Quaternary Glaciations – Extent and Chronology, Part III
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The High Glacial (Last Ice Age and LGM) ice cover in High and Central Asia

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1. Introduction: The state of research up to 1973 in relation to the author's observations

A synopsis of older results and views on the Pleistocene glacial cover of High and Central Asia has been provided by von Wissmann's compilation (von Wissmann, 1959; see also Bobek, 1937). Glacial cover of Tibet is discussed in recent Chinese literature by Shi & Wang (1979), and has also been reproduced by CLIMAP (Cline, 1981) in a map of the 'Last Glacial Maximum'. These authors speak of a 10% to maximum 20% ice cover of the mountains and plateaux of Tibet. Even in the 'Quaternary Glacial Distribution Map of Qinghai-Xizang (Tibet) Plateau' published in 1991 by the Chinese author group Shi Yafeng, Li Binyuan, Li Jijun, Cui Zhijiu, Zheng Benxing, Zhang Qingsong, Wang Fubao, Zhou Shangzhe, Shi Zuhui, Jiao Keqin and Kang Jiancheng (*cf.* Shi *et al.*, 1992) this opinion is to a large extent repeated, with one major exception. Zhou Shangzhe, a member of this group, agreed with the author's reconstruction of an ice sheet on part of the

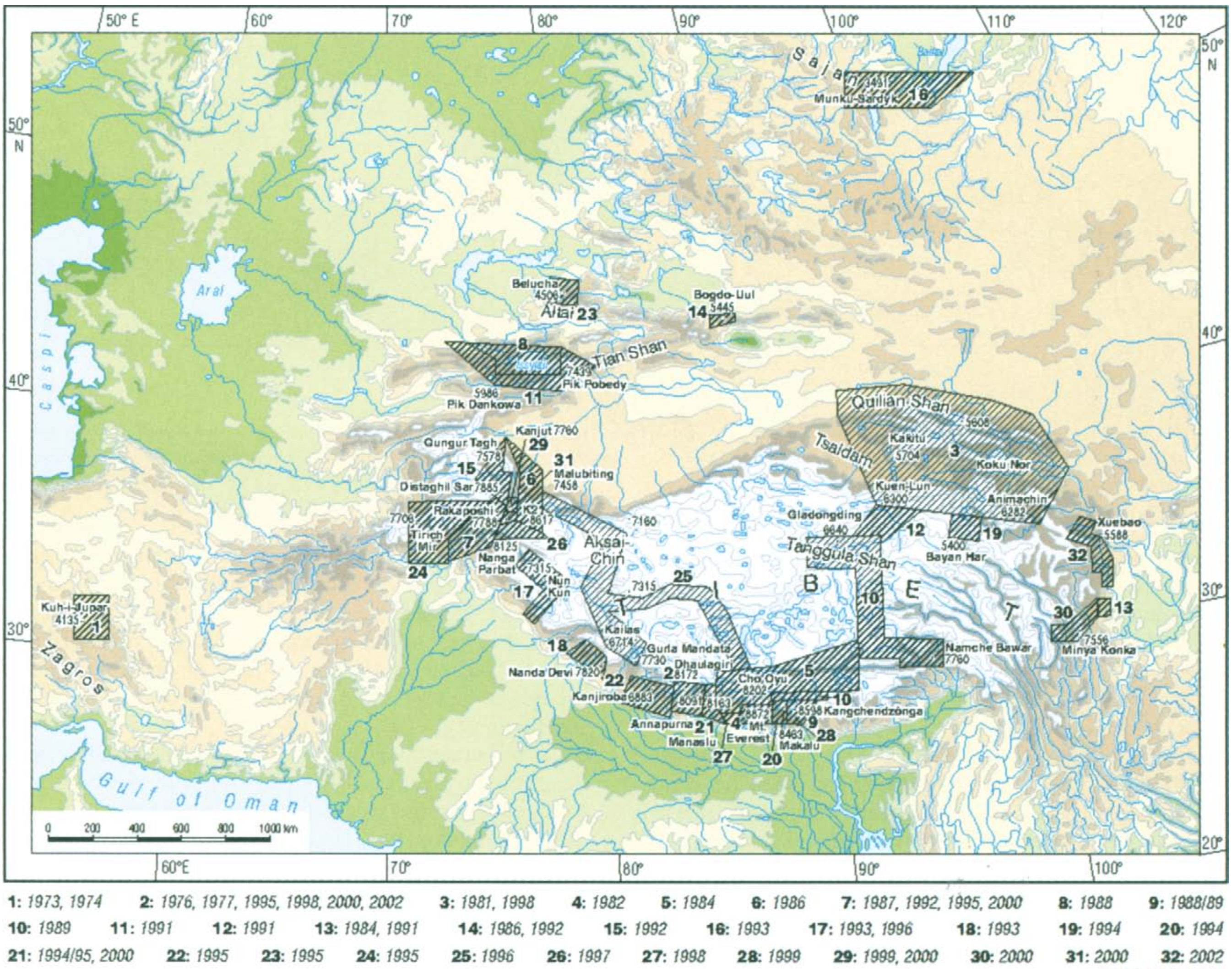


Fig. 1. Investigation areas in High- and Central Asia.

