ are only to be found downvalley from this last-named ice margin or at the same level as the LGM glacier surface. This is confirmed by pre-Quaternary laterites occurring on the unglaciated domes of the Himalaya Hills. Small talus fans rest on the incised ground moraine deposited in the trunk valley. In the ice margin zone we find a characteristic thaw environment with kames. However, the kames in the middle reaches of the Buri Gandaki are of Late Glacial origin. This means that the mudflow-alluvial cones whose feeder streams make their way through the kames must be younger than these glacial accumulations and therefore of Postglacial age. Being the result of Late Glacial deglaciation, the collapse debris accumulations are chiefly Postglacial or in many cases historical in age. The destruction of the rounded parts of the valley flanks implies that they were of prehistoric glacial origin.

Only moderate debris cover at sometimes extreme relief energy in the humid Central Himalayas: the Makalu massif (8463 m) with the Barun and Arun valleys

The easternmost study area is the Makalu region with the Barun and Arun valleys (27°17′ N–27°55′ N/86°50′–87°15′ E). Over a horizontal distance of some 60 km, Makalu (8463 m) is connected to the Himalaya foreland at an elevation of only 457 m near Tumlingtar. The middle Barun valley cuts into the Barun gneisses, while, in petrographic terms, the lower reach of the Barun valley already leads on to Navakot and Kathmandu nappes of the Arun valley (Bordet, 1961; Gansser, 1964, pp. 160–161).

Because of the high elevation of the upper Barun glacier the paraglacial lateral moraine valleys are only very slightly developed between 4700 and 5100 m here. Farther upglacier the moraine ridges adhering to the valley sides determine basal slope activity. The most active recent debris production occurs here in the snowline border zone. The Barun glacier surface bears a heavy load of supraglacial debris. It should be noted that the debris accumulations of the lateral moraine valleys of the upper Barun glacier are located above the forest line and therefore bear only a thin alpine meadow vegetation cover in the distal zones.

At the foot of the south side of the Makalu valley the Barun valley is very wide, with favourable conditions for debris accumulation at elevations between 4000 and 4700 m in the unglaciated high-altitude valley reaches. Between the base camp at Makalu (4800 m) and the Shershon alpine meadow there is an unglaciated valley section especially characterized by Late Glacial to historical moraine accumulations. The Late Glacial moraines at 4600–5000 m are several hundreds of metres high and have been resedimented by fluvial processes, producing a wide, almost 500 m long mudflow-alluvial cone consisting of coarse blocks and resembling an outwash plain. The glaciofluvial debris accumulation is composed of sometimes man-high blocks. In contrast to the upper catchments in the Karakoram, the presence of unglaciated, high valley floors enables such glaciofluvial debris accumulations to spread out at high elevations.

The transformation of the ice-age trough-valley profile into a V-shaped valley profile and its collapse debris accumulations (photo 39): The middle Barun valley between 3900 and 3200 m has a conspicuous glacial trough-valley shape strongly reminiscent of landscapes in Norway with their bell-shaped mountains (*Glockenberge*). In the basal part of the trough valley, i.e. the first hundred metres between the valley floor and just below the trough shoulder, a zone of frequent glacially induced collapse features has been established. One of the largest collapse features in the Barun valley can be found at 3800 m on the orogr. right-hand side between the lower Barun glacier tongue and the alpine meadows of Yangri Kharka (3595 m). At this locality the valley bears moraine terraces on which the landslide deposit rests.

Further down the Barun valley, the valley is completely filled with morainic accumulations, which now bear a thick vegetation cover. Only the undercutting river carves out

Altitudinal zone	Type of debris accumulations
Up to 800 m	Unconsolidated and consolidated owing to oversaturation of the talus cover, debris accumulations of sudden origin (slide accumulations) Autochthonous mudflow- and alluvial cones of relatively small dimensions (slant heights between 20-300m) with central incision Debris accumulations partly built up by resedimentation of glacigenic material
800–1500 m	Lower gorge area with very few debris accumulations, occasional coarse-blocky mudflow- and alluvial cones (cone radii measuring several tens of metres), otherwise glaciofluvial terraces Rockfall and landslide accumulations, release-joint-controlled, i.e. by disappearance of the Late Glacial and High Glacial glacier infill and by extreme saturation Many unspecific amorphous debris accumulations
1500–3400 m	Transverse gorge with many rockfall- and landslide accumulations At occasional sites connected to high-level catchment areas allochthonous debris accumulations, possibly avalanche-modified In the wider parts of the valleys moraines breached and resedimented by fluvial processes resulting in moraine-derived secondary debris accumulations
3400-3900 m	Frequent occurrence of allochthonous mudflow-alluvial cones, i.e. with nival and glacial catchment areas Glaciofluvial, extensive mudlow alluvial cones built of very coarse blocks, transitional cones True talus cones modified by avalanches Solifluction debris formations Prehistoric consolidated true talus cones
3900-5500 m	Paraglacial debris accumulations in the form of unconsolidated true talus cones and small, partly consolidated mudflow accumulations (radius in metre range) Composite accumulation forms of snow, ice and debris Periglacial debris mantles in the more gently sloping terrain of the arid Larkya Himal
5500 m and above	Formation of ice-avalanche talus cones where catchment area elevations permit

Figure 8. Debris accumulation zones in the transverse valleys of the southern slope of the Himalayas with reference to the Buri Gandaki and the Marsyandi Khola.

pronounced unconsolidated cliff walls, against which small talus accumulations have been deposited. In the middle Barun valley, between 3500 and 4000 m, the presence of two formation systems of different ages is obvious in view of the rounded accumulations and the craggy ones destroying them. The former are due to glacial accumulation processes and the latter to recent processes of linear erosion and collapse.

If we now leave the Barun to look at the Arun valley, we see that glacigenic V-shaped valleys are dominant. In the section between 600 and 1300 m fewer mudflow- and talus cones are visible, not least because of the narrowness of the valley. The fluvial catchment areas reach elevations of only 3000–3500 m and the regolith is stabilized by abundant vegetation. The valley sides are partly composed of slate and are extremely prone to landslides. Morainic deposits are often the only largish flat areas on the slopes (for example at Num, 1400 m, pers. comm. by Prof. Kuhle during fieldwork on 22 November 1994).

Synthesis of field results

The close link between glacial history and debris accumulations

Quaternary glaciation is the major control of the Postglacial debris accumulation landscape in the mountains of High Asia. In the middle and lower elevations of all the study areas, the morainic relicts of Late Glacial glaciation and the debris accumulations resulting from their redisposition dominate over primary debris accumulations due solely to slope and fluvial processes. On the one hand, the frequent occurrence of talus accumulations (talus cones and talus slopes) is due to intensive weathering processes and to the direct impact of the release of pressure on the valley sides due to the loss of ice support after deglaciation (glacial debris accumulations resulting from collapse processes). On the other, many of the talus slopes were shown to be resedimented morainic material and not primary debris deposits.

The glacial landscape of residual debris accumulations, i.e. the moraines that underwent post-depositional reworking by fluvial processes, displays features similar in appearance to depositional accumulations deriving from slope processes. Like terraces, which can be due to both accumulation and denudation, cones were shown, on the one hand, to derive from deposition, and, on the other, to have been sub-

sequently carved out of unconsolidated material. The latter results in a passive debris accumulation landscape which is created by fluvial dissection of glacial sediments rather than by recent supplies of new debris.
Because of the large-scale legacy of glacial sediments these allochthonous debris accumulations play a major role as debris suppliers. In most of the valley systems the type and distribution of debris accumulations are determined by the diverse morainic deposits and by their type and state of preservation. Bedrock plays a minor role in debris production. Basically, the residual glacial debris accumulations are better preserved in the Karakoram than in the Himalayas. The abundant debris of the semi-arid mountain areas is not due solely to climatic factors, i.e. to intensive weathering processes, but also to the former glaciation.

The disproportion between catchment sizes and accumulation sizes

The examples presented from the high mountains of the Hindu Kush demonstrate the disproportion between the size of the catchment area and the corresponding accumulation. Huge, fluvially shaped debris accumulations have been deposited at the mouths of small and short valleys. Such accumulations cannot derive from the autochthonous debris produced in the catchment itself for the simple reason that not enough debris is produced there. The only plausible explanation for the huge dimensions of the debris accumulations is that they also contain resedimented morainic deposits and a ground moraine base. The disproportion between catchment size and debris accumulation continues down to lower elevations, which constitutes evidence that the lower valley reaches below 1500 m were glaciated. By contrast, relatively small debris accumulations have built up below large catchments, implying that primary debris production – with no glacial influence – is low.

The distribution of debris accumulations as a function of topography and relief energy

Whereas cross valleys are dominant in the Himalayas, the Karakoram valleys are generally longitudinal, running parallel to the main mountain chains. As a result of these different relief configurations, the two mountain areas each display a specific pattern of debris distribution. The longitudinal valleys are very broad in places, creating favourable conditions for debris deposition. By contrast, the gorge-like cross valleys with very juvenile side valleys inhibit debris accumulation because of the lack of suitable deposition sites and because of the dominant transport capacity of the receiving stream.

For reasons of relief, i.e., high relief energy, entire debris accumulation belts may be absent from the geomorphological elevation pattern. For example, typical true talus accumulations are missing in parts of the steep slopes of the southern Himalayan declivity. The ice avalanches of the high source walls are directly succeeded by the fluvial zone, where there is a close interlinkage of debris accumulations with glacial and purely fluvial catchments.

The extent of Postglacial and current debris accumulation production

The current rate of debris production is turning out to be too low to account for the huge volumes of debris presently blanketing the valleys. High morphodynamics in the mountain relief primarily contributes to the remobilization of ancient unconsolidated glacial fill. In all probability, debris accumulation peaks immediately after each phase of deglaciation. This link was observed even at historical areas of glacier retreat.

Catastrophic debris accumulation

At the present time catastrophic debris accumulation is plainly visible particularly in the northwestern Karakoram. One single event, triggered by rainstorms, sudden meltwater flow or, more rarely, by an earthquake, can bring a debris accumulation close to its climax stage. Various subsequent debris supply processes have little morphologic impact on debris accumulation. A ‘mega-event’ is unlikely to recur at the same locality because the previous event has already removed the easily transportable unconsolidated material in the catchment area. Deviations from annual mean precipitation values at the level of extreme events can be decisive factors in debris accumulation.

The age of debris accumulations

The types of debris accumulations presented here are very young forms in geomorphological terms, i.e. the majority are not older than 12 000–10 000 years before present. A considerable proportion of these are composed of resedimented unconsolidated material, i.e. the debris itself may be much older than the accumulation it presently constitutes.

Regional-climatic and supraregional types of debris accumulation

In the course of the study it proved possible to distinguish between regional-climatic and supraregional types of debris accumulation. Regional types include aridity-induced unconsolidated true talus accumulations of low and middle elevations between 1000 and 3500 m in the very dry high mountains of the Hindu Kush, the Karakoram, and the Ladakh and Zanskar ranges. Upslope, these are followed by bare talus accumulations of the frost action region, which also occur on the southern Himalaya slope above the forest line upwards of 3600 m, and thus count as supraregional types of debris accumulation. These accumulations are devoid of vegetation mainly because of mass movements rather than lack of water. Whenever arid high-mountain regions have a forest zone, the unconsolidated true talus accumulations located in the periglacial and fluvial zones are distributed bilaterally. Debris accumulations with composite and complex debris supply (debris delivery by lateral subordinate talus- and mudflow cones, resedimentation of high-level morainic material etc.) occur primarily in dry regions, as do the broad mudflow-alluvial cones resulting from favourable topographic conditions (longitudinal valleys) coupled with a high debris supply. Secondary unconsolidated loose debris accumulations deriving from high-level morainic deposits can be found particularly in the wider stretches of the Karakoram valleys. By contrast, small, highly dynamic mudflow (alluvial) cones composed of semi-consolidated coarse blocks are widespread on the southern slope of the Himalayas. They receive debris from feeder gullies rather than from the adjacent slopes. Many of these debris accumulations are characterized by a high percentage of coarse blocks embedded in a fine matrix. Typical of the Himalayan foothills are the numerous oversaturation-induced landslide masses with unspecific deposits. Furthermore, the glaciofluvial terraces deposited at the trunk valley mouths compete strongly with the debris accumulations of the tributary valleys.

The similar course of glaciation during the LGM and the Late Glacial in the Karakoram and the Himalayas produced similar supraregional types of debris accumulation which were individually modified according to the prevailing climate. These debris accumulations include the various types of transitional and residual glacial debris accumulations in loose material and the collapse debris accumulations in bedrock. Formation of the last-named accumulations results in the destruction of the ice-age mountain environments which still dominate the landscape.

Debris accumulations in high-mountain regions of low relief

The low-relief high-mountain regions in which the glacial zone is absent, e.g. in Ladakh, in many cases do not even attain the lower boundary of debris accumulation and their high elevations are characterized by an extremely homogeneous debris accumulation pattern, mainly consisting of microforms with the debris creep of the periglacial zone.

Genetic series of debris accumulations

The present study sets great value on the perception of debris accumulations as genetic series, considering debris accumulations not only as isolated landforms but in a context of landscape genesis and evolution. By means of the identification of typical series of genetic debris accumulations – especially in the transitional area between slope-related and glacial debris accumulations – the individual debris landform can be set in an evolutional context and characteristic stages of transitional glacial debris accumulations can be identified.

Hypsometric morphological change of the debris accumulations

In the Karakoram and Himalayas debris accumulation types tend to become more similar with increasing altitude. In arid and humid mountain regions higher than 3600–3800 m we find similar types of true talus cones and avalanche-shaped debris accumulations – mostly as paraglacial debris accumulations.

