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The Maximum Ice Age Glaciation between the Karakorum Main Ridge (K2) and the Tarim Basin and its Influence on Global Energy Balance

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Abstract: A modern research approach and working techniques in hitherto unexamined areas, produced the following results: 1). The tongues of deca-kilometre long Karakorum glaciers belong to temperate ice-streams with an annual meltwater output. The short Aghil glaciers on the contrary are continental, arid and cold. 2). The present-day oscillations of the Karakorum glaciers are related to their own mass, and are contrary to and independent of the actual climate. Only the short glaciers, with steep tongue fronts, show a present-day positive balance. 3). ^{14}C- dated Late Glacial moraines indicate a 400~800 m thick valley glacier at the former confluence point of the K2-, Sarpo Laggo- and Skamri glaciers. 4). From the evidence of transfluence passes with roches moutonnées, striae and the limits of glacial polishing, as well as moraines and erratics, a High Glacial at least 1200 m thick ice-stream network between the Karakorums and the Kuen Lun north slopes was reconstructed. The Shaksgam and Yarkand valleys were occupied by glaciers coming from west Tibet. The lowest-lying moraines are to be found in the foreland down to 2000 m, indicating a depression of the High Glacial (LGM) snowline (ELA) by 1300 m. 5). The approximately 10,000 measurements of the radiation balance at up to heights of 5500 m on K2 indicate that with incoming energy near the solar constant the reflection from snow- covered ice is up to 70% greater than from rock and rock waste surfaces. 6). These results confirm for the very dry western margins of Tibet an almost complete ice sheet cover in an area with subtropical energy balance, conforming with the Ice Age hypothesis of the author which is based upon the presence of a 2.4 million km² Tibetan inland ice sheet. This inland ice developed for the first time when Tibet was uplifted over the snowline during the early Pleistocene. As the measured subtropical radiation balance shows, it was able to trigger the Quaternary Ice Ages.

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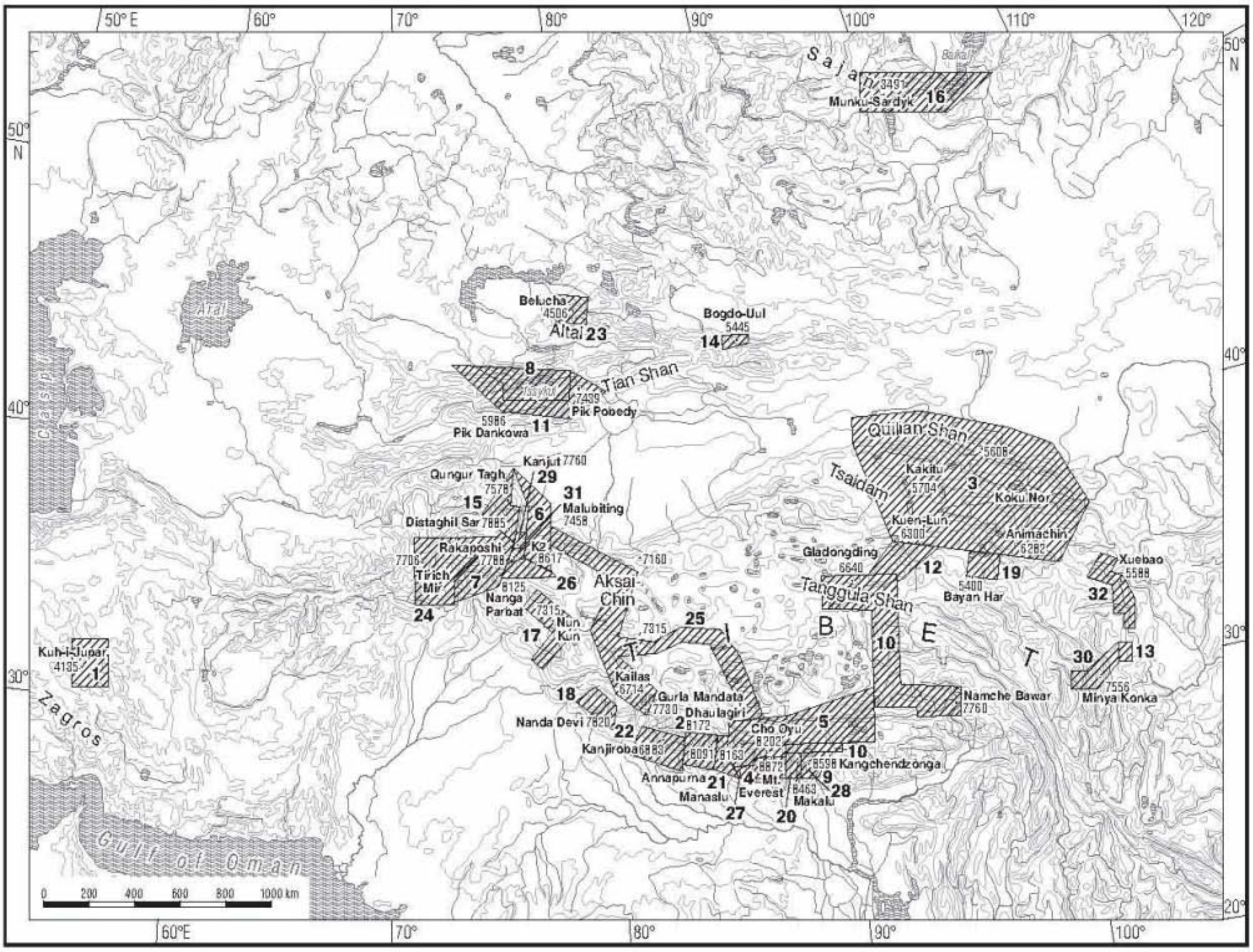
1 Situation of the Research Area, Logistics and Precipitation

As part of the project to reconstruct the Ice Age glaciation of Tibet and its surrounding mountains, in which the author has been engaged since 1976 (Figure 1), supported by the German Research Society (DFG) and the Max-Planck-

Society, the sixth Central Asian expedition was mounted between August and November 1986. On this occasion it led to the arid west of the upland, in the mountainous terrain between the northern slopes of the Karakorums, the Aghil range, the Kuen Lun system together with its northern foot, and the southern edge of the Tarim Basin (35°53'~39°N/76°~77°30'E; Figure 1 No.5; Figure 2 K2; Figure 3: inset). The expedition was a German-Chinese joint undertaking of the Geographical Institute of the University of Göttingen, and the Lanzhou Institute for Glaciology and Cryopedology of the Chinese Academy of sciences, under the leadership of Prof. Xu Daoming and the present author. It consisted of eight Chinese and six German scientists, as well as thirty technicians, camel-drivers, cooks, high-altitude porters and other assistants. The undertaking was made possible by the use of a camel train of seventy animals, and entered the north side of the Karakorums, where access is very difficult and a previously unresearched area of K2 (Figure 3 on the left below). The altitudinal range of the research area was 7200 m asl (1400~8600 m; cf. Figure 3). The precipitation, in so far as it is known or measurable - lies between less than 40 mm/yr in the Tarim Basin (Figure 3 No.45), to about 80 mm/yr on the valley floors about 4000 m between Karakorum, Aghil and Kuen Lun (Figure 3 Nos. 10, 23, 30, 39), and rises at altitudes of from 5000 m to 7000 m by a few hundred millimetres to a maximum of 2000 mm/yr (Figure 3 Nos.7, 3, 6).



1: *1973, 1974* **2:** *1976, 1977, 1995, 1998, 2000, 2002* **3:** *1981, 1998* **4:** *1982* **5:** *1984* **6:** *1986* **7:** *1987, 1992, 1995, 2000* **8:** *1988* **9:** *1988/89*
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21: *1994/95, 2000* **22:** *1995* **23:** *1995* **24:** *1995* **25:** *1996* **26:** *1997* **27:** *1998* **28:** *1999* **29:** *1999, 2000* **30:** *2000* **31:** *2000* **32:** *2002*

Draft: M. Kuhle (2002)

Figure 1 Research areas in High-Asia under investigation by the author; No. 6 is the area treated here.