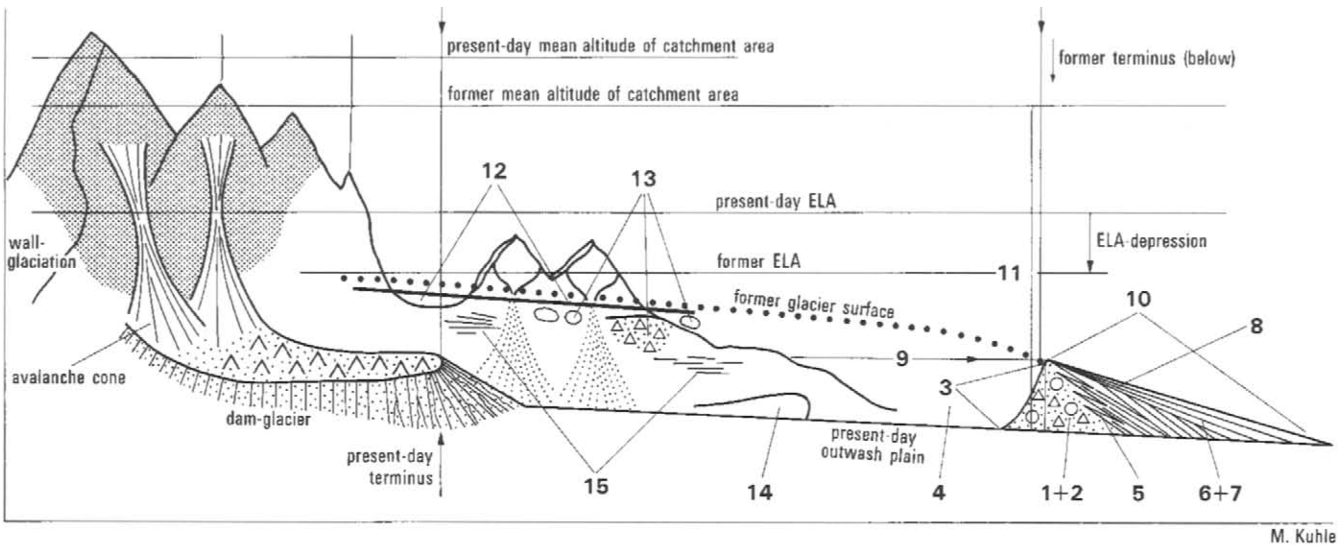


Fig. 2. Distribution of important key landforms for the reconstruction of the extent of Pleistocene glaciation in High and Central Asia.

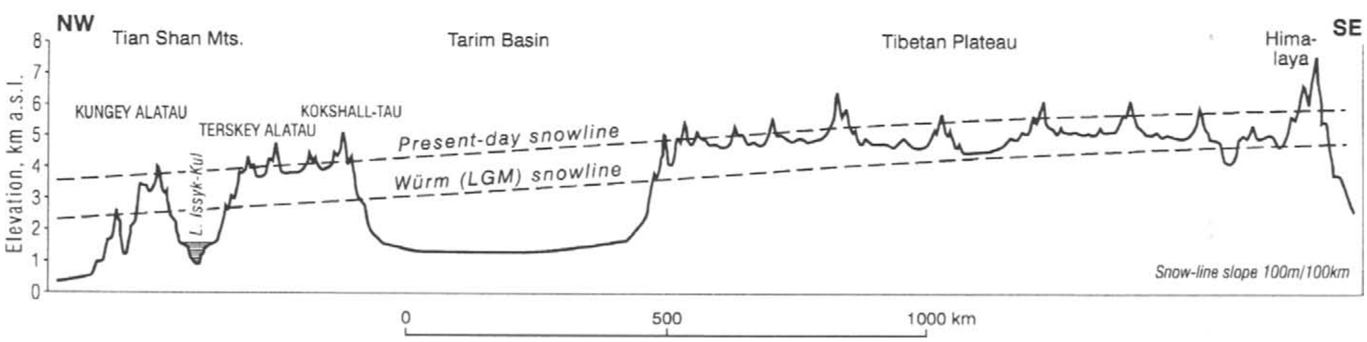


Fig. 3. Generalised north-west-south-east profile across the northern Tian Shan, Tarim basin, Tibetan plateau and Himalaya based on the author empirical data of the. The profile shows the relationship between the present-day and LGM (High Glacial, Würmian) snowline (ELA) as compared to the topography of the land surface.

Tibetan plateau in the Animachin region (*cf.* Fig. 1, No 3) (Kuhle, 1982c, d, 1987c and 1988g; see also Zhou *et al.*, this volume). In this map he showed a plateau glacier, some 400 x 300 km in size.

In contrast to common opinion, starting at the turn of the 19th to 20th century, there have been single researchers, such as von Loczy (1893), Oestreich (1906), Handel-Mazzetti (1927), Dainelli & Martinelli (1928), Norin (1932), de Terra (1934) and others (*cf.* Kuhle, 1988b: 416-417, 1988j), who reported ancient ice-marginal positions scattered throughout the high regions of Asia. According to the author's calculations, this work represents ELA (equilibrium line altitude) depressions of more than 1000 m and indicate, locally, a glacial cover significantly more excessive than von Wissmann (1959) had envisioned. However, these authors neither drew nor gave voice to such conclusions. Other early researchers, such as Huntington (1906), Tafel (1914), Odell (1925), Prinz (1927), Trinkler (1932) and Zabirov (1955) (*cf.* Kuhle 1988b: 416-417), making direct use of the data they obtained by field investigations, had reconstructed larger areas of former glaciation which, depending on the altitude of the mountains or plateaux, had required a few hundred metres of ELA depression.