Between 1500 and 3000 m broad and thick moraine-influenced mudflow-alluvial cones occur in the wide reaches of the Karakoram valleys. In the Himalayan foothills, however, there is less fluvial formation of debris accumulations. The narrow transverse valleys prevent debris from accumulating.

Centre-to-periphery distribution

Transitional glacial debris accumulations are most common in the middle reaches of the valleys. From there, morainic deposits – and therefore secondary accumulations – decrease in both directions, upvalley towards the upper catchments and downvalley towards the lower elevations.

Paraglacial debris accumulations

Extensive glaciation in the northwestern Karakoram and the fact that the glaciers stretch far below the equilibrium line lead to a high percentage of paraglacial debris accumulations in this study area. The highly active, lateral moraine valley debris accumulation with a composite debris supply from avalanches, mudflows, rockfalls and glacial catchment area is presented as a category of debris accumulation.

The catchments of the debris accumulations

Debris accumulations with an allochthonous catchment – the place of deposition is located at a lower elevation than the source area – occur very frequently in mountain areas with strong relief. Many catchments of the Postglacial true talus accumulations underwent major modification in prehistoric times. This is especially true of catchments located in the fluctuation zone of the equilibrium line shifts during the LGM and Late Glacial. They were transformed from glacially shaped to nivally or fluvially shaped catchments.

The results of the study in the context of current research

The results of the study stand in sharp contrast to previous – and sparse – publications on debris accumulations in the high mountains of Asia with regard to both the origin and the age of such accumulations. The first aspect refers to glacially induced debris accumulation, the second to the young age of the deposits. The high percentage of glacially influenced debris accumulations down to the low elevations of the mountain forelands stands in contradiction to the traditional-minimalistic opinions of the extent of glaciation in these high mountains.

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The history of glaciation of the Rolwaling and Kangchenjunga Himalayas

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Abstract

The extent of the Postglacial is characterized by a main end moraine, which is called Great Lateral Moraine. In general its outer slope is very steep and the recent ice terminal retreated inwards and lost much volume. Between this stage of historical/latest Neoglacial an ice marginal position was found, which can only be classified into the earliest Neoglacial because of its glaciogeomorphic position. It lies ca. 5–6 km outside of the historical moraines and leads to snow line depressions of 300–600 m. This stage can not mixed up with the latest Late Glacial stage. Relating to the Late Glacial only moraine terraces or remnants were found in the steep valleys. In the Kangchenjunga Valley there is a large end moraine complex of Late Glacial at 2700 m, 27 km down-valley of the recent glacier termini and in the Yalung Valley (Simbua Khola, Kangchenjunga SW) we found a lateral moraine wall 600 m above the valley bottom of Torontan. In the Rolwaling Valley several indicators imply a former glaciation of the whole valley, which stretches out into the Bhote Kosi. In consideration of the maximum glaciation of Last Glacial (LGM) which has extended lower than 1000 m in the investigated areas it can be assumed that the levels of moraines valley- inwards are younger. Snow line depressions of 300–600 m for the Neoglacial (earliest stage) and 900–1200 m for the Late Glacial can be calculated.

Introduction

The extent of glaciation is a question of current interest in the reconstruction of prehistoric climate, since glaciers directly document climatic change. This study provides a record of Post-to Late-Glacial glacier stages, the sequences of which are assigned chronologically. The chronology follows Kuhle's classification (1994) in which the sub-recent to historical glacier stages from 1950 AD to 1700 yBP are differentiated from the Neoglacial stages (1700–5500 yBP) in the Post Glacial and the latter are differentiated from the Late Glacial.

The compilation of a relative age classification according to their glacio-geomorphologic position is supported by a calculation of snow-line displacements according to the method used by Kuhle (1988). Particular importance must be placed on the elevation of the catchment area, which has a decisive influence on the extent of the glaciers. When calculating the snow line, the average summit elevation is related to the final height of the glacier. The snow-line depression is obtained by subtracting the recent snow-line from the calculated snow line (Sm). The extended method uses the factor snow-line difference (FED) to determine a real snow-line value (Sr). This factor is determined empirically and takes into account the different gradient conditions of the accumulation and ablation areas. For reasons of comparability and due to the lack of a cartographic basis, the snow-line depression is determined using the calculated snow line (Sm), unless stated otherwise. 14C samples were taken to determine absolute age, but most of the results are not yet available.

The key locations include the signs of glaciation found outside of the encountered glacier stages in the glacier approaches and considerably further down the valley. If glaciation indicators are assigned to the Last High Glacial, then the ice margins beyond the historical stages are Neoglacial or Late Glacial. In the areas studied, a dimension is achieved for the High Glacial that can only be explained with the aid of the catchment areas of the southern Tibet Plateau and its outlet glaciers. In the light of such ice filling, it should also be mentioned for the Late Glacial advances that it is not known to what extent the High Glacial ice has disappeared in the meantime or to what extent it contributed to Late Glacial ice accumulation.

Only a short selection of previous studies of former glacial extents in the adjacent areas to Rolwaling and Kangchenjunga Himalaya can be given here. Observations have been done by Heuberger (1956) and Heuberger and Weingartner (1985) in the Dudh Kosi (Everest South slope). For the glacial extent of Last Glacial Maximum in the lower Khumbu Himal (Dudh Kosi glacier) below 2500 m they calculate a snow line depression of 1000–1100 m (1985 p. 79). Further indicators were ranged into older glaciations (Heuberger, 1986, p. 29). Postglacial glacier stages were investigated in W Khumbu (Cho Qyu southern slope) by Kuhle (1987) with the help of 14C datings. Many authors have discussed the glacial fluctuation in the Langtang Valley. Shiraiwa and Watanabe (1991) stressed out, that the Lama stage at 2600 m only allows a classification as Neoglacial

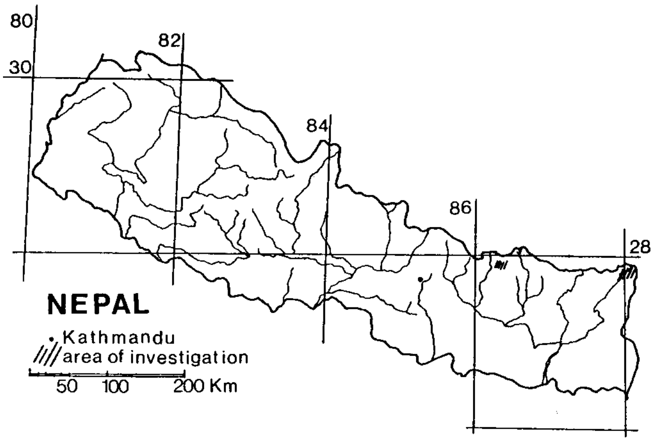


Figure 1. Area under investigation.

and not Late Glacial. The glaciation history of the Annapurna and Dhaulagiri range is interpreted in the detailed study of Kuhle (1982). Quite recently on the central and eastern Himalayan southern declivities, deep ice margins from Tibetan outlet glaciers at 460–900 m with snow-line depression values of up to 1600 m are described by Kuhle (1990, 1997, 1998). For instance, the deepest signs of glaciation in the catchment area of the Manaslu Himalayas are found in Buri Gandaki on the SE declivity at 680 m and on the SW side in Marsyandi Khola even as far as Dumre at 460 m (28°07′20″ N, 84°26′ E) (Kuhle, 1997, p. 125, 127). In contrast, Jacobsen (1990, pp. 78–79) describes maximum glaciation characteristics in the Manaslu region Marsyandi Khola only up to 1050 m and 1040 m in the Buri Gandaki. Fort (1986, p. 108) described Neoglacial moraines at 1400 m in the Seti Khola, (Annapurna III and IV) and a Late Glacial glacier extent to 1127 m. At Thumma in the Tamur Valley of the Kangchenjunga Himalayas, Kuhle (1990, p. 420) found an ice-margin indicator at 890 m and in the Arun Valley, the catchment area of which includes the Makalu SE side with the Barun Valley, at up to 500 m (27°24′ N, 87°08′30″ E) (Kuhle, 1997). Kalvoda (1979, p. 20, 21) described Late to High Glacial glaciation features only in the Barun Valley of the Makalu SE massif.

In this article, the boundaries of the Post Glacial to the Late Glacial are differentiated taking the Rolwaling Khola and the Kangchenjunga Massif (Figure 1) and their times since Last Glacial Maximum (LGM). In Rolwaling as well as in Yalung/Simbua Khola on the Kangchenjunga SW side, Neo- to Late Glacial ice margins can be distinguished.

Rolwaling Khola: Description of the area studied

The Rolwaling Valley (27°52′ N, 86°25′ E) is located in central Nepal on the southern declivity of the High Himalayas (Figure 2). At an east-west extension of 24 km, the Rolwaling River flows into the Bhote Kosi at 1400 m. The Bhote Kosi originates in the Tibetan Highlands and crosses the Himalayas from north to south. The glacial trough profile of the upper part of the valley to Beding changes downstream into a glaciofluvially carved, gorge-like, V-shaped valley.

The valley flanks are very steep on both sides and are characterised by a steep lower slope that is covered with thin debris cones, and a very steeply inclined valley shoulder above, which is heavily polished and abraded in the middle longitudinal section of the valley (Photo 1). Flank glaciers which end at approx. 5100 m hang down from the valley ridges, especially in southern exposure. The upper tree line, consisting of Rhododendrons, occurs at 3900 m.

The largest glaciers, Trakarding (Photo 2) with a length of 17 km and Ripimo (Photo 3) with a length of 11 km, the catchment areas of which are mostly south-facing, make up the valley end. Ripimo is an avalanche basin and Trakarding a firn hollow glacier type, each of them having heavily debris-covered glacier tongues. The real snow line (Sr) (method: Kuhle, 1988) of the Trakarding is at 5600 m. The average catchment area level is 6350 m, with the highest peak being at 6943 m. Both glaciers end at approx. 4500 m.

The Ripimo glacier is channelled through a 5500–4800 m high intermediate valley ridge in the valley basin (Photo 3). A neighbouring, 4 km long valley glacier, Kang Nachugo (Photo 3), forces its way from orographic right next to the Ripimo glacier to the valley outlet and ends with a steep terminal moraine at a base elevation of 4600 m. During a higher glacier stage, medial moraines were formed here. A further small valley glacier, Ripimo Nup (Photo 3), ends in the wide lateral moraine valley of the Ripimo at 5100 m (Figure 2).

In the NE-facing Yalung basin orographic left, there are 3 short hanging glaciers, the largest of which is the Yalung (Photo 4) with a length of 3.3 km. The recent snow line of the pure-ice glacier Yalung Ri (Photo 5) was determined to be 5150 m using Lichtenecker's method. Kuhle's method with the factor for snow-line difference results in 5308/5292 m.

Further hanging glaciers exist on the orographic right and left Rolwaling Valley flanks, beginning at ridge elevations of 5400–6700 m.

Historical and neoglacial glaciation

Large Historical to Neoglacial terminal moraines of 300 m fill the valley confluence area. A displacement or change in the flow direction of the former glacier tongue can be seen in the Ripimo glacier. At least 3 areas of displacement of the former glacier terminus can be seen from deposits of moraine material at the base of a basal moraine (Photo 6). It can be clearly seen that there was an ice flap protruding over the left lateral moraine, where the glacier leaves the valley flank and turns down-valley. The flow direction towards the opposite valley flank is also clear. The meltwater at present flows through an outlet that was created by the outburst of a small dammed lake in 1991 (Mool, 1993). Mud flowed off as a result of the fluidity of the loose moraine debris.

An equally large terminal moraine complex forms the boundary of the Trakarding glacier. The current glacier terminus calves into a glacial lake, the Tsho Rolpa (Photo 2, 7), which has tripled in size since the 1950's. At this time, it is 5 km long and 0.5 km wide. In the latest frontal moraine part, there is a 2.5 m wide opening through which drainage occurs. On its way downstream, this water also

↑*Photo 1.* Looking downvalley towards the West into the middle section of the Rolwaling valley between the settlements Na and Beding (▼). The U- shaped valley flanks are strongly undercut by the river at both sides. The portion of debris along the lower parts of the valley flanks is less. The higher parts of the flanks are polished and incised by the meltwater (↙) of the small hanging glaciers. Locality Rolwaling Khola. (Photo S. Meiners, 30 October 1997.)

↑*Photo 2.* Looking towards the North East over the Tsho Rolpa Lake and the steep glacier front of the Trakarding glacier at 4500 m. The glacier tongue of the 17 km long Trakarding glacier breaks off into large ice floes. If huge pieces break off, there is a big risk of a glacial lake outburst, because of the water wave, which is able to destroy the moraine dam. Former glacier surface heights from the subrecent stages to the Postglacial can be seen (◀). The peaks with flank ice are towering high (6660 – 6729 m) above the glacier. Locality Rolwaling Khola. (Photo S. Meiners, 6 October 1997.)

↑ *Photo 3.* View from 4800 m towards the North into the Ripimo basin with the Ripimo glacier (■), the Ripimo Nup glacier (○) and the Kang Nachugo glacier (▲). The lateral moraines of the Ripimo and the Kang Nachugo glacier formed medial moraines. With a maximum altitude of 6801m the recent Ripimo glacier stops at 4500 m. The historical end moraine of the Nup glacier has been partly destroyed by a mudflow (↙), whose material deposited into the lateral moraine valley of the Kang Nachugo glacier. The Nup glacier was not connected with the Ripimo and Kang Nachugo glacier during the Latest Glacial Maximum. The valley divide is covered by ground moraine material up to 5550 m. One of the former glacier surface levels can be seen at the orographic left side of the valley divide above the small lake (– –). During the late Late Glacial the valley divide was partly overflown by ice, but during the early Late Glacial it was overflown completely (see Photo 11). Locality Rolwaling Khola. (Photo S. Meiners, 13 October 1997.)