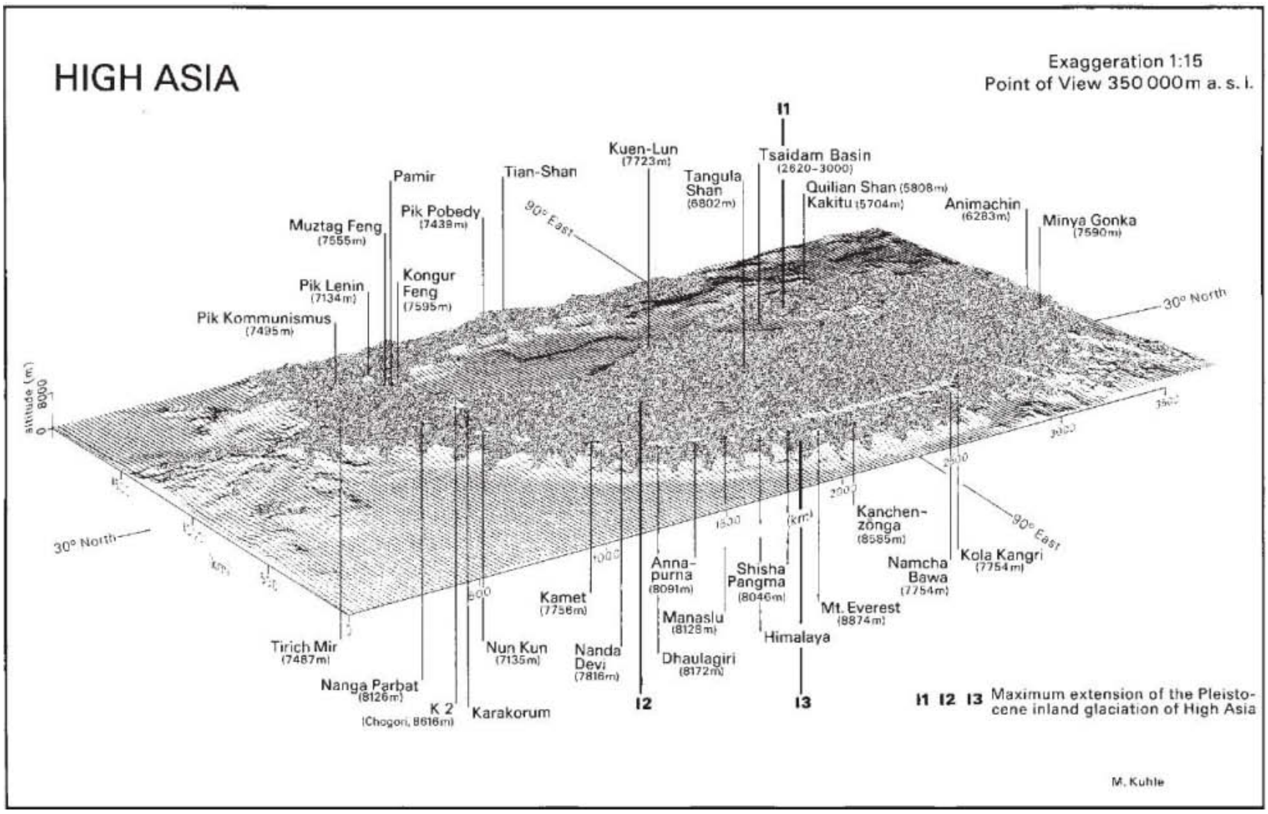

Figure 2 The central Tibetan ice sheet I2 covered the entire high plateau; I1 and I3 are the ice-stream nets of the mountains surrounding Tibet, including the Karakorum in the west. They are connected to I2.

2 The Present-day Glaciers of the Karakorums and Aghil and their Mass Balance

Special to the glaciers of the Karakorums - the glacier complex here represents the largest valley glaciation complex outside the Arctic and Antarctic regions - is the combined feeding by primary precipitation in firn basins and on sections of firn streams, together with the secondary nourishment by avalanches (see Schneider 1962). On the 23 km long K2 glacier, in the highest source areas above the snowline, about 70 cm of freshly fallen snow was recorded from middle September to middle October; at the same time the medium to very large avalanches were observed with considerable frequency (Photo 2). Some of these were the consequence of ruptures along transverse crevasses on the 3400 m high NNE and WNW walls of K2 (Photo 1 ▽; Figure 3 below No.3).

The large avalanches, with over 1500 m of vertical fall, burst into ice dust. They run along both glacier source branches for some kilometres, and surge up against the opposite slopes. In some cases they even strew dust particles over the next transverse ridge. The expedition members were able to observe table- to room-sized granite blocks that had been torn out of the wall by such avalanches (cf. Photo 1 below ▽).

In the K2 glacier, as is also true of the largest glacier in the research area, that is the 43 km long Skamri glacier, a classical dendritic valley glacier system is present (Figure 3 Nos. 3, 7, on the left below 6), the tributary components of which in many places are connected by ice falls over confluence steps of several hundred metres (Photo 2). The ice pyramid forms, which reach up to 30 metres, derive not only from a combination of overlying and subjacent glaciers (in the sense of VISSER 1938, pp 57~74) but also from the overlying avalanche cones, adjusted to the glacier (Kuhle 1982a, 1983b).

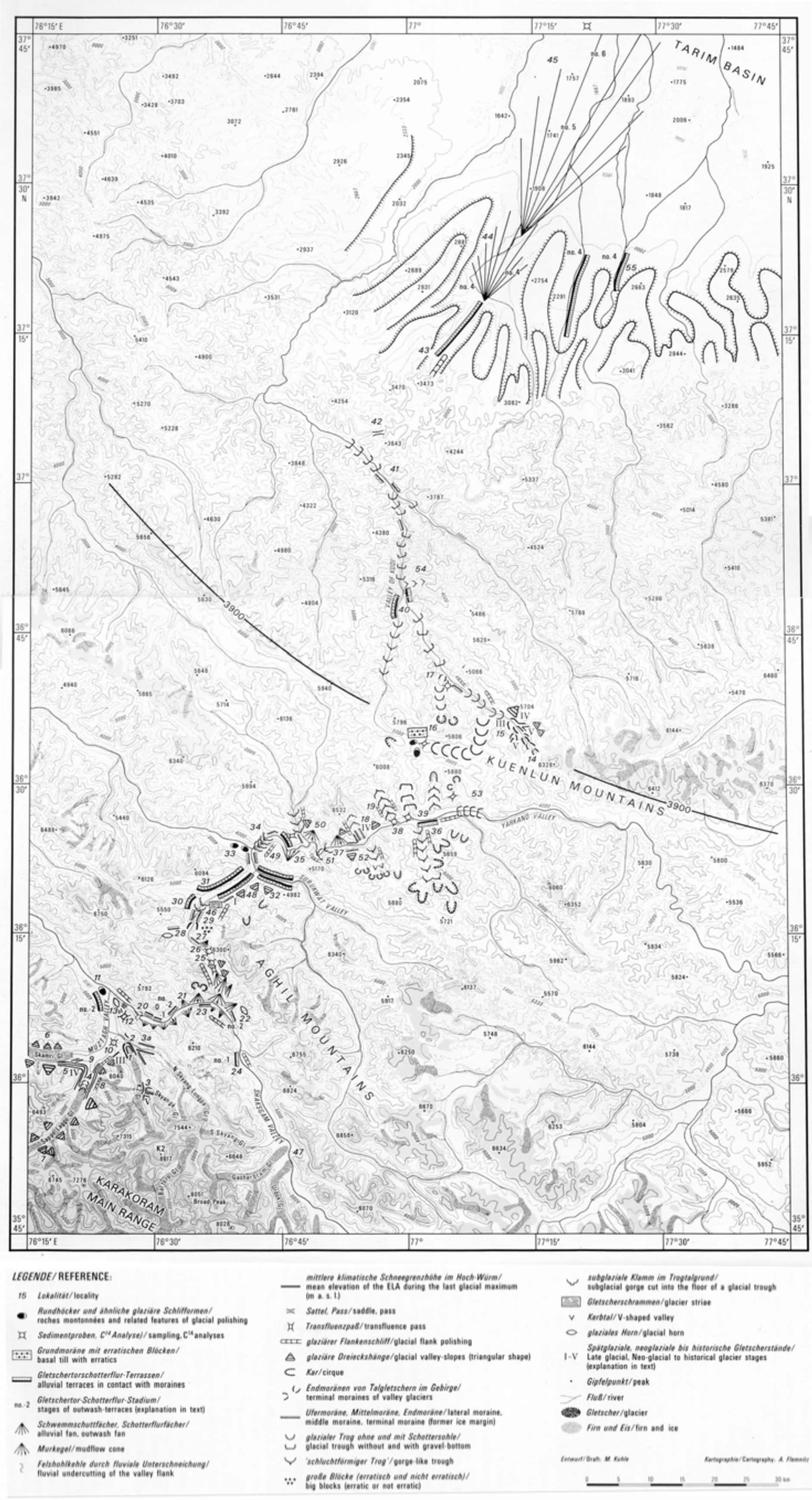

Figure 3 The map shows areas of the Karakorum with the 8617 m high K2, the Aghil (6,755 m) and Kuenlun (6,460 m) as well as of the Tarim Basin (1,484 m) (cf. Figure 1 No.6)