The author has carried out about 30 expeditions and research visits since 1973 (Fig. 1) with the purpose of reconstructing the extent of Pleistocene glaciers in Asia. The distribution and large number of investigated areas permit reconstruction of the formerly glaciated areas to be made for all of Tibet and major parts of Central Asia. Reconstructions are in accordance with data reported by some earlier authors (see above), but they are in strong contrast to the negligible ice cover envisioned by CLIMAP as late as 1981 (Cline, 1981) and the "Quaternary Glacial Distribution Map of Qinghai-Xizang (Tibet)

Fig. 4. Granite erratic on vertically-layered evaporites, Hunza valley, north-western Karakoram (Fig. 1 Nos 7 and 15; 36°28'30"N 74°00'50"E) at 3370 m a.s.l., 900 m above the valley floor. This erratic proves a minimum ice thickness of 900 - 1000 m in this profile. The till (♦) on the opposite valley flank and the traces of abrasion document a minimum ice thickness (----) of 1600 – 1700 m. Photograph: M.Kuhle.

Fig. 5. Light granite erratic on dark metamorphic sedimentary rocks on the 3750-m high Sani pass between the Tirich Mir and the 2050 m lower Mastuj valley in Chitral, Hindu Kush (Fig. 1 No 24). Together with the till (♦) this is evidence of an ice-stream network filling the valley system with a glacier some 1000 to 1600 m thick (----). Photograph: M. Kuhle.

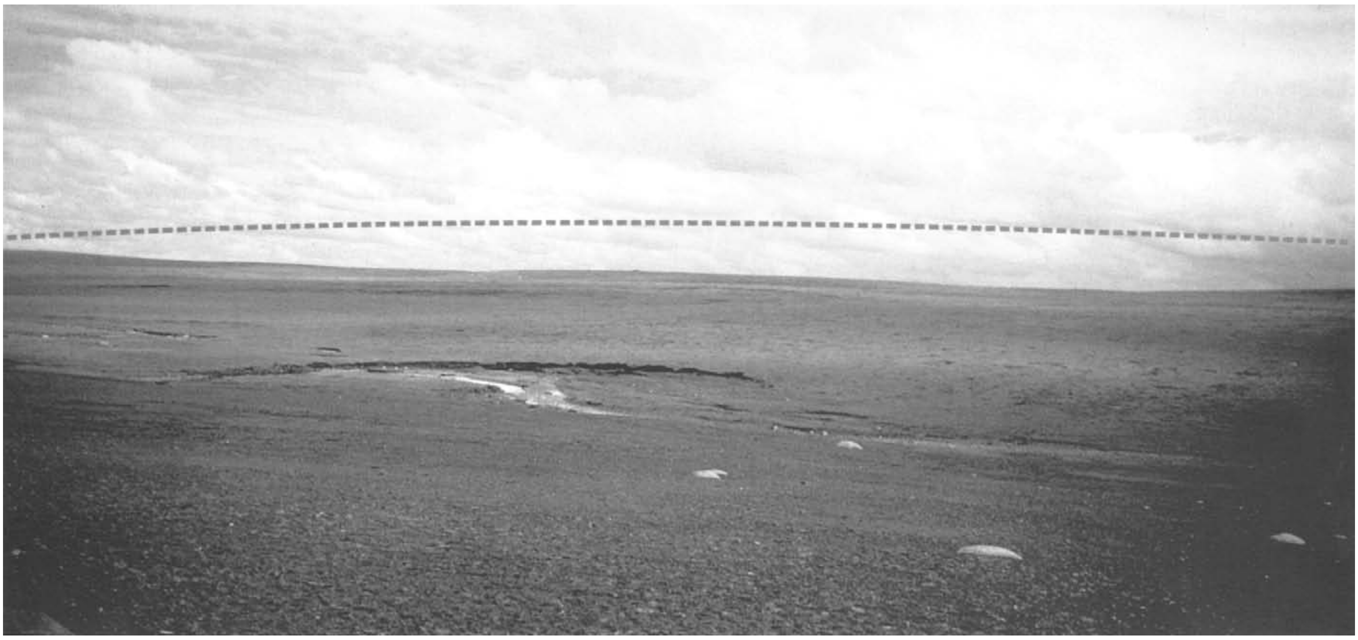


Fig. 6. Light erratic granite boulders on reddish sandstone bedrock in North Tibet (4400 m a.s.l.; 34°16'N 97°53'E; Fig. 1 No 3) transported over tens of kilometres, demonstrating complete coverage by an ice sheet (----). Photograph: M. Kuhle.

Fig. 7. Several metres thick till, with metre-sized far-travelled granite boulders, in the form of a 1-1.5 m-thick active layer over the permafrost table at 4580 m a.s.l. in Tibet, west of the Animachin (34°11'10"N 97°46'10"E; Fig. 1 No 19). Being 200 km away from any glaciated mountain range, this site is evidence of a complete inland ice coverage (----). Photograph: M. Kuhle.

Plateau" (Shi Yafeng *et al.*, 1991). For example the extent of glaciation of Tibet during the Last Glaciation is given as approximately 2.4 million km^2, with an estimated ice thickness of about 2 km in the central areas. From this ice sheet, steep outlet glaciers discharged through the surrounding mountains (e.g. Kuhle, 1989b, 1998a).

2. Dating method

The field investigations to reconstruct the extent of Pleistocene glaciation in the mountains and highlands of Central and South Asia have concentrated on identifying former glaciations and their spatial arrangements.