↑ *Photo 4.* The 3.3 km long Yalung pure ice glacier lies in the Yalung basin, which has a northern exposure. The lateral moraine at the left side sets in at 5175 m and represents the oldest, early neo-Glacial stage. At the same time, there was no contact to the hanging glaciers of Yalung Ri (see Photo 5). A small meltwater lake was dammed up below the cirque –step. Locality Rolwaling Khola. (Photo S. Meiners, 14 October 1997.)

↑ P*hoto 5.* The small hanging glaciers Yalung Ri (■) and the neighbouring glacier (▲) facing North- East. The recent snow line runs at 5150 m with a catchment area at 5630 m. The historical moraines of the latest Glacial Maximum (□) are sharply divided from a neoglacial lateral (➞) moraine. Locality Rolwaling Khola. (Photo S. Meiners, 13 October 1997.)

↑ *Photo 6.* View from 4200 m into the upper Rolwaling valley, where the glaciers Ripimo and Trakarding left their terminal moraines of the historical and neo-Glacial period. The Ripimo glacier drains through a mudflow channel, which was formed after an outburst of a small moraine dammed lake in 1991 (➨). Next to the mudflow the elder part of neoglacial moraines can be seen (➞).In the background the ridge of the Trakarding end moraine is visible (▽). The main discharge drains next to a big boulder. The stability of the slope can be destroyed, if the boulder comes out of its position or if the water penetrates into the moraine body. The risk of lake outburst is permanently given. Locality Rolwaling Khola. (Photo S. Meiners, 5 October 1997).

↑ *Photo 7.* The Tsho Rolpa lake in front of the Trakarding glacier is ca. 5 km long and 0.5 km wide. The lake is dammed by the terminal moraine at 4500 m. The steep inner slopes of the lateral moraine are undercut by the lake. In the middle ground the terminal moraines of the Ripimo (↙) and the Kang Nachugo glacier (▽) join the upper Rolwaling valley. During a higher glacier surface level, the Ripimo-ice flew through an outlet of the left lateral moraine. Moranic material at the spur of the Kang Nachugo ridge (↘) indicates a late Glacial ice filling of the Ripimo basin. Locality Rolwaling Khola. (Photo S. Meiners, 7 October 1997.)

↑ *Photo 8.* The lateral moraine terrace accumulated in the valley section near Na area at 4100 m on the orographic left side (– –) can be classified into the early neo-Glacial or the late Late Glacial. The level of the terrace slopes downvalley to 3900 m (see Photo 12), but an ice terminal does not exits any more. For this reason this the valley section of Na was glaciated to a minimum altitude of 3900 m. Locality Rolwaling Khola. (Photo S. Meiners, 13 October 1997.)

↑ *Photo 9.* Looking downvalley from the Yalung basin in the direction of North to the Ripimo Shar (▼). There is a huge ridge (■) between the former glacier tongue basin with its end moraine at 4820 m and the Yalung glacier, which is running at the right side of the basin. Considering the low catchment area of 5400 m of the Yalung Ri glacier and the small neighbouring glacier (see Photo 5), the extent of that glacier tongue basin seems to be surprisingly large. Consequently, they must have had a larger catchment area. Locality Rolwaling Khola. (Photo S. Meiners, 12 October 1997.)

↑ *Photo 13.* The longitudinal weals in the ground moraine (↘), lieing on the orographic right Rolwaling valley flank next to the cloister of Na (◇) are marked by deposited rockfall material. These glacigenic exaration furrows (/ /) were built through prehistoric glacier polishing. Locality Rolwaling Khola. (Photo S. Meiners, 3 October 1997.)

↑ *Photo 14.* The Late Glacial glacier level reached a minimum thickness of ca. 400-600 m above Beding (3700 m). There medial moraines (▲) are deposited on the flat valley shoulders at the orographic right side. During that time the hanging glaciers joined the main Rolwaling glacier. In this case, the medial moraines can also be understand as a reverse filling against the main glacier or they are moraines of retreat. Locality Rolwaling Khola. (Photo S. Meiners, 14 October 1997.)

↑ *Photo 15.* The shape of the tributary valley outlet at the orographic right side near Beding was completely rounded during the Last- and Late Glacial period. The 150 m high step into the main valley is sharply incised by meltwater. The only possible reason for its development is subglacial water under hydrostatic pressure. The step had to be climbed to ascent to the Gaurisankar (7146 m) basecamp from South. Locality Rolwaling Khola. (Photo S. Meiners, 30 September 1997.)

← *Photo 16.* View from 1985 m near the settlement Lamobager directed towards South into the orographic left Rolwaling flank and the valley exit. The polished and rounded flanks indicate a glacier level of the Last Glacial Maximum of ca. 800–1000 m in the Bhote Kosi. During the Last Glacial Maximum the Rolwaling glacier joined the Bhote Kosi glacier, which seems to be an outlet glacier from the Tibet plateau. Consequently the ridge projecting laterally from the Daldung range where the monastry of Simigaon (⇩) was erected on at 2000 m must have been formed primarily by an ice overflow in the High Glacial and secondly during Late Glacial as a medial moraine. Locality Rolwaling Himalaya, Bhote Kosi. (Photo S. Meiners, 18 October 1997.)

↑ *Photo 17.* The photo shows an outcrop at 1020 m lieing at the edge of the second highest fluvial terrace, 15 m above the deepline of the Bhote Kosi (Tama Kosi; orographic left). A huge piece of rock projects the material from erosion. The boulders with a maximum diameter of 50 cm were rounded and angular-rounded and cemented with fine material. In addition there are nummerous large boulders, which also rise above the flat fluvial terraces. The only reason why they were deposited here, is glacifluvial transport (as a high energy flow) or by ice itself. Locality Rolwaling Himalaya, Bhote Kosi. (Photo S. Meiners, 22 October 1997.)

↑ *Photo 20.* View from 5000 m towards the west flank of the Kambachen (▲) (7902 m). The snowline sm (method Kuhle, 1988, 1990) of the Ramtang glacier (firn hollow type) can be calculated at 5700 m. The actuell end of the glacier tongue moves back to 4580 m (⏶) and the glacier becomes lower in volume. Historical terminal moraines were left at ca. 4500 m at the exit of the Kambachen valley (○○). The neoglacial lateral moraines join the moraines of the Kangchenjunga glacier (↗↗). Further down (◇) marks the lateral moraines of the avalanche fed hanging glaciers at the left side. Locality Kangchenjunga massif, West range. (Photo S. Meiners, 12 November 1997.)

↑ *Photo 21.* Looking north upvalley from 4175 m towards a lateral- and end moraine (△△), which blocks the main Kanchenjunga valley. This ice terminal can be assigned to the hanging glaciers of the left side (see Photo 20) (●). During the latest glacial maximum the glaciers reached the valley bottom and the glacier ice was pushed over the lateral moraine. The main river was pressed against the opposite valley flank. Generally, the glacial- geomorphic risk potential is high because of mudflows running down the steep valley flanks at the right hand side, which are undercut by the river and also covered by loose ground moraine material. At any time the river can be blocked by mudflows. In the background left the neoglacial terminal moraines of the Kangchenjunga and Ramtang glacier can be seen (↓) (see Photo 23). Locality Kangchenjunga massif, West range. (Photo S. Meiners, 6 November 1997.)

↑ *Photo 22.* The 25 km long Kangchenjunga glacier ends at 4580 m. A small meltwater lake has developed at the front of the glacier tongue. The postglacial lateral moraine ridges (– –) stretch out on the wide lateral moraine terrace which is directed in towards southeast. In the background the tributary Llonak glacier valley joins the Kangchenjunga valley at 4660 m (↓), whose glaciers stop at 5000 m. Locality Kangchenjunga massif, West range. (Photo S. Meiners, 6 November 1997.)

↑ *Photo 25.* View from 4500 m downvalley into the Ghunsa Khola. A lateral moraine terrace at the left hand side and a lateral moraine ridge at the right hand side mark an early Neoglacial glacier level (■). These morainic remnants discontinue at 3600 m before Ghunsa, but they do not leave an ice marginal indicator. The polished valley flanks prove a high glacial glacier level of more than 1000 m (see Kuhle, 1990, fig. 4). Locality Kangchenjunga massif, West range. (Photo S. Meiners, 12 November 1997.)

↑ *Photo 29.* The Yamatari glacier valley joins the Ghunsa valley at 3500 m just below the settlement. On the left side of the photograph, two end moraines at 4050 m (■) and 3900 m (– –, left) mark the glacier extension during the historical and latest neoglacial stage. The vertical distance to the recent glacier tongue end is 150/300 m. Close to this, a lateral moraine of the earliest Neoglacial continues to the valley exit (– –, right) and forms a wide tongue basin. The lower end of the ridge orographically left is polished and ground moraine material is accumulated along the flanks (◓). Because of this a contact with a main valley glacier already at latest Late Glacial can be detected here. Locality Kangchenjunga massif, West range. (Photo S. Meiners, 1 November 1997.)

↑ *Photo 31.* This photo shows the former glacier tongue basin of the Yamatari glacier (early Neoglacial), which has its positon at 3500 m at the valley exit near the permanent settlement of Ghunsa (3455 m). (▲▲) marks the lateral moraine, which can be assigned to the tongue basin. Locality Kangchenjunga massif, West range. (Photo S. Meiners, 15 November 1997.)

↑ *Photo 32.* Smooth terraces, sharply undercut by the river, are formed at the orographically right side downvalley of Ghunsa between 3300–3200 m. The settlement of Phole (■), just as Ghunsa (left side) lie on it. The valley flanks of both sides are polished and completely abraised. In consideration of the downvalley terminal moraine at 2700 m (see Photo 33) it can be assumed, that this smooth terrace belongs to a tongue basin of the Ghunsa and the Yamatari glacier, which only allows a classification as latest Late Glacial. Locality Kangchenjunga massif, West range. (Photo S. Meiners, 15 November 1997.)

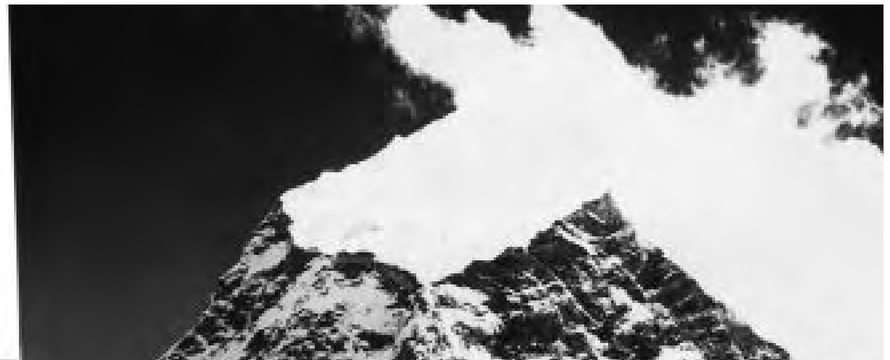
↑ *Photo 34.* View from 4600 m into the Yalung glacier valley. In the background left the main Kangchenjunga peaks (8586 m (▼), 8505 m, 8476 m), the middle the Kapru peaks (7338–7350 m) and right the Ratong (6678 m) (☐) and the Kotang (○) are towering above the glacier. The length of the Yalung glacier is 23 km and it stops at 4200 m (⊃). A wide and not glaciated valley connects at 3900 m. It leads to the Kangla Khang pass (5560 m) at the Indian borderline (↓). Only short hanging glaciers exist in the orographic right side of the Yalung ridge. In general, they end in a well pronounced podest moraine, which is built onto the wide ablation valley bottom (↓ thin arrows). The latest glacier stage (historical) is marked by the steep end moraine at 4000 m (⇗). Farther, two lateral moraine stages can be delimited (latest Neoglacial) at 3915 and 3930 m (→ ←). The next stage lies at Tseram, 3870 m (middle Neoglacial) (– –).The highest postglacial level (earliest Neoglacial) (△△△) crosses the exit of the Kangla Khang valley and ends at 3570 m. For this a snowline depression of 315 m is likely. The valley divide (4500 m) between the Kangla Khang valley and the main valley is polished (◓) and completely covered with fine morainic material at the right hand side. An ice level of more than 700 m during the Late and Last Glacial is proved by this. Kangchenjunga Southwest massif, Yalung glacier. (Photo S. Meiners, 16 November 1997.)

↑ *Photo 35.* The temporary alpine hut ‚Nyamgyalama‘ at 3600 m was errected on a lateral moraine wall (■) 600 m above the valley floor of the Simbua Khola (locality 'Torontan'). This lateral moraine wall demonstrates the minimum elevation of the former glacier surface. If an ice margin can be extrapolated at 2400 m, a snowline depression of 900 m places it in the late Late Glacial. This locality (27°32′ N/ 87°54′ E) is at the true right side. The top of the main ridge reaches 3947 m. The valley flank above this is also covered by fine morainic material. Because of this the accumulation can be ranged into a late Late Glacial. Further down there are some more indicators for a complete ice filling during late- and high glacial stages. Locality Kanchenjunga Southwest massif, Yalung/ Simbua Khola. (Photo S. Meiners, 25 November 1997.)

↑ *Photo 36.* The valley exits of the Simbua/ Yalung Khola and the Ghunsa Khola (↓) join at 1500 m into the Tamur river (see Kuhle, 1990, fig. 5). The intermediate valley ridge was overridden by ice during the High Glacial. The rock has a polished surface (◓). At the orographic right valley flank of the Simbua Khola, which is covered with morainic material, the locality of 'Nyamgyalama' at 3600 m (Photo 35) can be seen (▲). Locality Kangchenjunga Southwest massif, Tamur river. (Photo S. Meiners, 31 November 1997.)