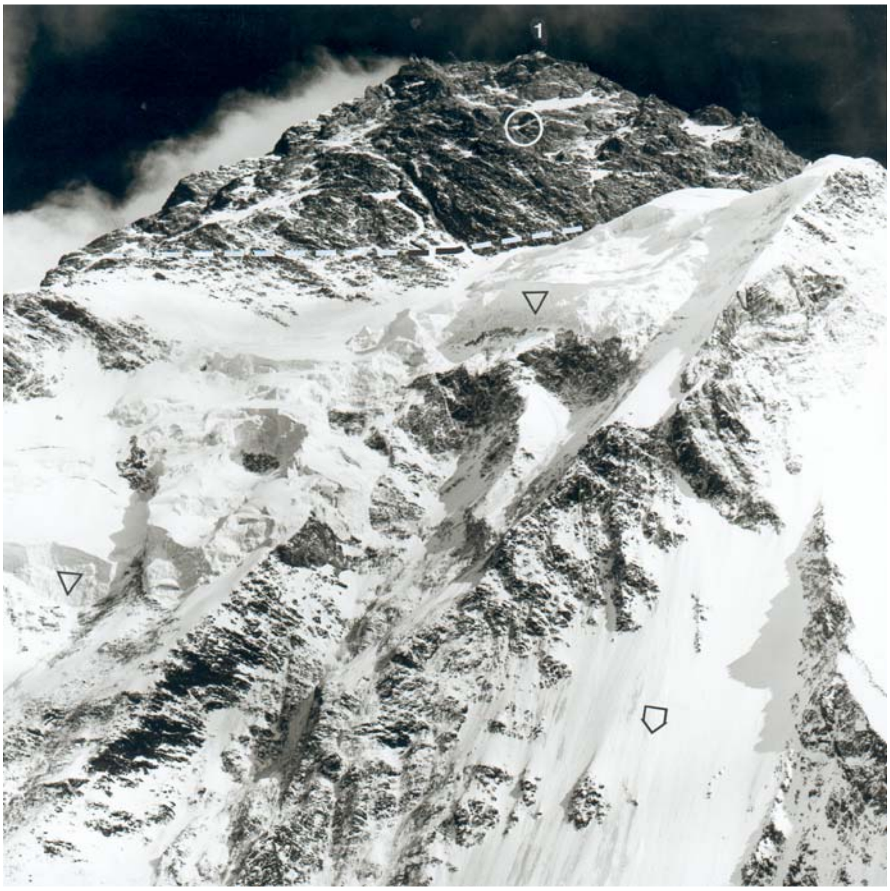

Photo 1 WNW face of K2 (1) between 8617 and c. 5800 m asl, taken at 5500 m. Above c. 6900 m asl (----) glaciation and flank icing (○) stop, because the very cold and therefore dry snow on the steep rock face has been blown off before the snow- to ice metamorphosis. In spite of great steepness a flank ice cover (⬠) clings to the rock wall surfaces below (----). On the less steep faces of the K2 flank 10 to more than 100 metre thick ice was accumulated, breaking off at ice balconies (▽). Viewpoint: 35°54'N/76°26'E (Figure 3 on the left of K2)
Photo: M. Kuhle, September 23, 1986

Photo 2 The fourth and highest of the weather stations on the orographic left-hand tributary branch in the feeding area at 5330 m asl (cf. Figure 3 on the left above K2; Figure 12), weighs 75 kg and was taken up on a sledge pulled by the scientists. It operated for 17 days, from the 21st of September to the 7th of October 1986. Every 20 minutes the 12 different measurement data were averaged and stored together with the extreme values. Their batteries were charged by S-facing solar collectors and were maintained in working condition. No.1 = Skyang Kangri, 7544 m; No.2 = 6869 m peak; No.3 = c. 6400~6600 m high peaks in the ridge between the Skyang Kangri and K2 glaciers as they are running between Skyang Kangri and the 6640 m peak; No.4 = 6526 m saddle towards the Godwin Austen glacier (Baltoro glacier system); beneath this high relief there is the firn cauldron of the orographic right-hand (eastern) tributary branch of the K2 glacier. Viewpoint: 35°54'45"N/76°28'30"E
Photo: M. Kuhle, September 21, 1986

The present-day glacier of the Aghil ridge, as a function of a snowline at 5400 m compared with the ridge elevation of 6000~6500 m, is poor and correspondingly cold (Figure 3 to the right and left of Nos. 29 and 30). The ice temperatures are low, as a consequence of the aridity. This is confirmed by the steep edges and ice-cliffs of the short hanging- and cirque glaciers. The few wall-foot glaciers are covered by thickly debris.

The flow of meltwater is broken during the day time even in summer (August), which also suggests cold to temperate glaciers for the Aghil down to its tongue end.

By far the greatest part of the ablation of these small glaciers is by sublimation — another characteristic of continental arid glaciers. For the long Karakorum glaciers, extending far beyond the equilibrium line, with tongues, which are mantled with debris over many kilometres, the conditions change, favouring in part the presence of warmer ice streams, rich in meltwater (Figure 3 Nos. 3 to 1, 7 to 4, 5 to 6).

The behaviour of the lowest ice margins during the last decades has been determined primarily by the dimensions of the glacier, and secondarily, with respect solely to rapidly-reacting short glaciers, by climatic variation. The K2 glacier has retreated since 1937 for about 1.9 km (cf. SPENDER map; Figure 3 No 1); the large Skamri glacier, over twice as large, 0.1~0.2 km (Figure 3 above No. 5). However, in 1986 the K2 glacier was advancing as is shown by the very steep swollen tongue end, whilst the Skamri glacier was still retreating. Its tongue was flat, and covered with debris down to the gravel floor. The glacier mouth has been moved several decametres behind the front of the glacier tongue. A similar dependence on the glacier dimensions was demonstrated by the counter oscillations of the Skamri- and Sarpo Laggo glaciers: whilst the smaller Sarpo Laggo glacier has already melted back from the confluence area with the Skamri valley, the locality was reached by the Skamri glacier tongue, which extended into the side valley in the shape of a hammerhead (Figure 3 Nos. 4 to 9).

This is confirmed by the lateral moraines of the Sarpo Laggo glacier, which have been reshaped by the Skamri frontal moraines (Figure 3 between No. 4 and 5). The small hanging glaciers of Karakorum and Aghil, as well as short valley glaciers, revealed a positive mass balance in their steep advancing ends. Thus in 1986 the glaciation was in progress, as the result of favourable conditions of temperature, precipitation and radiation (cf. for the Alps KUHN 1983, pp 90).

3 The Historical, Neoglacial and Late Glacial Sequence of Glacier Cover

Research on glacial history is as lacking in the region as that on actual mass balance. In the literature the paper by Desio (1936) argued the possibility for the pre-historical Shaksam glacier of a valley glacier thickness of 500~600 m in the Muztagh -Shaksgam confluence area (Figure 3 No. 11). Mason (1930, pp. 263) suggested a transfluence over the Aghil pass (Figure 3 No. 25), with the upper Shaksgam glacier formerly reaching a confluence with the Urdok glacier (Figure 3 No. 47). The author has found moraines 200 to 400 m above the present valley floors, away from the glaciers in the Skamri and Sarpo Laggo valleys (Muztagh valley), that from their morphological characteristics date back at most to the Late Glacial (later than LGM = Last Glacial Maximm = Stadium O, older than 12,870 ± 180 ^{14}C years: Figure 3 No.10). From the 14 ^{14}C-data obtained during this expedition the dating introduced here (12.870 +/- 180 ^{14}C years) is the most important. The reason for this is that the sample has been taken from a depth of only 1 m in a valley-damming position on the orographic right side of the Muztagh-valley at 36°03'N/76°25'20"E at 3990 m asl (Figure 3 No. 10). It consists of mud built-up on the underlying ground moraine by moor and spring grass, as well as pelites from granite and quartzite. The sampling site is situated 2 m above the current brook of glacier meltwater in the talweg and underneath a root zone reaching at most 30 cm below the surface (riparian exposure). It concerns ground moraine (lodgement till) of the late glacial period, more exactly of the Dhampu (III)- or Sirkung (IV) Stadia (Kuhle 1982a). Due to topographical reasons one is forced to conclude that this locality must have been overthrust for the last time during these two stadia of the Skamri- and Sarpo Laggo-, i.e., Muztagh valley glaciers. After that time, however, this didn't happen again, otherwise the ^{14}C-material taken in a valley-damming position of the talweg couldn't have remained.

Less marked, but because of erratic findings incontrovertible, are the Late Glacial moraines in the confluence of the Skamri-, Sarpo Laggo- and K2 glaciers, that lie up the slopes to a height of more than 800 m and point to a corresponding glacier surface level. Glacial erosion grooves in ground moraine (Figure 3 No. 10), which reach up the lateral moraine slopes indicate an age from Historical via Neoglacial (Stadia VII to V) to Late Glacial (Stadia I to IV). A marked ice margin site of the upper Muztagh glacier (= Skamri-, Sarpo Laggo glacier system) is situated below the K2 valley confluence step at 3950 m asl. It belongs to the Late Glacial period (Stadia IV to III; Figure 3 No. 2 to 3a).

The very well preserved glacial flank polishings in the Muztagh and Shaksam valleys, as well as a confluence barrier, reshaped to a roche moutonnée in the bedrock limestone and dolomite (Figure 3 Nos. 11~13), provide evidence for a Late Glacial confluence of the at least 600 m thick ice streams from the Shaksgam- and Muztagh glaciers. Thus the results of Desio (1936) are confirmed. Accordingly at that time there still existed an ice-stream network, which covered the entire Shaksam region. Since the deglaciation of the 3800~4000 m high valley floor, more than 200 m thick mudflow- and alluvial fans have been deposited from wall gullies and Shaksgam tributary valleys (Figure 3 Nos. 20~23).