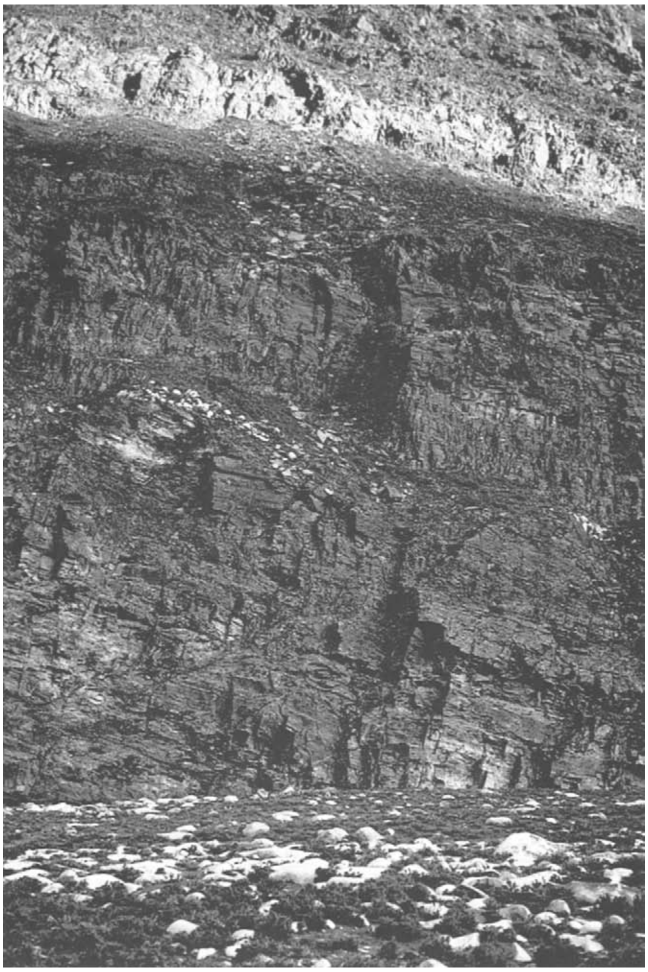


Fig. 8. Till with up to a few metres large erratics of two-mica granite on the Lulu valley floor in South Tibet (Latzu massif south slope: 28°48'N 87°14'E, 4950 m a.s.l.; Fig. 1 No 5). Boulders of this type have also been observed (↓)higher up on the valley flank on basalt. They have been transported over tens of kilometres, confirming that the Pleistocene Lulu Glacier in fact filled the entire valley. Photograph: M. Kuhle.

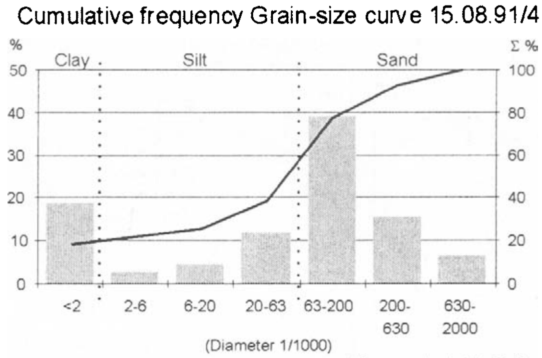


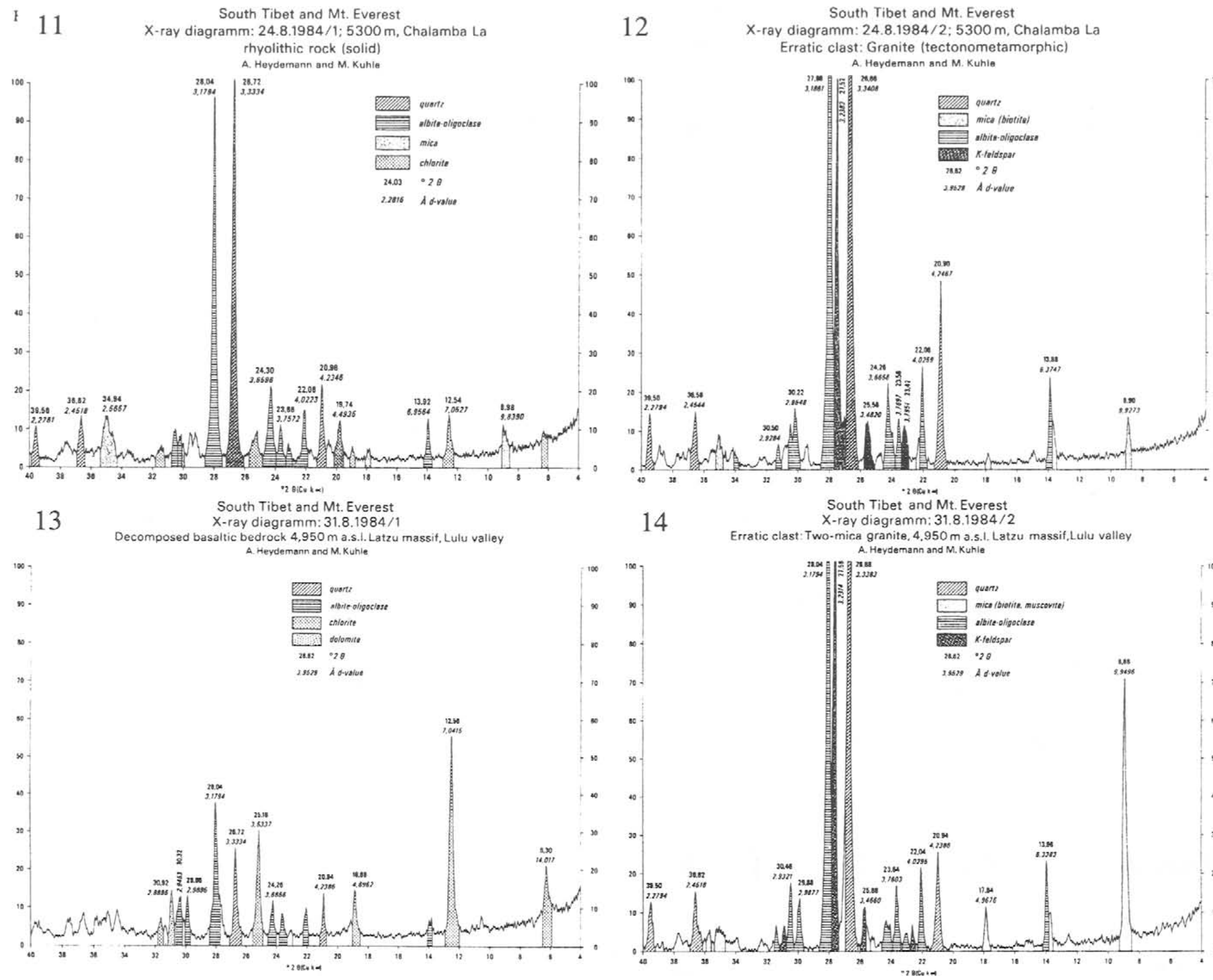
Fig. 9. Typical till matrix deposited by glacial ice. Locality: northern central Tibet (Fig. 1 No 12; 35°15'N 93°05'E; 4560 m a.s.l.). Characteristic of the important communition by the ice are the substantial proportion of clay (19%) and the bimodal grain-size distribution with peaks both in the clay and the sand fractions. This matrix shows a very high portion of glacially-crushed quartz grains (Fig. 15 diagram 15.08.91/3/4). Sampling: M.Kuhle.