↑*Photo 10.* A panorama of the different glacier surface levels of the former Trakarding glacier at the true right side of the Tsho Rolpa Lake. At least three levels (▲▲) can be seen from the latest, e.g., historical phase to the Late Glacial. At the end of the Tsho Rolpa Lake the terminal moraines of the Ripimo and Kang Nachugo glacier have been deposited in the Rolwaling valley. Locality Rolwaling Khola. (Photo S. Meiners, 6 October 1997.)

↓*Photo 11.* An intermediate valley ridge separates the Ripimo from the Ripimo Nup glacier (▲). A small mudflow fan breakes through the steep end moraine of the Nup glacier whose basic height is 4700 m. During the Neoglacial the Ripimo Nup glacier terminates between the Kang Nachugo glacier and the valley divide. A lake was dammed there after the beginning of the glaciers retreat. The longitudinal profile of the valley divide (↓ ↓) is terraced in a typical glacigenic way and is completety covered by ground moraine. During the late Late Glacial the valley divide was partly overflown by ice, but during the early Late Glacial it was overflown completely. Locality Rolwaling Khola. (Photo S. Meiners, 8 October 1997.)

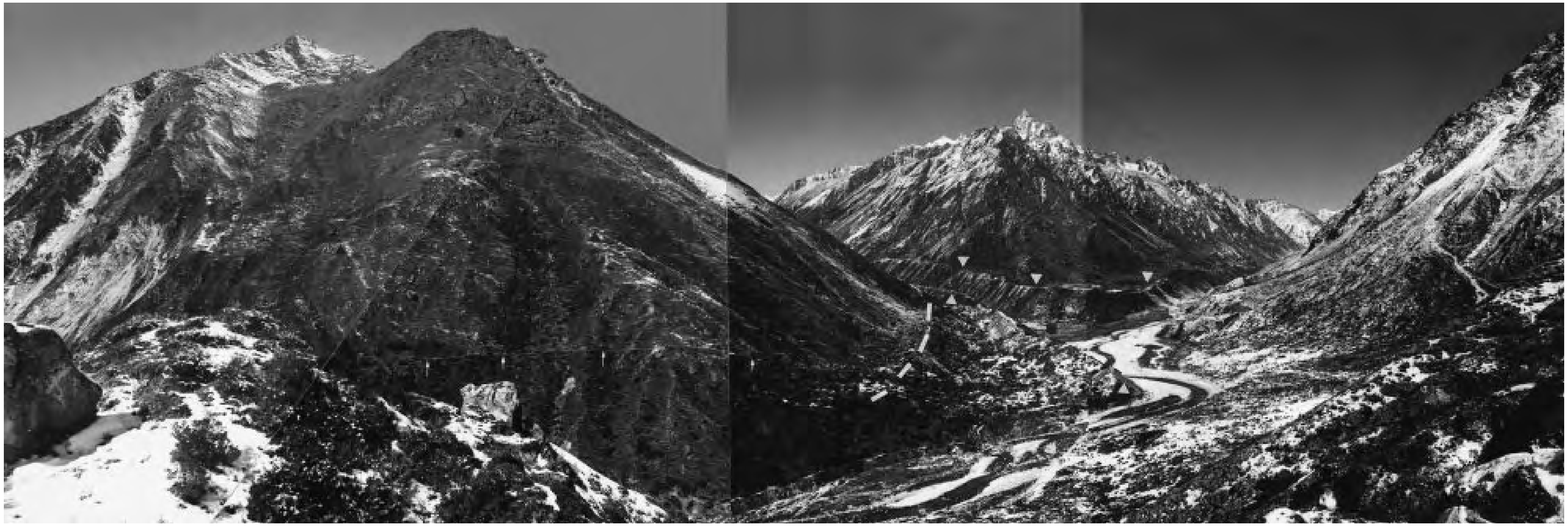


↑ *Photo 12.* View from 4260 m is southwards against the orographic left flank of the Rolwaling Khola. The peaks whose average height is 5500 m are less glaciated. In the middleground remnants of a moraine terrace (late or middle Late Glacial) ca. 400 m above the valley floor are well developed only at this locality (⇘). The coverage with ground moraine stretches out beyond this level. Looking upvalley, large mudflow cones (■) cover the morainic material at the valley flanks. In the foreground, the wide alluvial fan of Na (●) is spread out on the orographic right side at 4100 m. Downvalley a small lateral moraine terrace of the Neoglacial or late Late Glacial can be seen (– –) (see Photo 8). Locality Rolwaling Khola. (Photo S. Meiners, 4 October 1997.)

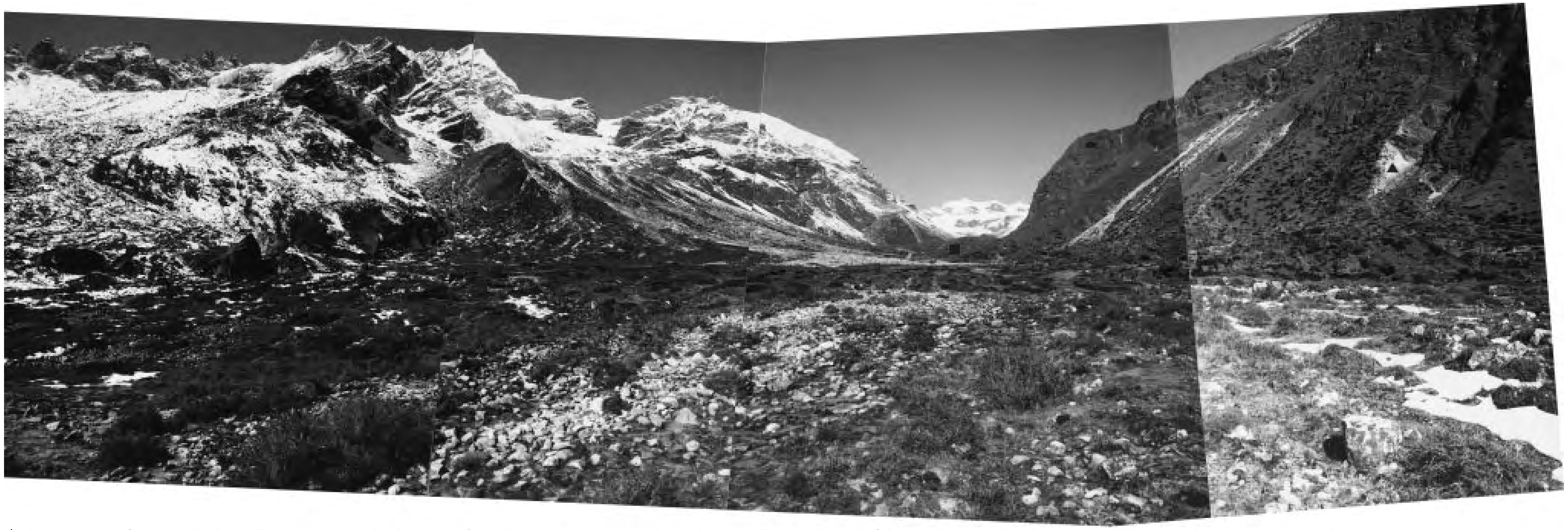
→ *Photo 18.* View from 5230 m into the upper course of the 25 km long Kangchenjunga glacier. The glacier type can be described as a dendritic firn hollow glacier, which is partly fed on breakoffs of the ice balconys and avalanches of the steep flanks of the Kanchenjunga peaks (↙↘) (main 8586 m, West peak 8420 m in clouds). The glacier surface level of the historical to neoglacial maximum is marked by (⇗). After Kuhle (1990:410) this ridge of rock (◓) was completely overflowed by glacier ice during the maximum glaciation. Locality Kangchenjunga massif, West range. (Photo S. Meiners, 7 November 1997.)

← *Photo 26.* During the latest glacial maximum the Jannu glacier reached repeatedly the steep end moraine crest (▲) (historical and late neoglacial stage) and destroyed it by ice. Later, the glacier surface sunk in and the fluvial outlets (↘) became deeply incised. A remnant of a lateral moraine wall (– –) on the right hand side, which formed a lateral moraine valley, corresponds with a moraine terrace level (●) at the opposite side. The inner edges of the lateral moraines were undercut by meltwater flow. These stage can be ranged into the early Neoglacial. Several mudlfows lie thickly on the surface of the glaciofluvial terraces. Locality Kangchenjunga massif, West range. (Photo S. Meiners, 12 November 1997.)

← *Photo 19.* The glacier tongue end of the 11 km long Jannu glacier stops at 4150 m (▼). Its glacier surface sink 120 m into the frame of the lateral moraines. The end moraine of historic to neoglacial stage was cut twice by outlets (↙↘). For this reason the former glacier surface must have lain flat against the edge for a longer period. If a new glacier advance set in, a glacier dammed lake could develope quickly. In the background (right) the Jannu peak (▲), 7902 m can be seen. In the background (left) the tributary Kambachen valley joins the Kanchenjunga main course at 3900 m. Lateral moraines of neoglacial and late Late Glacial period prove the former connection with the main Kangchenjunga valley (▽▽▽). Locality Kangchenjunga massif, West range. (Photo S. Meiners, 12 November 1997.)



↑ *Photo 27.* Photograph taken from the edge of the Jannu end moraine looking upvalley to the settlement ground of Kambachen at 3900 m (■). The glacier level of the early Neoglacial can be established by a lateral moraine (▼▼), which continues downvalley along the main run and the tributary valley. A less continunous level lies directly above this (– –). The top of the central peak in the foreground was overridden by ice during High Glacial because of the polished valley flank and the rounded form (●). Ground moraine material is widespread at the flank, which is marked by typical triangle form in the loose material (▲▲). The main foot path (↑ ↑) crosses the loose material section and because of this rock fall is most dangerous for inhabitants and tourists. Locality Kangchenjunga massif, West range. (Photo S. Meiners, 12 November 1997.)



↑ *Photo 28.* View from Kambachen village, 3900 m in the direction of Northwest into the Kambachen tributary valley. At the end of this U- shaped valley there are small hanging glaciers whose nourishment areas rises 5500 m on average. In the middle ground a late Neoglacial end moraine (■) was accumulated at 4470 m. The flanks of both sides of the valley are covered by ground moraine material (▲). The former tributary glacier will not have contact to a main glacier unless the snowline lowers at least 400 m. This was likely during the early Neoglacial. The glacial flank polishing and smoothing (◓) are evidence of an ice filling during Late and Last Glacial Maximum. Locality Kangchenjunga massif, West range. (Photo S. Meiners, 5 November 1997.)

↑*Photo 30.* View from 4050 m into the Ghunsa valley (↓) on the left side of this photograph. In the background the end moraine of the Yannu glacier (▲) (Historical /latest Neoglacial) can be seen. On the right side the lateral moraine of the Yamatari glacier (earliest Neoglacial) (– –) can be distinguished from the lower level of Neoglacial (latest stage) (– –) which continues down to the valley exit. (⬀) marks the historical glacier extend. In the middle part, there is the Nano Ma peak (5250 m). The lowest level of its cirques (●) is at c. 4500 m, which hints at a former snowline altitude 900 m lower than today. The rounded valley shoulders demonstrate a minimum level of Last Glacial Maximum (◓). Locality Kanchenjunga massif, West range. (Photo S. Meiners, 15 November 1997.)

↓*Photo 33.* View from 2800 m into the lower Ghunsa valley downwards the settlement. The U- shaped profile changes into a steep V-valley. A glacial tongue basin at 2700 m (■) is surround by a huge terminal moraine (150 m) (▲). This ice marginal position marks the extent of a middle late glacial Ghunsa glacier. The whole valley flank is covered by ground moraine material. There, two higher moraine marginal traces indicate an early, late- to high glacial ice filling (– –). Locality Kangchenjunga massif, Southwest range. (Photo S. Meiners, 1 November 1997.)

↑*Photo 23.* This end moraine at 4250 m (■) is described to the neoglacial stage of the Kangchenjunga and Ramtang glacier. Both glaciers joined in the neoglacial period. The lateral and end moraines in the foreground originated from the two hanging glaciers at the orographic left side are of the same age. (see Photo 21). A late glacial moraine terrace stretches out downvalley (– –). In the background the Kambachen tributary valley exit is visible (↓). Locality Kangchenjunga massif, West range. (Photo S. Meiners, 11 November 1997.)

↓*Photo 24.* Several lateral moraine walls follow the Kangchenjunga glacier on it's true right side (↓ ↓). They were deposited in the extraordinary wide and flat ablation valley. The Kambachen peak (▲) (7902 m) towers high in the background. The historical end moraine of the Ramtang glacier (◓) blocks the valley exit. The ablation valley is preferred for pasturing livestook, because there is no risk of avalanches and rock fall. The high glacial glacier level overrides the range at the orographic right side (●). Locality Kangchenjunga massif, West range. (Photo S. Meiners, 7 November 1997.)