4 The Maximum Glaciation (probably Würm = LGM = Last Glacial Maximum = Stadium O) between the Karakorum and the North Slopes of Kuen Lun

4.1 Glacial polished landforms in the Shaksgam system

The flanks of the middle and lower Shaksgam valley (Figure 3 Nos.20~23) are built of massive reef limestones (90% calcite, cf. Figure 4) and thinly bedded dolomites. They are smoothed up to 1200 m above the gravel floor (Photo 3 ◓ large,◓ small). Provided that in interpolation of the trough cross profile the gravel thickness above the bedrock valley bottom is c. 200 m, the former glacier thickness might have been about 1400 m. Since subaerial frost weathering and the resulting rock fall and avalanche trails have eroded the slopes and walls of the valley, this is a minimum value for an integral ice thickness, which represents the last permanent maximum position. The dimensions of these processes can be made clear by the frost weathering and denudation above the youngest levels of the K2-, Skamri- and Sarpo Laggo glaciers. Thus the maximum ice level may have even been several hundred metres higher. Another, opposite, extreme is the earth pyramids of comparatively low resistant ground moraine (Photo 3 ■) at other places of the Shaksgam trough (orographically to the right of the junction with the valley from the Aghil pass; Figure 3 above No. 23). They are preserved on the polished flanks up to a height of 300 m.

The reconstruction of the ice infilling is completed by evidence of roches moutonnées fields and striated polishings on and above transfluence passes up to about 5300 m. Besides the Aghil pass in the Yarkand system there is for example a classical transfluence in the Muztagh valley (Figure 3 No. 12). On the latter transfluence pass, which is eroded in limestone, blocks of uniaxial mica granite were observed, reaching lengths of 1.5 m, some rounded and facetted, at an altitude of 4400 m. These plutonic erratics are found 500 m above the Shaksgam gravel floor, and also dolomite erratics on bedrock calcites (Figure 4). This type of morainic deposits could be observed up to 4700 m.

Considered in detail, the soft forms of the roches moutonnées surfaces, which nevertheless show a small-scaled relief, are evidence for the still thick glacier above the pass (Figure 3 No. 12), because they reveal in the specific selective basal glacial polishing a low viscosity ice, close to the pressure melt-point.

A further key-form of glacial erosion in the Shaksgam region is the glacial horn. It is present in the form to be found in Greenland and in Scandinavia on the edges of the fjells, as for example at Romsdal near Andalsnes in central Norway. One such is situated at the confluence with the Muztagh valley. It is sharpened up to the peak at 4730 m (Figure 3 No. 13). A further impressive huge horn, reaching 5466 m, dominates the orographical right-hand valley side of the

Photo 3 View from the mudflow cone (4250 m asl.) at the exit of the "southern Aghil pass valley" from the orographic right-hand flank of the Shaksgam valley facing a spur-peak of the Aghil range (6) (Figure 3 between Nos. 23 and 25). Late Glacial ground moraine material is preserved (■), which is attached to the mountain foot of limestone rocks. It consists of isolated large blocks in a matrix with great portions of fine material. This points to a significant trituration on the ground of a very thick, fast flowing valley glacier. Above there follow abrasional forms of glacier polishing. As a result of backward erosion of the sharp crest of the mountain spur - which in its upper part is still intact - , these have produced a facetted glacigenic triangular shaped slope (◓ large). Though this crest has also been reworked by the glacier up to the High Glacial (LGM) polish line (----), it still remained comparatively sharp because of the decrease of the pressure in the ice body (◓ small). In addition, due to the greater interval to the deglaciation, it has already crumbled away more strongly than the lower lying polishing surfaces. For comparison of the size see on the bottom right our camel caravan. Viewpoint: 36°08'30"N/76°38'10"E
Photo: M.Kuhle, October 20, 1986

Shaksgam some 28 km upstream at a confluence with an Aghil cross valley (Figure 3 No. 22). In its dimensions this "Shaksgam Horn" resembles the alpine Langkofel. These horns are the better preserved the closer their summits are to the Late Glacial (not High Glacial) ice level, since that the glacial polishing remained intact until relatively recently, and the nunatak phase is limited to the last thousands of years of the deglaciation.

The adduced reconstructions (Figure 3) provide evidence of a High Glacial ice-stream network, forming the great Shaksgam glacier, with only 5100~5300 m high crests and peaks towering above its level (Photo 3 above ----0). In the side valleys the surface of tributary streams in the direction of the Karakorum main ridge in many places reaches up to 5500~6000 m, so that the highest summits are about 2000 m above the levels of the ice-stream network.

The Shaksgam ice-stream network was the more southerly of the two great northwestern outlet glaciers that flowed down from the west

Tibetan ice-stream network, which was connected to the Tibetan ice sheet (Figure 2 north of K2). The following report shows its communication with a northern ice complex, the parallel Yarkand valley that also led down from the western margin of Tibet.

4.2 Glacially-polished landforms and moraines in the Yarkand system

The glacial landforms of the mediating Aghil pass, so for instance roches moutonnées and glacial flank polishings (Figure 3 No. 25), show that the Shaksgam ice-stream, with a thickness of at least 400 m, overrode the pass into the Aghil valley, a southerly side valley of the middle Yarkand valley. If this valley is followed for about 600 m downstream, orographical left-hand polishings on the limestones can be compared with polishings of granites on the right-hand, which are of the same age (Figure 3 No. 26). The forms in the limestones are in many places better preserved than those in the dolomites in the Alps, and in the massive crystalline rocks they are as good as those in Jotunheimen in Scandinavia. There, where at 4200 m numerous side valleys of a lower order come together, triangularly shaped slope facets are found in company with roches moutonnées and glacigenic pinnacles (Figure 3 Nos. 27, 28). They are dissected through V-shaped side valley exits. Corresponding features are found 600 m lower in the Surukwat valley (Figure 3 Nos. 29, 30). As for the glacigenic V-shaped valleys that were completely filled by ice, these facets are elements of glacial shaping, scarcely to be met in European mountains but present in the semi-arid Andes (Desio 1936; v.Klebelsberg 1929, pp 201, 202; Kuhle 1984b) and in the equally arid Tibetan Himalayas (Kuhle 1982a, 1986c, 1987). A further 600 m downstream, to the confluence of the Aghil valley in the Surukwat valley, great thicknesses of this branch of the ice-stream network on the middle Yarkand glacier are made evident by trough-like concave polishings in the granite and outcrop polishings in the red sandstone (Figure 3 No.46 to 32).

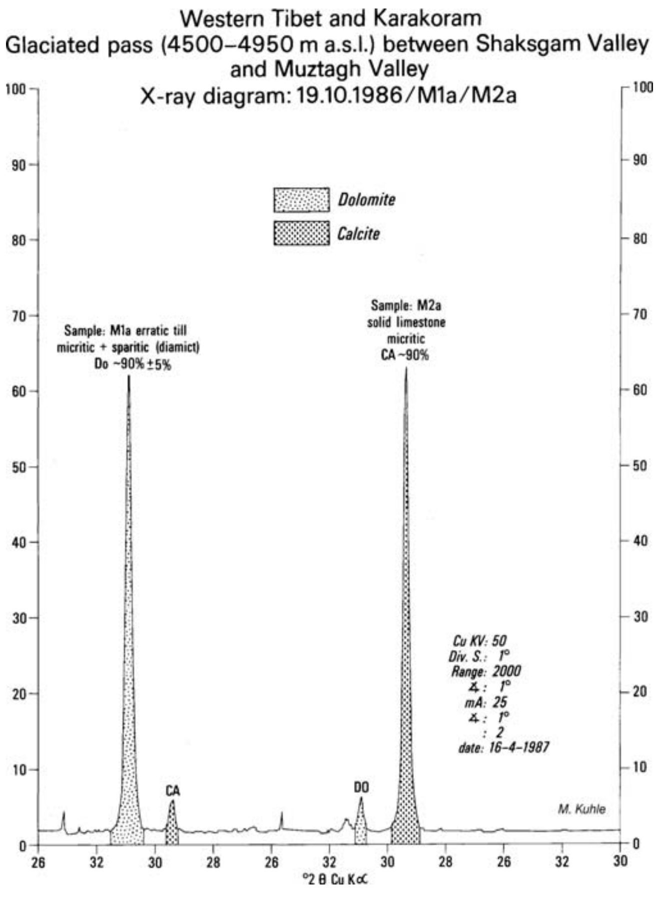

Figure 4 The erratic dolomite blocks and the dolomite scree (left peak) are mixed with up to 1.5 m-long mica-granite blocks from the upper catchment area of the Shaksgam valley. The erratic dolomites lie on top of bedrock calcites (right-hand peak). The calcite rocks have glacigenically polished surfaces in the form of glaciated knobs. They are on the 4500 m-high Shaksgam-Muztagh valley transfluence pass. Locality of the sample: 36°05'N/76°28'E; Figure 3 No.1 2

Extended fresh glacial polishings with striae occur on the orographic right-hand flank of the deepest valley chamber of the Aghil valley at about 3700 m asl (Photo 4, Figure 3 No.46). These polishings are associated with roches moutonnées and confirm the large overlying glacier thickness, for they continue immediately in the lee of abruptly steep cleft steps, indicative of plastic flow close to the pressure melt point.

There, where the upper Surukwat valley joins the Aghil valley, the flank polishings and abrasions confirm a glacier level of 700 m above the present gravel floor. Since the thickness of the gravel infilling can be estimated from the valley width as about 300 m, a glacier thickness of 1000 m is suggested (Figure 3 Nos. 32, 48).