Fig. 10. Classic East Tibetan glacial landscape. The glacigenically-rounded and abraded fjells (>) and interposed trough valleys are evidence of a continuous inland ice sheet (air photograph at 8000 m a.s.l.; Fig. 1 east of No 10 and ENE of the Namche Bawar: 30°40'N 100°E). The troughs contain Late-glacial lateral and end moraines (♦) (c. 14 - 17 Ka). The LGM overdeepenings and tongue basins (⊂) are filled by post-glacial lakes. Photograph: M. Kuhle.

This glacial gemorphological approach, on which the digital map is based, has been discussed in detail in previous publications (Kuhle, 1990d; 1991a).

Figure 2 shows 15 features characteristic of a glacial landscape. Even if only some of these key landforms can be identified in a given area, they are still indicative of former glaciation and a misinterpretation can be ruled out with high probability (Kuhle, 1990d).

The schematic presentation (Fig. 2) shows a selection of the most important key landforms. For the reconstruction of the extent of Pleistocene glaciation, the spatial arrangement of the landforms is of key importance. For instance, *roches moutonnées* (Figs 18, 20, 22, 24 and 28) are found within the tongue basins of former glaciers (Fig. 2 No 14) (e.g. Figs 10, 32 and 35) and thus upstream of the end moraines (Nos 1-3) (e.g. Figs 10, 35, 36 and 40). At the same time they may be partly submerged in the outwash plains



Figs 11-14. The X-ray analyses of Figs 11 and 12 present the composition of the bedrock and the far-travelled erratic boulders on the Chalamba La (also Tschü Tschü La: Fig. 1 No 5; 29°42'N 90°14'E). The rhyolithic bedrock which occurs over large parts in the surrounding area shows chlorite. In contrast, the erratic granite boulders contain potassium feldspar. The erratics are over 1 m-long. They are proof of a minimum thickness of the ice sheet, i.e. ice-stream network of 1200-1400 m. Figs 13 and 14 describe the bedrock in the Lulu valley (Fig. 1 No 5; 28°48'N 87°14'E) as decomposed basaltic rock and the erratic boulders as two-mica granite. The boulders are up to several metres in length and lie in a till matrix on the valley bottom. They have also been observed on ledges 170 m up the valley flanks (see Fig. 8).

of younger glacier events. Lateral moraines (No 13) (e.g. Figs 10, 35 and 39), on the valley flanks always show a down-valley inclination towards the correlative end moraines (Nos 1-3) which they join at their lowest point, i.e. at the former glacier margin. Their inclination is steeper than that of the valley floor. Glacial striations (No 15) (e.g. Fig. 23) also follow the valley with a gradient somewhat steeper than the valley floor. Their sheaf-like arrangement, slightly converging and diverging, and their characteristic length ranging from centimetres to decimetres, makes them also unmistakable indicators of former glaciation (No 15). End moraines are characterised by steep proximal and more gently dipping distal slopes (Nos 3, 10) (*cf.* Fig. 35). The sediments on the distal slopes tend to be better sorted by meltwater activity (Nos 6, 7) than on the proximal side, whilst the moraine cores show a chaotic composition (Nos 1, 2). Glacial deposits differ from other types of sediments mainly by two characteristics: the size range of the rock fragments found incorporated in the moraines and their spatial arrangement (Figs 28, 29, 30, 32 and 36). Room-sized boulders (Figs 8 and 18) can be moved and redeposited by the glaciers. However, the morainic deposits are generally matrix-supported, i.e. major clasts are isolated from each other by fine sandy to clayey material (Fig. 2 Nos 1, 2). Figure 9 presents the grain-size composition of a typical morainic matrix found between large boulders in basal till. This unsorted sediment mixture (Figs 34, 36 and 39) is completely different from layers sorted by fluvial transport (Nos 6-8). Marginal sandurs or ramp-like ice-marginal outwash fans (IMRs), descending