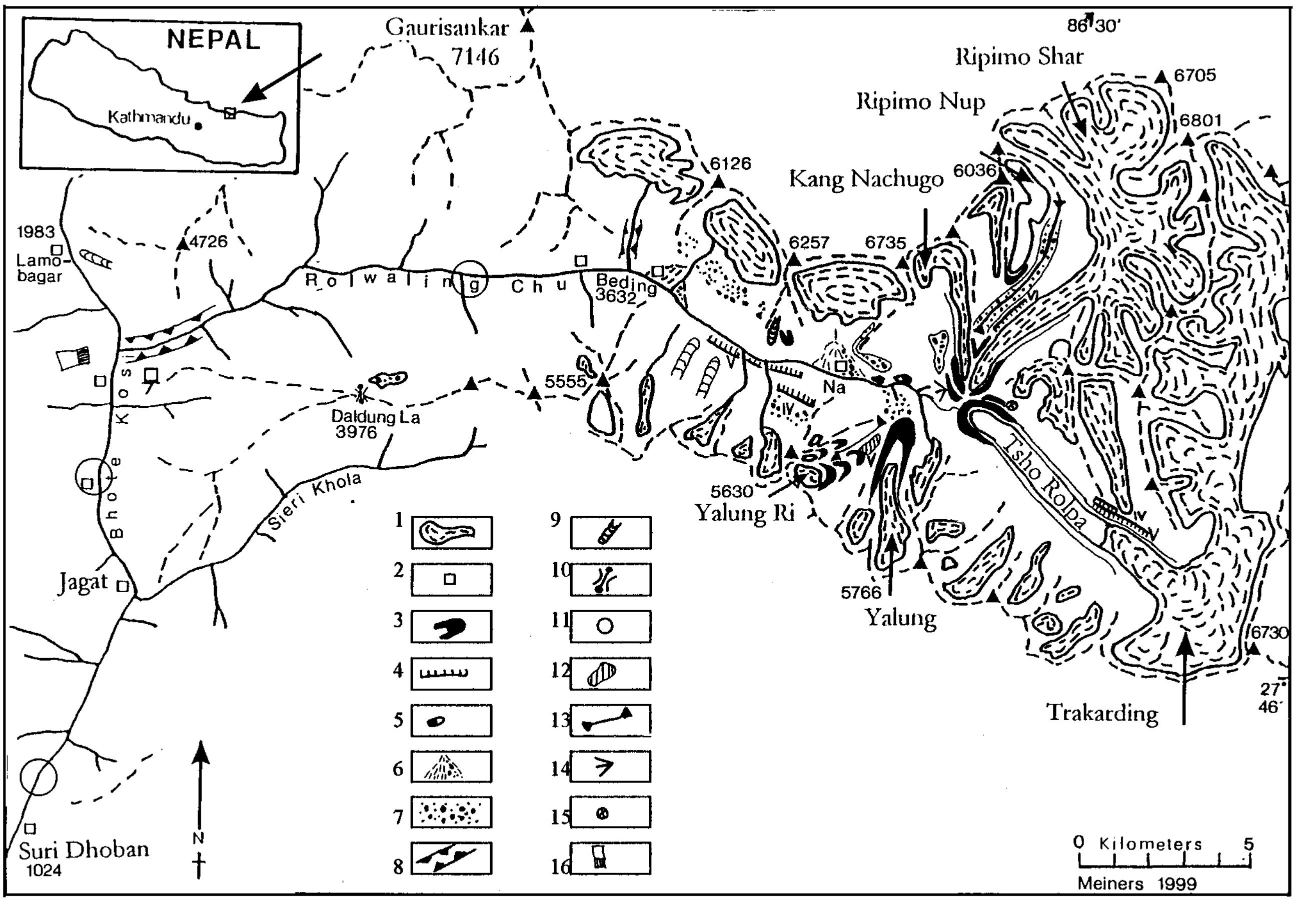


Figure 2. Glaciogeomorphological sketch of the Rolwaling Khola. (1) glacier; (2) settlement; (3) Great Lateral Moraine (GLM) (historical/Neoglacial) = stage VI–X after Kuhle, 1994; (4) lateral moraine (VI = middle Neoglacial; V = early Neoglacial, IV = latest Late Glacial; (5) hummocky moraine; (6) debris cone (including till); (7) till of Late Glacial/Last Glacial; (8) gorge; (9) glacial flank polishing; (10) transfluence pass; (11) exposure of glacifluvial outwash (high energy flow); (12) tongue basin; (13) intermediate valley ridge; (14) mud flow (1991); (15) 14C sample locality; (16) kames.

flows around the base of the Ripimo terminal moraine. An isolated remnant of a moraine directly before the frontal moraine of the Trakarding glacier was 14C dated (Figure 2). This result shows an age of 2220 $\pm$ 79 yBP (dating performed in the Physics Institute of the University of Erlangen), which confirms the classification of middle Neoglacial. In the north-facing Yalung basin, the three pure-ice, small hanging glaciers are preceded by Historical frontal moraines (Photo 5).

A glacier level approx. 100 m higher than Ripimo corresponds to a moraine level on the orographic right side of the Trakarding glacier (Photo 10). At that time, the Ripimo Nup glacier extended up to the Kang Nachugo. Since no further terminal moraines can be found in the upper Rolwaling Valley, it must be assumed that the multiple-phase terminal moraines of the main glacier represent the Historical to Neoglacial glacier extension. Dotted circular osers near the valley bottom above Na at 4050 m (Figure 2) and a small lateral moraine terrace down-valley orographic left (Photo 8) point to the existence of a common glacier tongue of at least approx. 3900 m. For this a snow line depression of 200 m can be calculated.

In the light of the minimal recent glaciation in the Yalung basin, it is surprising to see the size of the tongue basins with terminal moraines at 4900 m (Photo 9) and 4820 m, followed by a lower-lying tongue basin that is also bounded by a terminal moraine at 4790 m. The stepped longitudinal profile is continued with a flattened valley slope at 4675 m, although there is no terminal moraine here. The tongue basins are in no way related to the larger Yalung glacier which is separated from them by a high lateral moraine. The ice margins up to 4675 m are classified as Neoglacial, because snow line depression is calculated between 93–206 m.

Late Glacial

A glacier level in the Trakarding/ Ripimo confluence region that is at least 200 m higher is demonstrated by the lateral moraine level on the Trakarding glacier (Photo 10) as well as by an intermediate valley ridge on the Ripimo glacier that is covered with moraine material on its lower parts (Photo 11). During this phase, the glaciers flowed together. Their range cannot be demonstrated by terminal moraines. Indications of a corresponding glacier fill are present in the form of lateral moraine ledges about 400 m above the valley floor orographic left of Na (Photo 12). These correspond to longitudinal weals in the loose moraine material on the opposite side of the valley below the cloister, which are marked by deposited rock-fall material (Photo 13). Extrapolation of an accompanying glacier terminus at 3000 m at the bridge near

Dongang points to a snow line around 840 m lower than that of today. If this rough estimation is approx. accurate, it can be ranged into the Late Glacial. This means that the alluvial fan of Na (Figure 2) is definitely more recent than the ice fill, so it must be Latest Late Glacial to Neoglacial.

The Yalung glaciers did not have contact to the main glacier in this phase either, because a lateral moraine of Yalung Ri orographic left which covers the intermediate valley ridge and that of the Yalung glacier come to an end before reaching the valley bottom.

Late Glacial/High Glacial

During a larger valley glaciation, the Ripimo intermediate valley ridge was completely covered by ice, because there is ground moraine on it. In the section of the main valley between Na at 4100 m and Beding at 3700 m, polished and over-steepened valley flanks and the glacigenic U-profile demonstrate the existence of a glacier that filled the whole valley. Medial moraine sanders above Beding orographic right are also proof of this, and should be interpreted as reverse filling against a body of ice of at least 400–600 m that abutted here (Photo 14). However, they could also be interpreted as the result of a retreat phase when the main glacier had already decreased in volume and the smaller flank glaciers were retreating.

The orographic right hanging valley outlet at Beding that leads up to Gaurisankar Basecamp is a classical polished stage into which the meltwater had already carved gorges subglacially (Photo 15). Pure ground moraines adhere to the valley flanks near Na (Photo 13). Down-valley, debris cones on the valley flanks contain a morainic core. Kuhle, Iturrizaga, Meiners (1998, p. 89) described such type of debris cones which derive directly from the redeposition of moraine material and stressed their natural hazard potential.

The Rolwaling Valley outlet is a gorge cut several metres deep into the outcropping rocks. The formation of such a gorge is only made possible through subglacial water under hydrostatic pressure, which proves that ice filling existed to this point.

Glaciation continuing over the Rolwaling Valley (see König, 1999) has been demonstrated through the ground moraine covering of the Daldung La (4000 m) on the orographic left Rolwaling Valley outlet (Figure 2). Light yellow ground moraine remnants on the right-hand valley outlet at 4000 m corresponds to this massive 2000 m ice fill. In addition, abraded valley flanks in Bhote Kosi upstream of the Rolwaling Valley outlet at Lamobager point to an Ice Age Bhote glacier. The remains of a kames terrace on the orographic right Bhote Kosi flank at ca. 2300 m directly across from the Rolwaling valley outlet demonstrates the existence of a valley glacier of at least 900 m. Corresponding to this is a medial moraine spur at Simigaon on the orographic left valley outlet on which the cloister of the same name was built (Photo 16). This is probably a result of the retreat stage of the Last Ice Age glacier. During the High Glacial, the Yalung basin was also completely glaciated and fed into the Rolwaling glacier.

At Bote Kosi's valley floor elevation of 1020 m near the settlement Suri Dhoban at the Khare Khola tributary valley outlet is an outcrop in which large boulders in a fine matrix are protected from erosion by a very large block. The unsorted boulders are sharp-edged, round-edged, and rounded, and are of varying size. Material of this size can only have been transported to this location by a glacier or as 'glacifluvial outwash' by a powerful meltwater current (Photo 17).

Rolwaling Khola: Summary

All the glaciers at Rolwaling Khola form a GLM (Great Lateral Moraine) that is no longer filled with ice. The existing glaciers have greatly sunk and their termini have pulled back several hundred metres. Just as in Karakorum (Meiners, 1997), these glaciers show a clear decrease in volume. The GLM terminal moraines from Historical to Late Neoglacial show snow-line depressions of 50–150 m. In the main Rolwaling Valley, no further terminal moraine deposits remain other than those mentioned above.

Various lateral moraine levels help to differentiate Neo- and Late Glacial stages from the increasingly relief-filling glaciation of the High Glacial. In the north-facing Yalung Basin, snow-line depressions of 130–400 m for Neoglacial and Late Glacial could be identified and four glacier stages differentiated. For a late Late Glacial Rolwaling glacier, the snow-line depression measured approx. 800 m. In summary, it should be stressed that the main Neoglacial glaciation (latest stage) did not reach farther than the deepest-lying and therefore oldest part of the terminal moraine complex. An older Neoglacial stage can thus be differentiated from that latest main glacier extension.

The indicators shown here point to a probable valley-filling glaciation in the Rolwaling Valley that lasted beyond the Late Glacial. A snow-line depression can not be calculated for the Last Glacial Maximum because the catchment area of the Bhote Kosi outlet glacier have to be taken into account. Nevertheless it can be assumed that the Rolwaling glacier came into contact with a Bhote Kosi glacier.

Kangchenjunga massif: Description of the area studied

The Kangchenjunga mountains (27°34′–47′ N, 87°58′–88°02′ E) drain into the Tamur River, which has its source in this massif. In contrast to Rolwaling, contact to the Tibetan highlands exists over passes that are higher than 5000 m. The Kangchenjunga massif (Figure 3) has three peaks over 8000 m, several over 7000 m and includes a much larger glaciation area. The extent of glaciation can be divided into three groups: (1) the two large glaciers in the main valley, Yalung (23 km long) and Kangchenjunga (25 km long); (2) medium-sized valley glaciers Llonak, Ramtang, Jannu and Yamatari having lengths of 10–12 km; and (3) small, pure-ice hanging glaciers. The many small hanging glaciers, the majority with a southern exposure, end in platform ter-

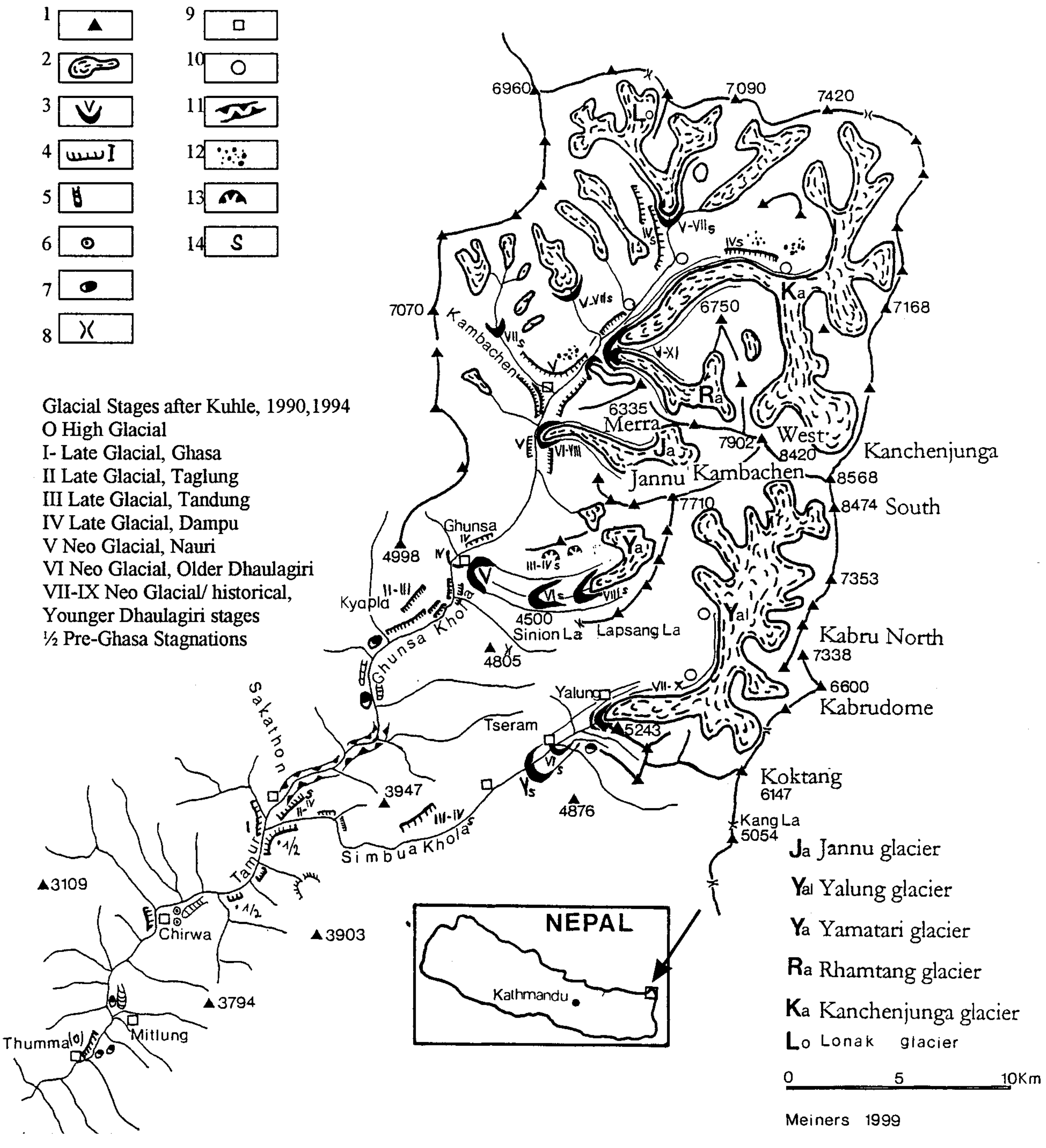


Figure 3. Glaciogeomorphological sketch of the Kangchenjunga massif. (1) peaks and ridges; (2) glacier: (3) terminal moraines (V) = Neoglacial (Nauri stage); (4) lateral moraine (l) = Late Glacial (Ghasa stage): (5) polished rock surface glaciated walls; (6) subglacial potholes; (7) roches mountonnées; (8) pass; (9) settlement; (10) pasture; (11) gorge; (12) till; (13) cirque; (14) marks findings by the author, compare Kuhle, 1990, p. 421.