In the confluence area of the Surukwat and Yarkand valleys, at the location "Ilik", there are for a further 10 km downstream at 3400~3600 m large roches moutonnées, formed in vertical bedded lightly metamorphosed phyllite (Figure 3 No.33). Over large parts of these 200 m high roches moutonnées, "drowned" as they are in Late Glacial gravels, well-preserved glacial polishings are present, today still reflective (Photo 5). Its fresh condition in the outcropping edges of the strata of highly fissile rocks makes it likely that there was Late Glacial activity in this valley cross profile which reaches down to 3250 m in the country rock. Here also the polished slope surfaces and the trough profile of the confluent upper Yarkand valley indicates a glacier thickness of 800~900 m. In order to reach this roches moutonneés area, the Aghil north glaciers of this alimentation region, now at its lowest reach 4800 m (Figure 3 left of No.28), would require a depression of the snowline by 700~800 m. The inferred 800~900 m glacier thickness may be correlated with a last High Glacial snowline depression of about 1200~1300 m (see below), and makes a lower confluence with the Shaksgam glacier at 3050~2800 m asl possible (on the left, i.e. to the W, outside the section of Figure 3). We follow the Yarkand valley from the Surukwat confluence upwards, in order to find

Photo 4 Detail of a quartzite rock face on the orographic right-hand flank of the western Surukwat valley at 3700 m asl, with striae from a pre-historic glacier (Figure 3 No.46). The size of the striations (↓ ⬆) (which are horizontally arranged) can be estimated by comparing them with a ski stick on the right (which is vertically arranged). (△) mark the somewhat larger, more extensive injuries to the rock, like "chattermarks"; (◀) mark much more significant sickel-shaped rock outbursts in the direction of the ice movement (from right to left), which are to be attributed to detraction with the aid of regulation processes. The quartzite areas show iron manganese crusts, which point to considerable potential evaporation of this semi-arid to arid N-slope of the Aghil mountains.
Viewpoint: 36°20'N/76°36'E
Photo: M.Kuhle, August 28, 1986

Photo 5 Main (LGM) to Late Ice Age glaciated knobs with preserved polishing (◓ ⇓) in vertical pelitic metamorphites (phyllites). These glaciated knobs are in the confluence area of the Surukwat valley and the Yarkand valley (Figure 3 No.33). Their surface is about 3580 m asl, approximately 100 m above the present gravel floor of the two valley bottoms. Though shallow, the fluvially-formed plunge pools constitute evidence of the contribution of the rock surface formation made by sub-glacial meltwater (↓ ⬇). The surface of the glaciated knobs continues to be partially covered by ground moraine (behind rucksack). It has conserved the slightly frost-weathered rock surface since deglaciation, and prevented, or at least reduced, its frost-splintering. Late Glacial glacier outlet gravel-fields set these glaciated knobs into sediments from the bottom up (☐). Accordingly, younger, i.e. post-Glacial or Holocene debris and mudflow cones (▽), are in turn set into the present surface of these gravel fields. Viewpoint: 36°23'N/ 76°41'E, facing E
Photo: M.Kuhle, August 27, 1986

Photo 6 From a transfluence pass and mountain ridges, which are polished round by the glacier ice (◓ large), in the area of the orographic right-hand flank of the Yarkand valley (Figure 3 No.53) at 4420 m asl, looking across a right-hand side valley, facing E. The main valley runs below (----) down towards the right. The round-polished ridge (◓ large) is formed in relatively easily weathering outcropping edges of the strata of metamorphic sediment rocks, and over large parts, down to the slopes, covered with ground moraine (■ black). Though the moraine layer on the solid rock shows a fine matrix, it is preserved in metre- to decametre thickness. This indicates an only recently deglaciation (c. 15,000 years ago) of the valley chamber. A mixture of moraine material and residual detritus has built steep debris cones on the slopes (△). On the side valley floor at least three Holocene gravel terraces can be differentiated (▾). The valley bottom of the Yarkand lies behind the round-polished ridge (◓ large) 600 m below its culmination. From there glacial flank polishings (◓ small), in parts with ground moraine covers (■ white in the background), can be observed up to a level, which must be considered as High Glacial (LGM) minimum height of the ice surface (----) at about 5000 m asl.
Viewpoint: 36°28'30"N/77°05'15"E
Photo: M.Kuhle, August 24, 1986

further glacial erosion forms that indicate the connection of the thick ice filling, confirmed here, to the east, in the direction of the plateau. In addition to the numerous remnants of glacial polishing, mainly in the steep glacigenic granite gorges of the south slopes of the Kuen Lun, in the 35 km section as far as the settlement Mazar (Figure 3 No. 34 to 39), the great transfluence pass 17 km beyond Mazar is well preserved (Figure 3 left of No. 53). It is at 4420~4700 m and forms at a good 600~700 m above the main valley a kilometre wide overflow from the orographic right, i.e. from an adjacent valley on the Kuen Lun side (Photo 6).

On the margin between massive crystallines and debris-rich metamorphics runs the Yarkand valley, a large longitudinal trough with gently-formed polished flanks and rock barriers (e.g. east of Mazar Daran: Figure 3 No. 50), alternating with debris slopes up to 1000 m high.

Between the Surukwat confluence ("Ilik") and Mazar, in the present Yarkand valley floor at altitudes of 3500 to 3850 m, the Late Glacial moraine terraces were met. So for example 3 km from "Ilik", orographically left, they were observed in the form of 600 m long accumulation ledges (Figure 3 No. 49). 5 km further up-valley, and at the same level, more than 120 m thick moraines on a c. 450 m high rock base in the outer slope-area of the glacier were pushed into a valley bay (Figure 3 between No.34 and 50). The glacial polishings, stretching at least 300 m higher, indicate an age well after the glacial maximum (Stadia I to III).

Halfway between Mazar-Daran and Mazar (36°24'N/ 76°54'E) at heights of at least 650 m above the talweg, here elevated because of mudflow fans, both the valley flanks are plastered with lateral moraines of up to 100 m thick, or such moraines rest upon pronounced denudation terraces (Figure 3 above No. 37 to 52). All these glacigenic diamictites, formed from a loamy groundmass and a polymictic very differentially reworked block fraction, lie beneath the 200~400 m higher glacial polishing line in the bedrock. This is the characteristic outcome of glaciation of the whole valley from the High Glacial (= LGM; Stadium O) to the Late Glacial (Stadia I~III) with the ice both falling in level and narrowing and the gap between the ice and the valley walls becoming filled with moraine. In places above the lateral moraine terraces patches of thin ground moraine can be observed, clinging to the rocks, which contrast in its high content of fine material with the coarse-fraction-rich lateral moraines. This confirms the comparatively thin moraine sedimentation in these valleys during the maximum ice filling. During the later Late Glacial (Stadium IV), local moraine deposition in the main valley was due to the tributary glaciers, which no longer flowed into the main ice stream, but of which the end moraines still reached that far. An example is the 6532 m summit south glacier 13 km west from Mazar, the local moraines of which, 400 m thick, still reached the main valley (Figure 3 No. 18 IV).

Because of a similar glacial history it is possible to compare the orographically left-hand tributary valleys of the Yarkand valley, which is on the Aghil side, with those of the Kuen Lun side. Situated in more or less metamorphosed clastic rocks, they have a V-shaped profile, only broken occasionally by gorge-like narrowings (Figure 3 Nos. 36, 52), whilst the Kuen Lun cross valleys reveal some classical 100 m long gorge stretches below the Neoglacial (Stadia V to VII) ice margin sites (Figure 3 No. 18). Within these there are stuck blocks, 5~15 m cataracts and large pot-holes, excavated by cavitation corrosion. These features in the resistant granite of the Kuen Lun valleys authenticate the glacigenic V-shaped valley formation (Figure 3 No.18) with the help of well-preserved glacial polishing (Figure 3 No. 19).

4.3 The landscapes left after glacial moulding on the northern slopes of the Kuen Lun (cf. Figure 2)

We follow a transverse valley with its tributary valleys from the 6460 m high Kuen Lun main crest (Figure 3 No. 14) down to 2500 m, and leave the valley of Kudi to the east (Figure 3 Nos. 41, 42), to investigate representative parallel valleys at their lower exits and in the foreland. The lowest actual glacier tongue lies at 4600 m (Figure 3 No. 14). Below, a strongly dissected trough continues and shows all the characteristics of glacial activities down to 4000 m (Figure 3 No. 15). Here in the confluence region of the most important source branches, the valley narrows more and more to a "trough-shaped gorge" (Figure 3 No. 15 to 17)(Kuhle 1982a). In particular the stadial moraines of tributary glaciers dam the valley in alternation with large tributary mudflow fans, making the valley chamber irregular and producing steps in the infill of the valley floor. At 3000 m asl, above and below the settlement of Kudi (36°50'N/ 76°58'E) markedly well preserved trough profiles of the type "gorge-shaped trough" (Kuhle 1982a) with polished flank surfaces are evidence of a valley glacier or ice stream well over 1000 m thick (Figure 3 Nos. 40 and 54).