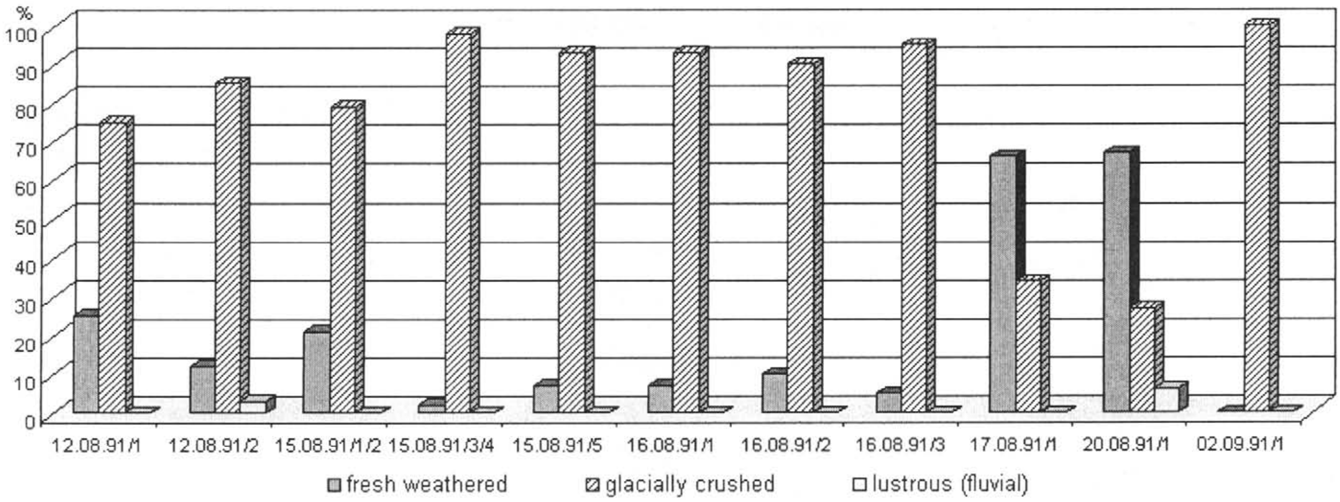


Fig. 15. 11 morphometric quartz grain analyses of till matrix samples from a cross section through central Tibet (Fig. 1 No 10,12). With the exception of the two samples 17. and 20.08.91/1 - which seem to contain a portion of 'freshly-weathered' grains probably taken up from the local bedrock - the group of 'glacially-crushed' grains (72-96%) is dominant. Sampling: M.Kuhle.

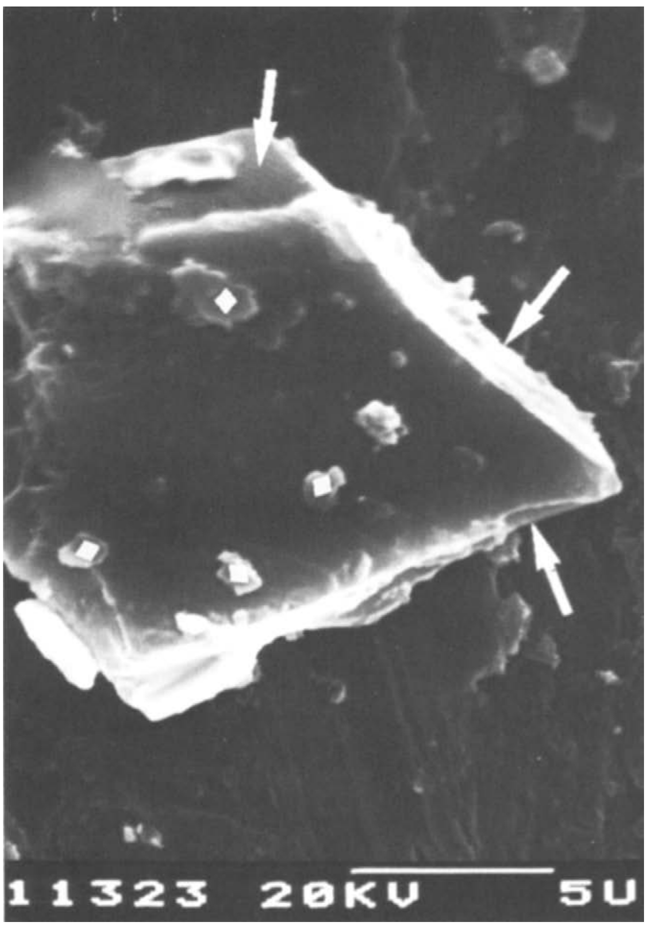


Fig. 16. Scanning electron micrograph of a glacially crushed quartz grain (see Fig. 15) taken from the varved sediments of Lulu in southern Tibet (Fig. 1 No 5, 28°38' N 87°04' E, 4320 m a.s.l.). (→) freshly broken edges caused by the communition by overriding ice. (♦) clay minerals. SEM: University of Hohenheim, B. Frenzel.