minal moraines in the large ablation valleys of the main glaciers.

Recent and Historical/Neoglacial glaciation

The two largest glaciers, Kangchenjunga (Photo 18) on the west side and Yalung (Photo 34) on the south west side of the massif, span a maximal relief energy of over 4000 m. The glaciers terminate at 4580 m and 4200 m (Figure 3).

The angle difference, calculated on the basis of different gradient conditions of the ablation and accumulation areas (method: Kuhle, 1988), causes fluctuations in the recent snow-line levels. For instance, the real snow line (Sr) calculated for the Kangchenjunga glacier is 6000 m, while that for the Yalung glacier is 5300 m. Without taking the gradient conditions into account, the calculation of the mathematical snow line (Sm) yields 5800–5900 m. Both glacier valleys are characterised by particularly wide ablation valleys.

Because there are lower reliefs on the orographic right Yalung range, several short hanging glaciers terminate in steep platform moraines here in the wide lateral moraine valley.

The medium-sized valley glaciers only occur on the Kangchenjunga west side. Their calculated snow lines (Sm) are between 5500–5700 m. On Yamatari, however, the snow line is calculated to be 5390 m, which Kuhle (1990) has already reported.

These glaciers, of the avalanche basin/ firn basin types (Jannu = Photo 19, Ramtang = Photo 20, 21 and Yamatari = Photo 30), pushed their great lateral and terminal moraines of the GLM (Great Lateral Moraine) type so far into the main valleys that they almost reach the opposite valley flanks (Photo 19). Today, the horizontal distance between the current glacier termini and the terminal moraines is less than 1 km. They all have in common a large loss of volume, which is illustrated by the deeply sunken glacier surfaces.

The Kangchenjunga glacier currently terminates at 4580 m. In the wide, orographic right lateral moraine valley, at least four generations of morainic walls can be found next to each other, whereby the innermost is strongly undercut by the current glacier (Photos 22 and 24).

The Ramtang glacier terminates before the confluence with the Kangchenjunga glacier and forms sub-recent to historical terminal moraines in the valley outlet region. Its lateral moraines, orographic left and deposited high on the valley slope, turn into the main valley and, together with the orographic right lateral moraines of the Kangchenjunga glacier, form a common terminal moraine of an earlier, Neoglacial stage at 4225 m (Photos 21 and 23). During this stage, the Ramtang glacier flowed from orographic left into the Kangchenjunga glacier. This confluence also explains the increased formation of lateral moraine walls on the right side of the Kangchenjunga glacier. Increased ice pressure and overlapping must have occurred here in the confluence region (Photo 24). Directly in front of the Kangchenjunga/Ramtang terminal moraine are terminal moraines of the same age from two hanging glaciers from the orographic left valley flank that currently nourish the regenerated glacier with sheared off ice-balconies. Depending on the different elevations of the catchment areas snow-line depressions of around 180 m (Ramtang) and 290 m (Kangchenjunga) are calculated for this generation of terminal moraines. These glacier phases are ascribed to the Historical to late Neoglacial Age.

The next older generation of moraines show that the valley basin was filled with ice up to just up-valley of Ghunsa (Photos 25 and 26) and that the Yamatari glacier reached to the point of the Ghunsa settlement (see Kuhle, 1990). The related lateral moraine level is especially clear in the valley basin of Kambachen. Furthermore a less continuous level lies directly above this (Photo 27). A terminal moraine cannot be detected above Ghunsa. At 3600 m, lateral moraine terrace remnants on the orographic right valley flank are exposed by the river. This accumulation is not continued down-valley. During this stage the glaciers had advanced about 5 km to this point. If the snow line is calculated from this locality, the Ghunsa glacier has a snow-line depression of 670 m, which places it in the late Late Glacial. In consideration of the other ice margins (Yamatari, Kambachen, Yalung) this accumulation should be placed in the earliest Neoglacial.

It can be assumed that a Kambachen glacier joined with a Ghunsa glacier, since the moraines continue far into the tributary valley. A terminal moraine at 4470 m (Photo 28) points to a snow-line depression of approx. 200 m. With a current glacier terminus at 4800 m and the elevation of the valley outlet at Kambachen at 3960 m, a snow-line depression of roughly at least 400 m would be necessary to facilitate this contact. This would prove that such contact took place in the early Neoglacial.

This also holds for the Yamatari glacier. The current Yamatari glacier terminus at 4200 m is located just off a Historical terminal moraine stage at 4050 m and a neoglacial stage at 3900 m (Photo 29). The outermost terminus is formed by a wide tongue basin at 3500 m with a terminal moraine at the tributary valley outlet below the settlement at Ghunsa (Photos 30 and 31). The snow-line depression of around 350 m calculated here only allows a classification as earliest Neoglacial.

The terminal moraine ahead of the Yalung glacier on the south-west side of Kangchenjunga massif consists of a flat base with a steep frontal moraine deposited on top of it. This terminal moraine rises 220 m above the valley bottom, while the recent debris-covered glacier terminus at 4200 m has dropped approx. 100 m and retreated, and now rests on a debris platform. The latest (historical) glacial maximum is represented by the frontal moraine with a flat base at 4000 m. Two ice margins at 3915 m and 3930 m (Photo 34) date to the Historical glacial stage. The next highest lateral moraine edge marks a glacier stage near the locality Tseram at 3870 m. Above this is a further moraine level that leads into an wall-like, deposited terminal moraine at 3570 m. On the right side of the valley, this level forms a moraine terrace on which the temporary settlement Yalung lies. This part belongs to the earliest Neoglacial with a depression of 300 m, while the ice margin at Tseram is classified as middle Neoglacial with a depression of 170 m.

Late Glacial

The further glaciation history in Ghunsa Valley is told by a smooth terrace located on the orographic left side and forming the settlement terrace of Ghunsa at 3450–3300 m which is continued on the other side of the valley at 3300–3000 m. A few houses and the Phole cloister stand here (Photo 32).

Farther down-valley an extended tongue basin with a 150 m high lateral moraine is preserved at 2700 m (Kyapla locality) on a valley extension to orographic right (Photo 33). Agriculture is practised in the tongue basin and on the lateral moraine terrace. An ice fill in the Ghunsa Valley up to 27 km away from the current ice margin has been demonstrated for this stage. A snow-line depression of around 1200 m can be calculated for this ice margin, which places it in the middle Late Glacial (see Kuhle, 1990). Above this tongue basin, there are three higher moraine levels on the valley flank (Photo 33). The highest seem to be is High Glacial and the two lower are Late Glacial. This shows that the thickness of the Late Glacial ice must still have been at least 600 m.

A snow line running at approx. 4500 m can also be detected on the currently unglaciated cirque below the Nano Ma peak (5250 m) on the orographic right valley flank of the Yamatari glacier valley. A snow-line depression of 1200 m is also found here, which places it in the middle Late Glacial. Contact between the Yamatari glacier and a Ghunsa glacier must be assumed in at least middle, if not even late Late Glacial. This is demonstrated by the polished and completely moraine-clad flanks of the tributary valley at the valley outlet orographic left up to 3955 m elevation (Photos 29 and 30).

In Yalung Valley on the south-west side of the massif, a deposited lateral moraine wall 600 m above the valley bottom at 3600 m (27°32′ N/87°54′ E) on the right side of the valley (Photo 35) demonstrates the minimum elevation of the former glacier surface. This indicator lies a further 5 km away from the earliest Neoglacial (3570 m). Above the lateral moraine, the valley slope is further strewn with moraine material. The section of the valley between 3000 m and 1500 m could not be inspected. Under the assumption that a hypothetical glacier terminus existed at 2400 m, this would yield a snow-line depression of 900 m.

Late Glacial/High Glacial

The two main valleys described, Yalung (Simbua Khola) and Ghunsa, which originate from the upper catchment areas of the Kangchenjunga massif, flow into the Tamur Valley at 1500 m near the settlements of Sakathon and Hellok. In the narrow Ghunsa Valley outlet, moraine terrace remnants are preserved orographic left. Kuhle (1990) describes similar remnants for the Yalung (Simbua) Khola outlet. These demonstrate the existence of a complete ice fill in the tributary valleys. A snow line calculation for these glaciation indicators yields a depression of 1350 m.

The intermediate valley ridge between the parallel valleys is completely polished and abraded (Photo 36). This demonstrates that the range of glaciation reached into the Tamur Valley. The maximal ice fill of the Last Ice Age reached an elevation of at least 890 m at Thumma. This indicator is described in detail by Kuhle (1990, 420) and is classified as High Glacial.

Kangchenjunga: Summary

For Historical to late Neoglacial glaciation on the W and SW side of Kangchenjunga with the formation of a large GLM, the snow-line depression values are calculated to be between 80–290 m.

An advanced terminal moraine in the Yalung Valley and lateral moraines in Ghunsa Khola for which snow-line depressions of 300–600 m are obtained, clearly deviate from this stage. They are classified as early to middle Neoglacial.

These are just as clearly distinguishable from a much larger ice fill with different phases of the Late Glacial. For this, a valley filling of the Yalung/Simbua Khola at Torontan at 3000 m valley floor elevation is demonstrated with a magnitude of 600 m. In Ghunsa Khola, a terminal moraine with a tongue basin at 2700 m and further accumulated lateral moraines supports the existence of three phases of Late Glacial glaciation. Snow-line depressions of 900–1300 m from middle to late Late Glacial were determined.

Further indicators such as glaciofluvial remains of a moraine terrace and flank polishing in the Tamur Valley demonstrate ice fill to at least 890 m (after Kuhle, 1990) which is classified as High Glacial.

Conclusion

The research of the limits of the Postglacial against the Late Glacial in respect to the system of ’Lagebeziehung’ = position of indicators for glaciation was carried out at 12 glacier systems of the Rolwaling and Kangchenjunga Himalaya. As a result the Postglacial can be divided into a younger stage which is marked by a Great Lateral Moraine (GLM). It also represents the historical glacier extent. Another, older stage of the Postglacial, which can be separated from lateral moraines or moraine terraces of the Late Glacial can only be found in few localities. Examples for this stage have been observed in the Yalung/ Simbua glacier valley (Kangchenjunga SW) at 3570 m, in the Yamatari glacier valley (Kangchenjunga W) at 3500 m and in the Rolwaling Valley. For these moraines, snow line depressions of 300–400 m can be calculated. Their horizontal distances to the recent termini are 5–6 km. The Late Glacial ice level can be divided into two or three phases. Its latest stage is marked by lateral moraine terraces and end moraines examplary in the Ghunsa Khola at 2700 m or in the Yalung valley at 3000 m. They are 11–25 km away from the recent glaciers. This study also shows that the Rolwaling Valley, the Yalung/Simbua valley and the Ghunsa Valley were filled with a more than 1000 m thick ice stream, overlain by the level of Last Glacial Maximum (LGM). For the calculation of the maximum (LGM) snow line depression, more complex catchment areas of the outlet glaciers of the glaciated high Tibet Plateau, which flew through the Himalayan range in the direction of South have taken into account.

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Preliminary results on the last-high-glacial glaciation of the Rolwaling Himal and the Kangchenjunga Himal (Nepal, E- Himalaya)

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Abstract

On the basis of empirical findings and inductive conclusions, the least extent of glaciation during the last ice age can be shown for two areas on the southern slopes of the Himalayas in Nepal – the Rolwaling Himal and the Kangchenjunga Himal. For the Rolwaling Himal, the snow line during the last ice age is calculated at 4000 m asl., i.e., 1500 m below the recent snow line. The last high-glacial snow line in the Kangchenjunga Himal is thought to be at 4350 m asl., the snow line depression here is 1150 m.