With these transverse valleys of the Kuen Lun, with their very high relief energy, extremely steep hanging valleys are connected, as is shown by the valley of Kudi (Figure 3 Nos. 16, 17 and 40). They reach above the present-day snowline. Their shortly-connected inflow brought to the main stream of the glacial ice net during the High Glacial, and still during the Late Glacial, a considerable thickness of rapidly moving ice. The rocks, polished down to the unweathered and resistant material beneath, are encrusted over large parts with iron manganese, and this makes possible the use of light coloured rock resulting from recent erosion, as a diagnostic, accepting the dark colours as indicative of intact glaciated valley flanks (Figure 3 No. 40 to 42).

At the foot of the northern Kuen Lun the mouths of three large valleys in the foreland to the Tarim Basin were investigated. They are situated immediately south of the irrigated oasis of Yeh Cheng at 37°20'N/ 77°05'~35'E at 2000 m asl (Figure 3 No. 44 to 55). Here up to 700 m high moraine ridges (Photo 7 0■) are extending in the form of lateral or medial moraines to the mountain valleys up to over 20 km in the foreland (Figure 3 No. 43 to 44). A good occurrence of exposures permits a sure identification of the diamictites as glacigenic, with a polymictic content of blocks of limestone intermixed with various metamorphic rocks and massive crystallines, such as granites. The groundmass in which the isolated edged, rounded or in many cases facetted blocks are found — up to room size (Photo 7) — is lean-sandy to loamy and fat-clayey. As often observed, glaciolimnic sediments and gravel layers and -nests of lateral sanders are compressed in the bank formations (Photo 7). Flexures are numerous but complete faults were not observed. In the immediate mountain rim polished surfaces in massive limestones are in contact with very thick medial moraines.

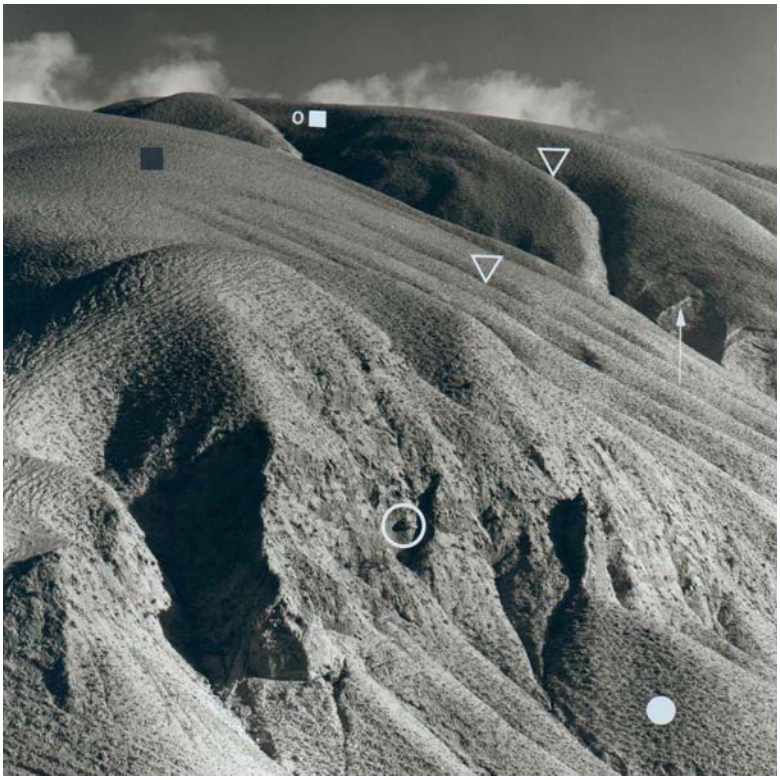

Photo 7 View of the orographic right-hand end moraine of the "Pusha moraine valley" in the northern Kuenlun foreland, facing S up-valley (Figure 3, centre, between Nos.43 and 44). The High Glacial moraine ridges (0■) reach relative heights of 400~700 m. The time of their formation must be described as polyglacial, since outlet glacier tongues, which repeatedly reached the Tarim basin in the course of several Pleistocene ice ages, contributed to it. The moraines (■) consist of polymict, partly rounded and facetted blocks (of limestone, phyllite, crystalline slates), in part of significant dimensions (○). Isolated from one another, these blocks "swim" in a fine matrix. The moraine ridges carry a primary layer of loess, which is dissected by gully washings (▽). On particularly steep gully slopes the loess slips off in the form of more than one metre-thick "loess boards" (↑). At the gully exits at the foot of the slope, the down-washed secondary loess from higher up is sedimented in the form of shallow cones (●).
Viewpoint: 2000 m asl; 37°18'N/77°07'E
Photo: M.Kuhle, October 30, 1986

The Kuen Lun foreland landscape of parallel ridges of medial and end moraines can be divided into Young (LGM = Würm = Stadium O) and Old (pre-last Glacial Maximum = Riss = Stadium-I) Moraines. Beyond the very high steep-flanked fresh morainic ridges, i.e., towards the Tarim Basin, the strongly reshaped hills continue reaching down to about 1880 m (Figure 3 Nos. 44 and 55), fringing the lowest tongue basins. In them in places morainic deposits are exposed that they postgenetically have been subject to tectonic dumping (Figure 3 No. 45). Obviously the material is linked with the southern part of the subsidence region of the Tarim Basin, and falls now to the north (24°~30°) (see also v.Wissmann 1959, p.1335). The Old Moraines, that appear to belong to the Riss Glacial (Stadium I), show large lobe-formed ice margins, so that the evolution of the Pleistocene foreland glaciations was from wide reaching piedmont glaciers to narrow but very massive ice tongues, separated by medial moraines (Figure 3, compare the relief on both sides of No. 45 with that of No. 44 to 55). These northwest Tibetan foreland moraines were gradually accumulated throughout the Pleistocene ice ages. By means of their increasing abutment they canalised more and more strongly the outlet glaciers of each new glaciation.

4.4 The High Glacial gravel fields

Fields of glacial outwash gravels (No. 4, 5, 6), together with their deca-kilometre wide fans (Figure 3 near No. 43 to 45 and 55: No. 4, 5, 6) reach some 50 km north to the settlement of Yeh Cheng. Here, at 1470 m, they pass into glacio-limnic sediments, which can be easily ploughed. Their water-retentive qualities lead to the presence of springs and wells, and are the ecological basis of the town itself (north of Figure 3). Post-glacial fluvial erosion of the gravel fields has produced features resembling the glacial tongue basins down to 1750 m. Exposures of well-sorted fluvial material leave no doubt, however, that no glacial explanation can be entertained. This conclusion is not altered by the presence of thin interbedded diamictite bands or a scatter of cubic-metre sized blocks on the route to Yeh Cheng at 1500 m, for their origin might be attributed to mudflows initiated by glacier flow or outbreak of moraine dammed lakes.

4.5 The depression of the snowline (ELA) or the relative uplift of the mountain relief in the Last Ice Age (LGM; cf. Figure 5)

In the Karakorums, in the research area, the climatic snowline of the existing glaciers was determined by reference to snow-free areas, the presence of surface moraine and the beginning of ice-pyramid formation, as 5300 m asl. In the Aghil Mountains, and also on the Kuen Lun ridge, it ran at about 5200 m asl. The recent moraine deposits in the foreland at 2000 m indicate a descent of the lowest ice margin sites of at least 2600 m, and therefore a corresponding snowline depression of about 1300 m. (Snowline (ELA) depression = present ice tongue end height (m) —previous ice tongue end height (m)/2 = (4600-2000)/ 2 = 1300 m). Following the method of v.Höfer (1879), based on an average height of the enclosing ridge of the KuenLun alimentation area, which belonging to the lowest ice margin sites, at a maximum of 5800 m, the Würm snowline is calculated as 3900 m asl (cf. Figure 3) (Würm snowline = enclosing ridge height (m) — glacial tongue end height (m)/2 + glacial tongue end height (m) = (5800-2000)/ 2 + 2000 = 3900 m), and therefore at the same time a depression of the snowline by 1300 m. With the altitude of the central Shaksgam and Yarkand valleys lying between 3800 and 4100 m asl (Photos 5 and 6), the whole valley system was above the Ice Age snowline. At the same time the great northwest outflow ice-streams were initiated from 800 to over 1000 m higher, and even the moister western Tibetan plateau edge. With this combination of circumstances it is likely that the thickness of the ice-streams was much greater than the 1200~1400 m already demonstrated (cf. Figure 2 above K2).