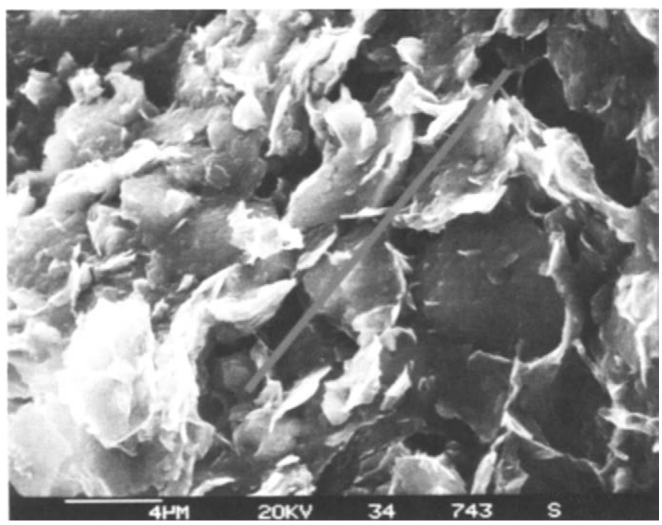


Fig. 17. Scanning electron micrograph of a till sample from central Tibet (Fig. 1 No 10, c. 32°10'N 91°50'E, c.4550 m a.s.l.), showing pressed and tightly-packed clay minerals and silt grains, orientated from lower left to upper right. Packing and orientation are considered to be indicators of overriding ice. The layers dip against the direction of former ice flow from left to right. SEM: Universität Kiel, F. Sirocko.

steeply from the end moraines are the result of such meltwater activities (Nos 5-10). Low-gradient outwash gravel fans, so-called valley trains, extend over many kilometres far into the glacier forefield. These landforms, that have accumulated directly in front of the meltwater portals, can be traced from the northern edge of the Tibetan Plateau and from the Tian Shan far into the inner-Asian deserts, the Takla Makan and the Gobi (Fig. 1 Nos 11, 15, 6, 14, 3).

Far-travelled, boulder-sized erratics (Figs 5, 6, 7, 8, 27, 32 and 33) are more likely to have been transported by ice than by water. The higher they are found up on the valley flanks, the more probable is their glacigenic transport

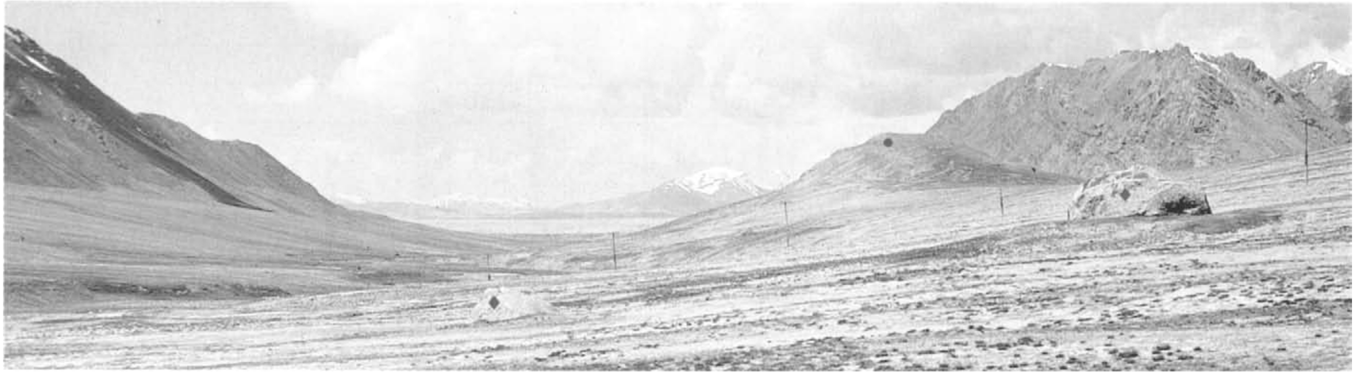


Fig. 18.Till overlies wide expanses of the Tian Shan plateau, giving evidence of a complete Pleistocene ice cover. Here, a high valley of the plateau between Terskey Alatau and Kookshal Tau (with Pik Dankowa; Fig. 1 No 11; Fig. 3; 42°01'N 78°08'E) is shown with a till sheet, a roche moutonnée (•) and two far-travelled boulders the size of a small house (♦) on the valley floor at 3300 m a.s.l. Photograph: M. Kuhle.

(Fig. 2 No 13) (e.g. Figs 4, 5, 8). Figures 12 and 14 show far-travelled erratic boulders contrasting the local bedrock. On the Chalamba La pass in southern central Tibet, an erratic clast of tectonometamorphic granite (Fig. 12) rests on rhyolithic bedrock (Fig. 11). Its position on a col at 5300 m a.s.l., some 1200 m above the level of the Tibetan Plateau, implies a corresponding minimum thickness of the former ice sheet. In the Latzu massif of South Tibet erratic boulders of two-mica granite (Fig. 14) were found to lie on decomposed basaltic bedrock (Fig. 13) on the valley floor as well as in positions high on the valley flanks (Fig. 8). Their arrangement provides evidence of both glacigenic long-distance transport and a certain minimum thickness of the ice.

Within the former tongue basins (Fig. 35), basal till is regularly found underlying the most recent outwash plain (Fig. 2). It is definitely situated within the formerly glaciated areas. The widespread till covers (Figs 7, 8, 16, 17, 18, 20, 25, 27, 28, 29, 30, 31, 33 and 34) and till remnants, as well as their altitude and spatial distribution, suggest that a former ice sheet had completely covered the whole of Tibet and the Tian Shan Plateau. These tills partly contain far-travelled erratic boulders. Their matrix differs from fluvial sediments by their high clay content and the bimodal grain-size distribution, with a primary peak in the silt or sand fraction (Fig. 9). Quite often the quartz grains in the matrix are sharp-edged (Fig. 16). These morphoscopic grain characteristics are interpreted as a result of glacial crushing.