Introduction

Within the framework of a joint expedition with Dr S. Meiners, the author had the opportunity to investigate two areas on the southern slopes of the Himalayas in Nepal. Glacial-geomorphologic field-works could be carried out in the Rolwaling Himal and the Kangchenjunga Himal between September 1997 and December 1997 (Figure 1).

In the Rolwaling, the route of the expedition passed through the valley communities of the upper Tamba Khola, the lower Bhote Kosi, the Rolwaling Khola and the Khare Khola. The working area is near the northern border of Nepal to Tibet, between the main breakthrough valleys of Bhote Kosi to the west and Dudh Kosi to the east. It covers a total vertical distance of about 6200 m; the highest peak is Gaurisankar (7134 m asl., 27°56′ N 86°20′ E).

The main ridge of the Kangchenjunga massif forms the Eastern border between Nepal and Sikkim and culminates in the 8586 m high Kangchenjunga main peak (27°42′ N 88°09′ E). In addition to the main valley of the Tamur river and Ghunsa Khola, the Simbua Khola and the Kabeli Khola were particularly investigated, starting from the Dobhan settlement.

Homologous, generally morphological features of a glacial landscape are brought out and related to one another. This approach makes it possible to make statements about the glaciation history of a valley with a high degree of probability (cf., Kuhle, 1991).

By documenting the experiments photographically, they could be compared to the findings from classical glacial-geomorphologic working areas, such as the Alps (Schwarzbach, 1983) and they therefore correspond to traditional glacial-geomorphologic field studies.

The values for the course of the prehistoric snow line, which were calculated using the methods of Kuhle (1986, 1988) and Louis (1954–1955), should be seen as approximate values.

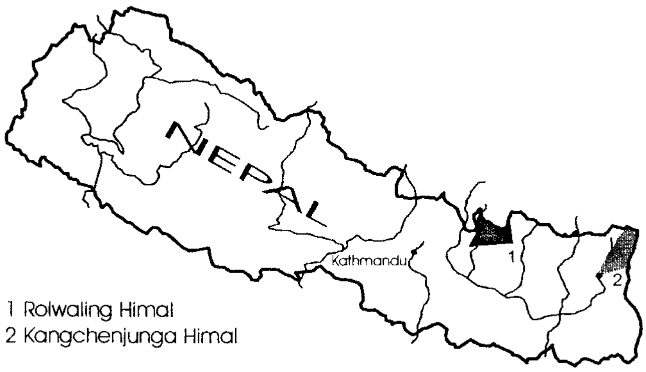


Figure 1. Sketch map of the areas studied.

The focus of the following illustration is on the high-glacial glaciation of the areas. Historic to post-glacial snow levels are only mentioned in passing (cf., Meiners, 1999, this volume).

For the Rolwaling Himal there are not yet any glacial geomorphological descriptions. The Kangchenjunga area has been described by Kuhle (1990) with regard to its glaciation history. Brief remarks on the glaciation of the upper Ghunsa Khola can be found in Dyhrenfurth (1931) and Kurz (1931). Concerning the temporal and regional allocation of the findings, studies from neighbouring areas of the south face of the Himalayas can be consulted. In particular, the publications by Fort (1986, Annapurna), Heuberger (1956, 1986, Everest), Heuberger and Weingartner (1985, Everest), Jacobsen (1990, Manaslu), Kuhle (1982, 1985, 1997, Annapurna, Dhaulagiri, Everest, Makalu, Manaslu), Yugo Ono (1986, Langtang) and Osmaston (1989, Xixabangma) must be taken into account.

For map material, the ‘Kangchenjunga’ map edited by Gondoni (no details) from the publishing house ‘Nepa Maps’ (1:175 000) and sheet 4 of ‘Rolwaling Himal’

(1:50 000) of the Nepal map system of the Arbeitsgemeinschaft für vergleichende Hochgebirgsforschung (Schneider, 1992) were consulted.

Indications of the extent of the last high-glacial glaciation of the Rolwaling Himal

Upper Tamba Kosi and lower Bhote Kosi

Two drifts to the north of Suri Dhoban (1020 m asl.) and at Jagat (1400 m asl.), both only a few metres above the depth line, can clearly be interpreted as moraine material because of their granulometric and petrographic characteristics. It cannot be ruled out that the materials have been shifted from higher hanging areas (Photo 1, Figure 2).

Up the valley, between Suri Dhoban and Manthale, there is evidence of flank polishing and triangular shaped areas. These are approx. 300–400 m above the recent valley floor (1100 m asl.) and, in conjunction with the striated pebbles found in the same section of the valley, should be considered glacial (Photo 2).

The orographic right flank of the Bhote Kosi between Lamobagar and Gongar is glacially polished to a height of at least 3800 m asl. In addition to roches-moutoneé-like forms, there are also glacifluvial accumulation forms at levels above 3000 m asl (Photo 3). The recent valley floor in this section of the valley is between 1400 m and 1600 m asl. The settlement of Lamobagar (1980 m asl.) is on a post high-glacial rock-fall site, which sealed off the valley and led to the creation of a small basin filled with fine material. This should be taken into consideration when calculating the possible high-glacial ice thickness. The orographic left flank of the Bhote Kosi clearly proves to be polished and smoothed at the height of Lamobagar. The upper limit of the polishing is at a height of between 3900 m and 4000 m asl. This polishing continues up to where the valley converges with the Rolwaling Khola (cf., Photo 4).

Rolwaling Khola

Photo 4 shows the orographic right flank of the Rolwaling Khola valley exit, i.e. the extension of the aforementioned orographic left flank of the Bhote Kosi valley, down the valley from Lamobagar. The height of the high-glacial polishing line was ascertained to be at least 4000 m asl here. The shortest vertical distance to the floor of the valley of the Rolwaling Khola works out to 1900 m, or 2500 m to the main valley. These findings tally with those for the northern slopes of the Sambur Danda chain in the region of the Daldung La (3976 m asl). The high-glacial ice covering here is evidenced by round roches-moutoneé-like polished ridges.

In accordance with the study presented by Meiners (1999), neo-glacial to sub-recent glaciation can be proved for the Rolwaling Khola. Late-glacial glaciation levels can be differentiated on the basis of moraine terrace remains. In the whole valley, there is evidence of high level flank polishing, morainic material, lateral moraines and terrace residues. Flank polishing between Ramding and the orographic right side of the valley of the Dozam Tsangpo can be identified as being glacial, bearing in mind the work mentioned above.

When ascertaining the extent of the high-glacial glaciation of the valleys mentioned, the valley exit of the Rolwaling Khola is of extraordinary significance in conjunction with the polishing described in the Bhote Kosi. The ice level to be determined in this area is no lower than 4000 m asl. This gives an ice thickness of approximately 2400 m.

Outline of Rolwaling Himal

On the basis of the findings indicated, the author comes to the probable conclusion that the high-glacial glaciation of the Bhote Kosi must have reached 1040 m asl, near the settlement of Suri Dhoban.

The calculation of the prehistoric snow line is based on the assumption of a minimum ice edge position, here at approximately 1040 m asl., and on the delineation of a relevant catchment area. This is difficult to apply to the Bhote Kosi, as this part of the glacier can be seen as a an outlet tongue of a Tibetan inland-ice (cf., Kuhle, 1997, 1998). However, the recent catchment area with an average height of the ridge of 6300 m asl. is to be determined for the Rolwaling Khola. The values mentioned give an arithmetical value for the snow line of 3650 m ((6300 m + 1000 m)/2) (cf., Louis, 1954–1955). On this basis, the high-glacial snow line depression is calculated to be 1850 m (5500 m recent snow line – 3650 m prehistoric snow line). It would be logical to assume local glaciation on both the orthographic right and the left exit of the Rolwaling Khola valley. However, this assumption does not tally with the finding of horizontal polishing in both localities (Photos 3 and 4). The upper line of the polish of a horizontally abrading glacier is at a height of 4000 m asl at the Rolwaling valley exit, which rules out local glaciation at this point. It must be assumed that the Rolwaling Khola was filled with ice to a level of 4000 m asl. near the valley exit during the high-glacial period.

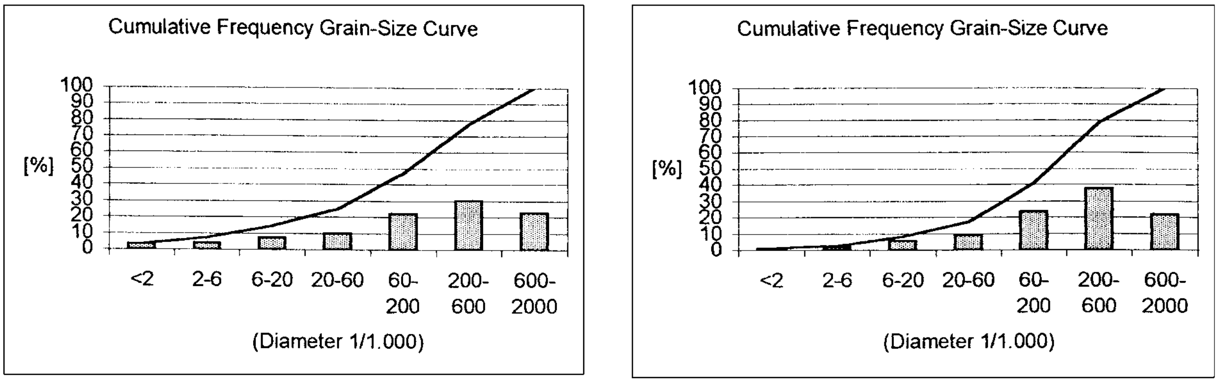
The following facts need to be taken into consideration for snow line calculation using Kuhle’s (1988) method:

– In order to calculate the real snow line, this must be on the surface of the glacier.

– The real snow line is down the valley from the Rolwaling valley exit, as it does not exceed the value of 4000 m asl., and therefore the glacier level discovered.

– In the section of the valley between Manthale and Gongar the probably high-glacial glacier surface is below the arithmetical snow line, on the basis of the findings for the glacier level (Photo 2).

The relativity of the length between the accumulation and ablation area can be derived from these three points, and can then be used to calculate the real snow line in accordance with Kuhle’s (1986, 1988) method. However, because the high-glacial catchment area for this value is significantly lower than the recent one, this value must first be corrected downwards. This is necessary because the high-glacial snow line is significantly further down the valley than the recent snow line. A catchment area with a height of 5700 m is not unlikely. On this basis, the real snow line works out at 3850 m–4000 m, i.e., about 200 m–350 m above the



a) Suri Dhoban (22.10.97 /1) b) Jagat (18.10.97 /2)

Figure 2. (a) Grain size distribution and cumulative curve of the fine soil in the outcrop (1020 m asl.) 1 km north of Suri Dhoban (cf., Photo 2). A comparison with the grain size curves published, among others, by Kuhle (1991, 1997) and Meiners (1996) supports the interpretation of the grain size distribution of this sample with regard to its glacial origins. (b) Grain size distribution and cumulative curve of the fine soil in the outcrop (1400 m asl.) near Jagat.

arithmetic snow line. Therefore the snow line depression is 1500 m–1650 m. This sort of positive discrepancy between the real and the arithmetic snow line is only found for plateau glaciation, or, it is suspected, for inland ice masses (cf., Kuhle, 1988).

As can be shown when considering the representation by Meiners (1999), the transition from high-glacial to late to post glacial glaciation is particularly marked in the Rolwaling Khola as far as the ice thickness is concerned. This leap becomes plausible if a Tibetan inland-ice is involved in the composition of the ice in the Rolwaling Khola. It is therefore possible that parts of the Rolwaling north chain were flooded by the inland-ice and formed an ice filling in this valley which was nearly independent of the recent or late-glacial catchment area.

As a result of the melting of the ice in the late-glacial age, the ice input from Tibet broke off. The result was possibly an accelerated melting of ice in the Rolwaling Khola because of the reduction of the catchment area. Each subsequent advance of the glacier no longer achieved high-glacial proportions and was therefore dependent on the height of the catchment area in the Rolwaling Khola. In addition, it should be taken into consideration that the Rolwaling Khola, when filled with ice during the high-glacial age, would have had a very large surface area in comparison to the glaciers possible on the basis of the recent catchment area and would therefore also have benefitted from primary accumulation, i.e. precipitation falling directly onto the surface of the glacier.

Indications of the extent of the high-glacial glaciation of the Kangchenjunga Himal

Tamur Khola and Ghunsa Khola

At the height of the Handrung settlement (800 m asl), three kilometres SW of Thuma, an orographic left side valley stream produces a drift which includes moraine material. In the following, this area is referred to as the Last Glacial Maximum (LGM). In addition, large blocks (up to 2 m in diameter) down the valley from the locality specified and only a few hundred metres north of the Dobhan settlement (730 m asl) should be mentioned. Near the community of Thuma (890 m asl) there are earth pyramidal eroded moraine remnants on the orographic right side of the valley (cf., Kuhle, 1990).

The morphological indicators for the prehistoric glaciation of the Tamur Khola and Ghunsa Khola detailed by Kuhle (1990) could largely be proved in the field. At this point, more information should be provided about these findings.

The section of the valley between Kyapla and Ghunsa is of particular significance. Round roches-moutoneé-like polished rock remnants prove the glacial over-filling of the orographic right side of the valley between Kyapla (2700 m asl) and Amjilassa (1500 m asl). The staggering of post high-glacial lateral moraine weal remnants makes it likely that the highest polishing edge on the slope is a form belonging to the last ice age. This polish area is at a height of 3100 m–3400 m asl. (Photo 5). The recent valley floor is below this locality at 2300 m asl. A few kilometres through the valley from Kyapla, moraine material at 2350 m asl supports this conclusion. Post high-glacial accumulated glacial and glacifluvial material forms a steep step across the longitudinal profile of the valley near Kyapla, meaning that the recent height of the valley depth line at Kyapla must remain unconsidered when ascertaining the ice thickness at the time of the LGM.