This lowering of the equilibrium line altitude (ELA) and extent of glacial cover in the western areas of Tibet, about five times more arid than the central plateau, has been confirmed by the author in many other research areas (Figure 1 Nos. 1~4, 6, 8, 9, 11, 12, 14~18, 20), and makes probable an average depression of the snowline in the Last Ice Age (LGM) of c. 1000~1500 m, and the development

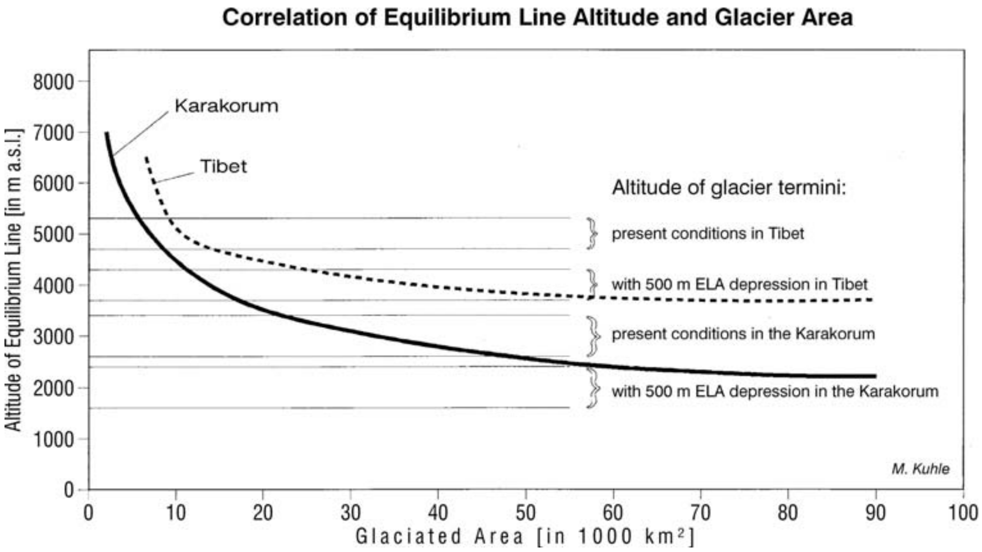

Figure 5 Increase in glacier areas in the particular area in the Karakorum and in the ice areas of the interior of High Tibet, which had been in contact with the pre-historic Karakorum ice-stream network in the east (see Figure 2). As an example a snowline (ELA) depression of 500 m relative to the relief surface (i.e. uplift of the relief by 500 m over the present-day snowline) was selected. This is a relative ELA depression that indeed had existed in early glacial periods of an initial ice age, and again in the Late Glacial period of the last ice age (= LGM = Würm = Stadium O). The graphs show that even during such a comparatively small ELA depression (the snowline depression of the Main Ice Age, however, amounted to c. 1300 m) an ice stream network of c. 100,000 km^2 was formed in the Karakorum, or an ice cover maintained in the interior Tibet. Although the two ice formations were connected (with the Shaksgam and Yarkand valleys draining the W-Tibetan mountain margin with its outlet glaciers) the different conditions of their reliefs become clear: the difference between the altitudes of the Karakorum valley floors and the Tibetan plateau was and is being compensated by the then and now lower ELA. That means, though the altitudinal difference between the two graphs is c. 1000 m, they are approximately parallel, and striving for the same increase in glacier area.

of a Tibetan ice sheet of 2.4 million km^2 (Figure 2) (Kuhle 1980, 1982a, b, 1983a, 1985a, 1986b, 1987, 1988 and others). Not included in this area is the ice-stream system of the Tienshan (Figure 1 Nos.7, 10, 13).

5 Climatic Measurements in Relation to the Energy Balance in the Karakorums

In order to evaluate the energy balance during the Pleistocene Ice Ages, in addition to the stations on the rock waste surface which comprises some 99% of the surface area of Tibet (as for instance in Photos 3~6), measuring instruments were installed on the snow surface of the glacial alimentation area up to a height of 5500 m (e.g. Photo 2). In order to retain a relationship with real conditions in the sense of the principle of actualism, a previous analogous radiation balance is assumed, in particular because the reconstructed level of the ice-stream network in the Karakorums reached the present level of the firn basins over wide areas, transparency leading to a similar energy reception, with a comparable atmospheric radiation

One of the two measuring stations in the K2 north glacial valley registered at 4130 m asl (Figure 3 No.1) on the surface of the rock waste from the 3rd September to the 12th October 1986 (38 days) an average global radiation maximum of 900~1000 W/m^2, which is close to the solar constant at the upper margin of the atmosphere for this period of the year at an average zenith distance of 36° (Figure 6). 60% of this energy was absorbed by the rock substrate, and returned to the atmosphere as heat by being transformed to long wave radiation (Figure 6). The deepest installed weather station registered corresponding radiation balances at 3980 m asl. Figure 7 shows such a measurement on the 18th October 1986 at 2 pm. The strong heating of the rock debris was confirmed by the soil temperatures in the measurement area. It had its greatest amplitude at 1 cm depth, and was damped with increasing thickness of the debris (Figure 8). The corresponding relationships can be understood from Figures 9 and 10, showing the conditions prevailing and examples of the rock waste surface ranging from the deepest valley floor to its highest occurrence. Here as a cross-check the reflected radiation is given: it varies between 15~22%. Figure 11 shows the representative balances for

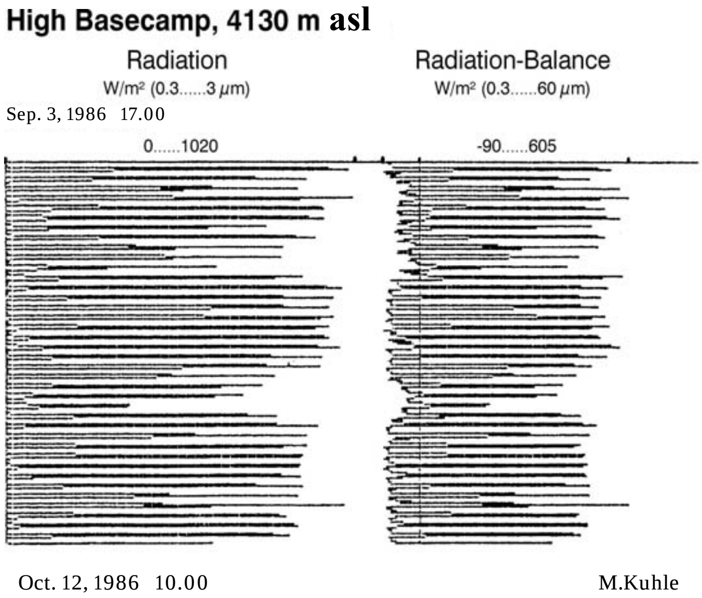

Figure 6 Exemplary detail of measurements of radiation and radiation balance, carried out at the second (from the base) of the four weather stations in the K2 north glacier valley in the forefield of the K2 glacier tongue end (locality: Figure 3 No.1) over very light granite moraine debris (cf. Figures 7 and 8)

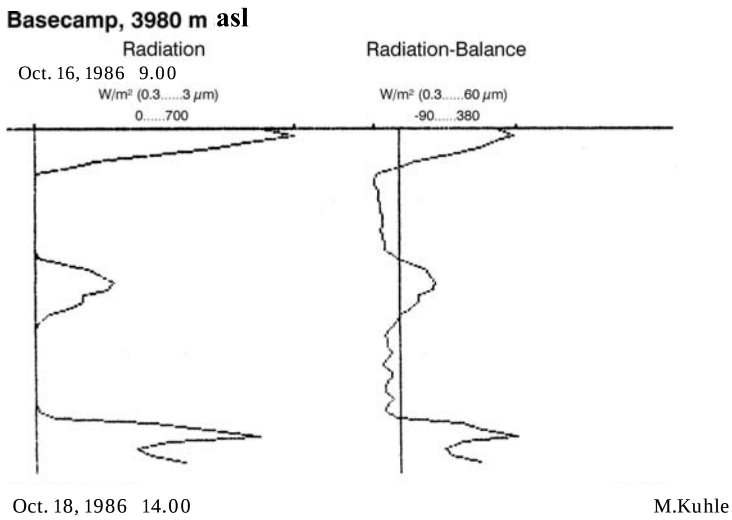

Figure 7 Exemplary detail of the measurements of radiation and radiation balance of the lowest of the four weather stations in the confluence area of the K2- and Muztagh-valleys (locality: Figure 3 No.10) over white quartz sand (cf. Figure 6).

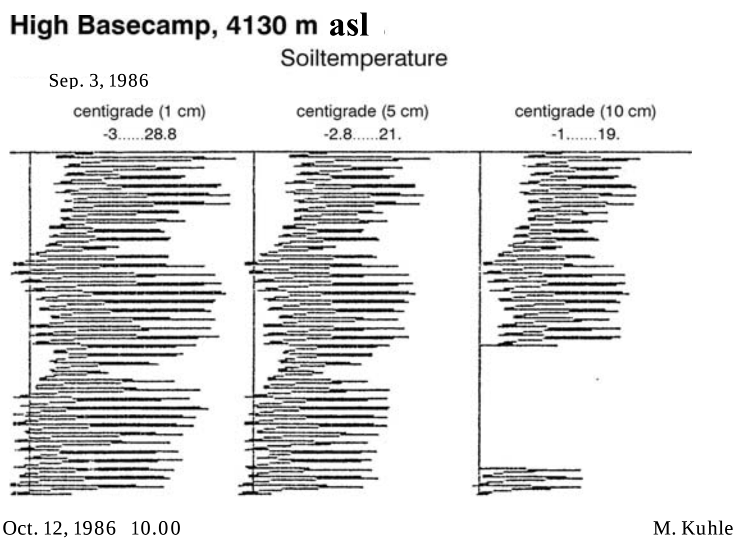

Figure 8 Soil temperatures, measured synchronously with the radiation and radiation balance at the second (from the base) weather station (locality: Figure 3 No.1) in very light granite moraine debris. The measurements confirm the related energy balance (cf. Figure 6)

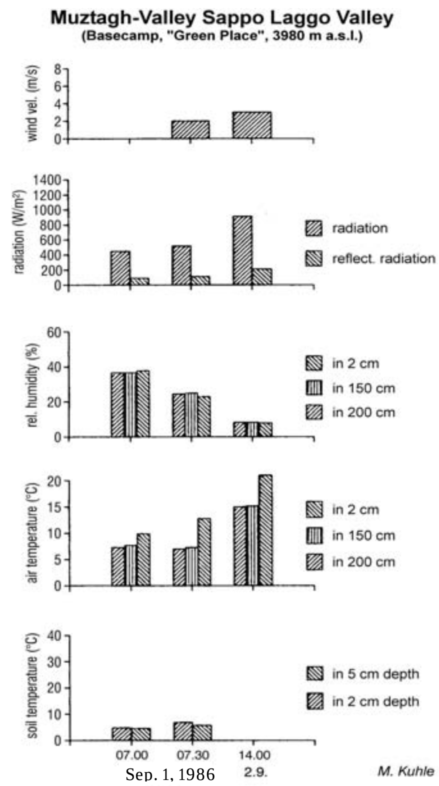

Figure 9 Exemplary measurements of climatic parameters in the lowest valley bottom region of the K2 north side (locality: Figure 3 No.10) on light debris with sparse grass (cf. Figures 10 and 11)

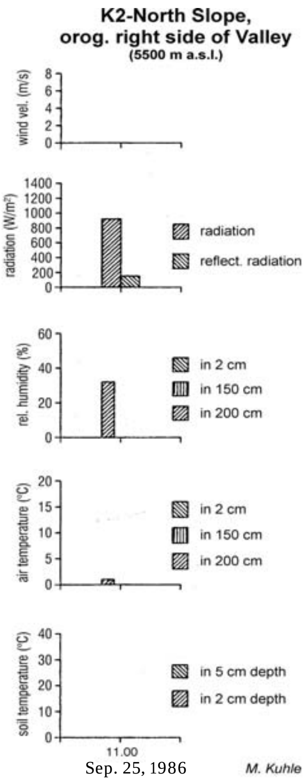

Figure 10 Exemplary measurements of climatic parameters on the highest snow-free debris surfaces below the K2 north face (locality: Figure 3 above K2) (cf. Figures 9 and 11)

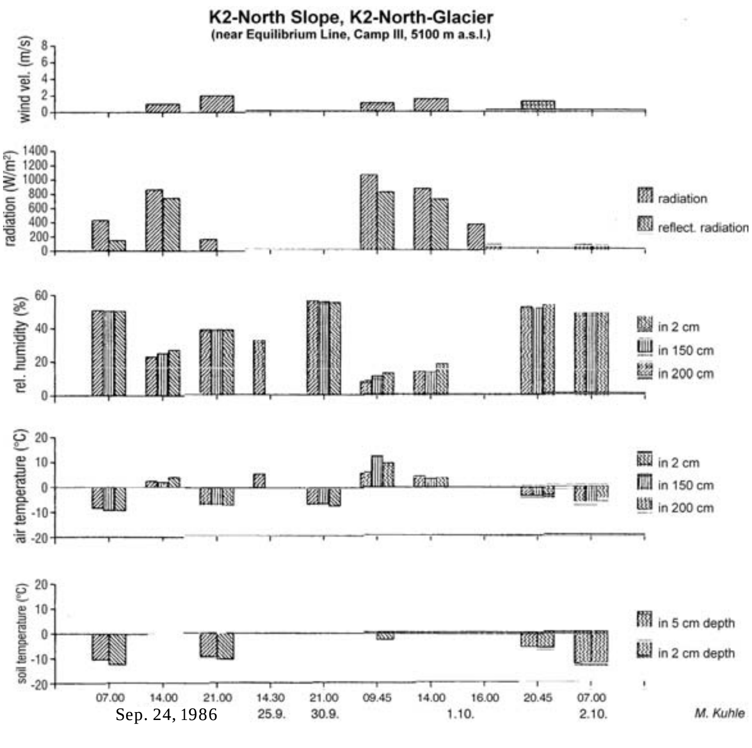

Figure 11 Exemplary measurements of climatic parameters in the centre of the K2 north glacier (locality: Figure 3 above K2) on snow-covered ice surface (cf. Figures 9 and 10)

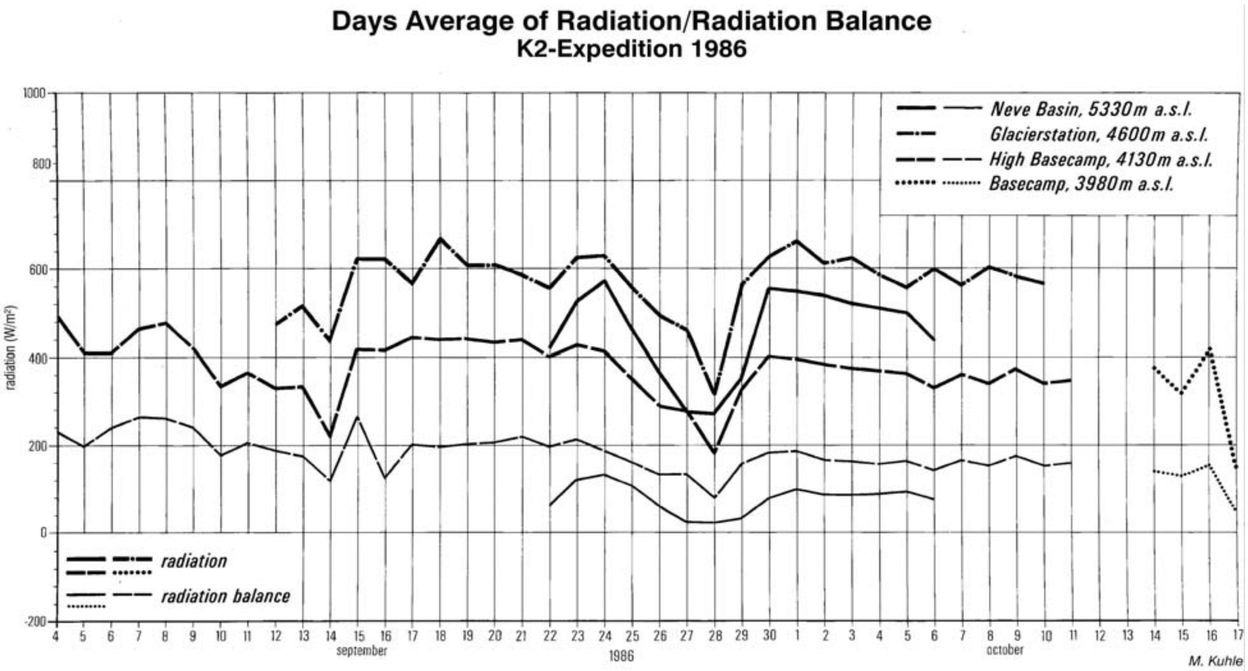

Figure 12 Comparison of synchronous measurements of the weather stations 4 (5330 m asl) to 2 (4130 m asl) with station 1 (3980 m asl) that has been measured later (14~17 October, 1986). Localities: station 1 (3980 m, cf. Figure 7) Figure 3 No.10; station 2 (4130 m; cf. Figure 6 and 8) Figure 3 No.1; station 3 (4600 m) Figure 3 No.3; station 4 (5330 m; cf. Photo 2) Figure 3 on the left above K2.

firn- and snow-covered glacier surfaces, which despite the steep subtropical angle of recipient radiation reflect about 80~90% of the energy back into space. That means a loss of heat for the atmosphere of up to 70%. Figure 12 is for comparing the averaged radiation and radiation balance measurements of the three stations at 4130 to 5330 m asl (Photo 2), which for the most part were done synchronously between 7 am and 7 pm.

6 Conclusions

The energy balances for the Karakorum systems and the mountains of west Tibet confirm the values obtained by the author in central and south Tibet as well as in the Himalayas (e.g. Kuhle 1985a, 1987, 1988). They mean that the 2.4 million km^2 heating surface of today, in the Ice Age in contrast functioned as a 2.4 million km^2 cooling surface (Figure 2), which although receiving about four times the incoming radiation as a comparable area at latitude 60° north or south, nevertheless reflected back into space about 70% of the incoming energy.

The Ice Age cyclical theory of the author, based upon this loss of radiant energy, thus made unavailable for the heating of the atmosphere, has been presented in detail elsewhere (e.g. Kuhle 1985a, 1987, 1988). Its basic idea can be described as follows: Tibet and its surrounding mountains have been uplifted over the ELA during the early Pleistocene. The result was an extended inland ice sheet of c. 2.4 million km^2. Due to the reflected high subtropical insolation energy back into space — which was affected by the ice — the global atmosphere experienced such a great loss of heat that the large north-hemispheric inland ices of America and North-Eurasia were built up and the Quaternary Ice Age began. The new data and observations of this paper add further support to this proposal.

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