Morphologically well represented polish lines at a height of about 4600 m asl above Killa evidence the glacial overfilling of the orographic right valley flank up to this level, and the triangular shapes in the outcrops are clearly interpreted as being glacigenous (Photo 6). At the height of the confluence of the orographic left side of the valley of the Yamatari glacier below Ghunsa, polishing and accumulation forms prove that both valley sides of the main valley were filled with ice during the high-glacial period to a height of 4600 m asl. Beneath the Nango Na (5200 m asl) in the Yamatari glacier valley, rounded and polished forms up to a level of 4600 m–4700 m asl testify to the fact that this valley was ice filled to the height specified (Photo 7). Moraine material at 4000 m asl. below a pass on the orographic left side of the Yamatari glacier valley backs up this interpretation.

The polish lines described add up to form a picture which leads one to believe that the ice filling in the main valley reached up to a height of minimal 4700 m asl in this part of the valley, which evidences a high-glacial ice thickness of approx. 1200 m.

Simbua Khola

The Simbua Khola begins with the southern slopes of the Kangchenjunga and ends at the confluence with the Tamur Khola at the settlement of Hellok (1600 m asl). The catchment area of the recent Yalung glacier reaches a height of about 7000 m asl.

In order to ascertain the high-glacial glaciation of this part of the working area, lateral moraine remains above the locality of Toronthan (3040 m asl) at 3600 m asl are of particular importance. About 300 m below the peak of the Sumathalung (3947 m asl) there is a morphologically well maintained terminal moraine valley. Photo 8 shows the flattened moraine wall and the steep-sided lateral moraine valley. Because moraine material can be found up the slope from this locality, it must be concluded that the lateral moraine described does not represent the highest glacier level.

In addition to flank striations and parts of the slope polished to a triangular form up to 4700 m asl on the orthographic right flank between Tseram and Lapsang (Photo 9), a rounded peak (4520 m asl.) which had been covered in ice on the orographic left Simbua Khola side of the valley at the height of the Yalung settlement proves that the minimum ice thickness in this section of the valley was probably about 900 m during the high-glacial period. At the top of the peak there is gravel-sized debris of different rocks, the transport of which to this level can be attributed to ice.

Kabeli Khola

In the Kabeli Khola, the section of valley between the Duphi pass (2630 m asl) and the Keshewa settlement could be investigated. In the upper Kabeli Khola to the north of Yamphuidin (1740 m asl), evidence of side striations and triangular forms make the glaciation of this part of the valley likely. On the orographic right flank of the Kabeli Khola below the Duphi pass, there are marked vertical glacifluvial watermarks, about 2.5 m high, in the outcrops about 50 m above the recent valley depth line (1830 m asl). The rounded, almost polished looking forms on the Duphi pass, together with a distribution of core grains which has been diagnosed as typical of moraines, back up the possibility that this area was glaciated. Rounded and facetted blocks 200 m up the slope from Yamphuidin (1740 m asl) support this assumption. A marked striation edge and roches-moutoneé-like polished rock remains on the orographic left side of the valley between Yamphuidin and Anpan makes it possible that this section of the valley was filled with ice up to a level of 1800 m asl, i.e., about 200–300 m above the floor of the valley.

Megnug and Pathibara

Starting from Tanjang (4878 m asl), the Deorali Danda chain initially forms the orographic left flank of the Simbua Khola and continues to become the orographic left side of the Tamur Khola through the Megnug (3903 m asl) as far as the Patibhara (3794 m asl). For a side valley in this chain which is exposed to the north-west, Kuhle (1990, cf., Figure 9) charts a last high-glacial terminal moraine at 2800 m below the Megnug. In a side valley with the same catchment area which is exposed to the south-east, the remains of a lateral moraine can be found at 2500 m asl on the left side of the valley. Between the settlements of Tambawa and Keshewa to the south of the Megnug and to the south-east of the Patibhara, there are glacifluvial water shapes and medium sized blocks (up to 1.5 m in diameter) which can be found at a height of 1150 m asl – about 80 m above the recent floor of the valley.

Calculation of last high-glacial snow line for Kangchenjunga Himal

The snow line depression for the Tamur and Ghunsa Kohla during the last-high-glacial period can be ascertained as follows. The glacier stretched from a catchment area averaging 6800 m–7000 m asl. down to a height of 800 m asl and its average total length was therefore about 85 km. On this basis, the arithmetic snow line lies between 3850 m and 3900 m on the surface of the glacier (cf., Louis, 1954–1955). It could be shown that the surface of the glacier reaches this level between Kyapla and Killa, i.e. the snow line separates an accumulation area, 40 km long on average, from an ablation area with an average length of 45 km. The result of this is a difference in angle between the accumulation and ablation area of about 0.5 °. Because of the specific relief parameters, the real snow line is actually 450 m–470 m above the arithmetic snow line (cf., Kuhle 1986, 1988).

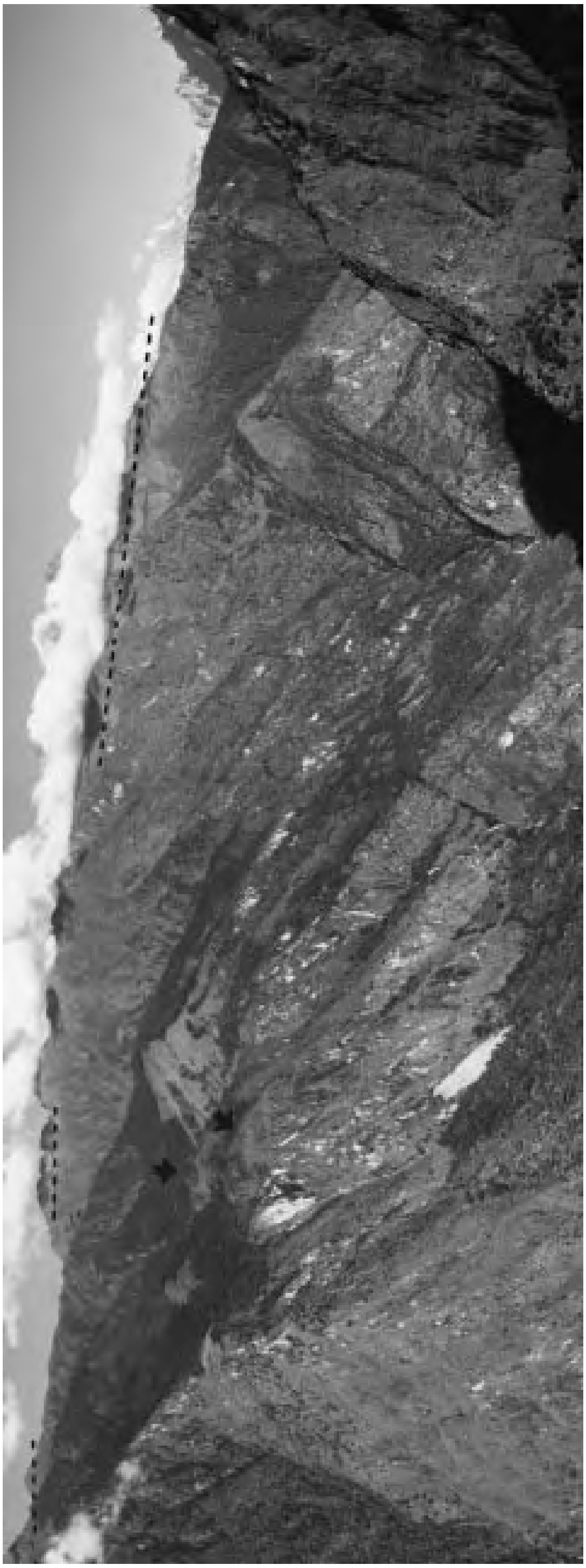
In the catchment area observed, the recent snow line is at a height of 5500 m asl, the resulting snow line depression is not 1700 m, as could be assumed on the basis of the arithmetic snow line, but is in fact only 1250 m.

Because of the orographic left lateral moraine at 3600 m asl in the Simbua Khola, as described above, a glacier level, which has to be beneath the snow line, can be reconstructed at this level. On the basis of the ice flow network proved for the Tamur/Ghunsa Khola, a similar assumption is made in terms of the height of the catchment area for Simbua Khola (7000 m asl) when calculating the snow line of the edge of the ice at Handrung (800 m asl). The arithmetic snow line is at 3900 m. On the basis of these empirical findings, the snow line lies between Thoronthan and Tseram on the surface of the glacier. The snow line, once corrected using the Kuhle (1988) method, lies at about 4370 m asl. The resulting high-glacial snow line depression is 1100 m–1200 m.

↑*Photo 1.* The faceted and largely rounded-edged blocks of an outcrop 1 km north of Suri Dhoban are embedded in a matrix of fine material (see above, Figure 2a). Some blocks have sharp-edged fractures. The resting top block (□□) reaches a diameter greater than 2 m. On the basis of its petrographic and morphographic characteristics, the outcrop can be interpreted as glacial. The locational relationship between the outcrop described, the outcrop near Jagat (cf., Figure 2b) and the polish line described in photograph 1 supports this interpretation. This does not indicate a position at the edge of the ice, but at least the necessary prehistoric extent of the ice up to this point (→ 0.15 meter ←).

↑*Photo 4.* Looking northwards from 2670 m asl. to the orographic right flank of the Rolwaling Khola above the settlement of Rigu (27°54′ N 86° 14′ E). The lighter coloured stone parts show the recent erosion form of the slope. Stone parts break off as small slats and keep the flank steep. Terrace edges (→) and polish lines (• • •) not caused by the lithography support the assumption of a probable last-high-glacial minimum ice level in this section of the valley up to a height of 4000 m asl. The trough-shaped form of the upper valley flanks in this section of the valley in particular support this interpretation.

← *Photo 2.* View of the orographic left flank of Bhote Kosi seen from 1800 m asl. in an easterly direction. The houses form part of the settlements of Khare and Salle (27°54′ N 86°13′ E). A probable late-high-glacial polish line (• • •) is found at between 1400–1500 m asl., approx. 300–400 m above the recent valley floor. The outcrop described in Figure 2a and Photo 2 is below the marked polish line on the right of the picture (down the valley).



← *Photo 3.* This photograph was taken from 1740 m asl. looking NE to the orographic right flank of the Bhote Kosi between Lamobagar to the north and point where the Rolwaling Khola merges into the Bhote Kosi to the south (27°53′ N 86°13′ E). The valley floor in this part of the valley is between 1400–1600 m asl. The polish line (– –) reaches heights of up to 3800 m asl. Glacial and glaciofluvial accumulation forms are found up to 3000 m asl. (→). The mountain chain in this section of the valley reaches a height of up to 4500 m asl.

← *Photo 5.* Looking SE onto the orographic right flank of the Tamur-Khola near the settlement Kyapla (2700 m asl., 27°36′ N 87°52′ E). Lateral moraine remains (• • • • •), round roches-moutoneé-like forms (➞) and polish lines (------) support the assumption of a high glacial ice level in this section of the valley up to at least 3400 m asl.

← *Photo 9.* The orographic right flank of the Simbua Khola above the community of Yalung (3950 m asl.), photographed from 4400 m asl. in a north-westerly direction (27°34′ N 87°59′ E). (– –) marks a possible late high glacial polish line at a height of 4600–4700 m asl. above flank sections polished to a triangular shape (➨). The dotted line (• • • • •) marks post-high-glacial local glaciation levels which are partly established by clear lateral moraine remains. The structure of the mountain side on the right edge of the picture is characterised by a vertical glacier movement. By contrast, the forms in the left part of the picture indicate an almost horizontal movement of the ice, which can be related to the lateral moraine remains below the Sumathalung (cf., Photo 8).

← *Photo 6.* The photograph shows the orographic right valley flank of the Tamur/Ghunsa Khola between Killa (2950 m asl.) and Ghunsa (3460 m asl, 27°39′ N 87° 56′ E). (• •) marks what is probably the highest late high glacial polish line (4600 m asl) above triangular abrasion forms (➨). This is suggested, among other factors, by the fall of the upper polish line down the valley, which can be traced as far as Kyapla (see above, Photo 5), and which corresponds with the polish line in the Yamatari valley (see below, Photo 7).

← *Photo 7.* The SE flank of the Nango Na (5200 m asl) at the point where the valley of the Yamatari Glacier merges into the Ghunsa Khola (on the right of the picture). The catchment area of the Yamatari Glacier reaches an average height of 6500 m asl. and culminates in the Jannu (7710 m asl.). On the left of the picture, the historical terminal moraine of the Jannu Glacier can be seen (🡇, 4020 m asl, cf. Photo 6). The line (• • • • •) marks a possible late-high-glacial polish line at a height of 4600–4700 m asl. The picture was taken from 4000 m asl. from the orographic left valley flank of the Yamatari Glacier valley.

↙ *Photo 8.* The location is situated at 3600 m asl. below the peak of the Sumathalung (3974 m asl.) in the lower valley section of the Simbua Khola on the orographic right side of the valley (place name: Nyamgyalama, 27°31′ N 87°54′ E). The view faces into the valley (cf. Photo 9). The mound (○○) that can be clearly seen in the picture is more or less in front of and parallel to the mountain side, but it recedes slightly down the valley. The mound is made up of fine material and embedded blocks that are partly jagged and partly with rounded edges. The small valley between the mound and the main flank of the valley is mainly filled with fluvial material (🡇). This form is interpreted as a remainder of a lateral moraine and makes an ice thickness of 600 m probable in this section of the valley. Up the slope from this locality is further moraine material. This could be interpreted as evidence of an even greater ice thickness.

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