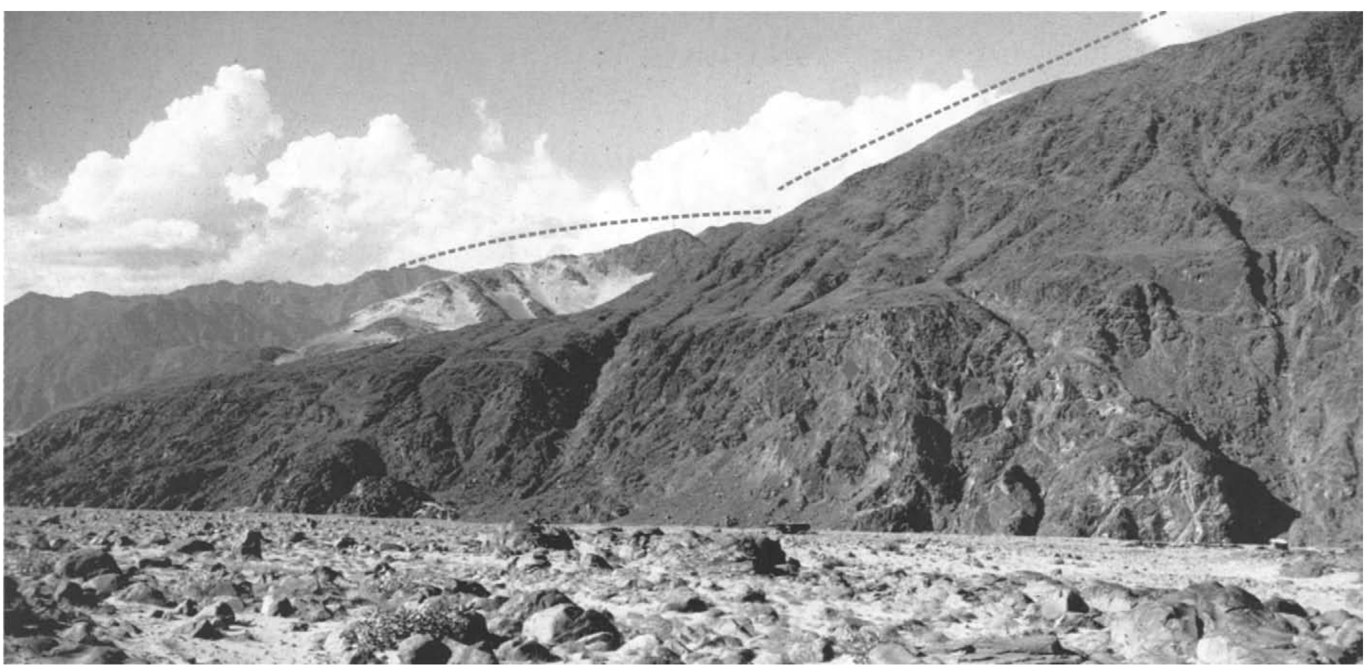


Fig. 19. The upper flanks of the lower Indus valley have been polished to a concave form (•), i.e. to a trough shape, by the Pleistocene Indus Glacier. At the settlement of Chilas (Fig. 1 No 7; 35°25'N 73°50'E), at only 1150 m a.s.l., this large parent glacier had still a thickness of at least c. 600-800 m (----). Subglacial meltwater erosion has undercut the trough flank and created an escarpment (♦) at the foot of the glacier-polished upper slope (•). Photograph: M. Kuhle.

Fig. 20. *Roche moutonnée landscape in central-western Tibet at 5200 m a.s.l. (Fig. 1 No 25 Aksai Chin, 34°38'N 80°19'E). The roches moutonnées (•) consist of dark metamorphous schist (phyllites). They are largely covered by a yellowish far-travelled till (■), mixed with local morainic material. During the LGM the landscape was covered by a cold-based ice sheet. Today it is semi-arid and free of vegetation, with a permafrost climate (-8°C mean annual temperature). In the Late-glacial an ice-dammed lake existed here, the shoreline of which with its steep rock ledges, i.e. cliffs (↓) has been worked into the roches moutonnées flanks. Photograph: M. Kuhle.*

Fig. 21. South-East Zaskar Himalaya (Fig. 1 No 17). Polished valley flanks in the monsoonal humid West Himalaya of the Chandra valley (longitudinal valley) seen from the settlement of Khoksar (3060 m a.s.l.; 17.5 km north of Manali). Massive banks of crystalline rock (granite-gneiss) have been polished across the edges by a more than 1000 m thick glacier (----) (Fig. 1 No 17; 32°23'N 77°14'E). Photograph: M. Kuhle.

Fig. 22. LGM to Late-glacial roches moutonnées with preserved polish in vertical pelitic metamorphites (phyllites). The site lies towards the north of, i.e., in the extreme precipitation shadow of the Karakoram and Aghil Mountains (100 - 60 mm/a) on the floor of the Surukwat valley, 1200 m below the lowest glacier tongues of today (Fig. 1 No 6; 36°23'N 76°41'E; 3580 m a.s.l.). Photograph: M. Kuhle.

Fig. 23. Glacial striae on the flank of the Mayangdi valley at 2095 m a.s.l., c. 200 m above the thalweg (Dhaulagiri Himalaya; Fig. 1 No 2; 28°35'N 83°22'E). The striae testify to an outlet glacier reaching from the southern margin of the Tibetan ice sheet in this transverse valley through the Himalaya main ridge and down the southern side to c. 1000 m a.s.l. Photograph: M. Kuhle.

Fig. 24. Pothole at c. 1000 m a.s.l. on the highest point of a roche moutonnée of gneiss in the middle of the Arun valley floor, 40 m above the thalweg (Fig. 1 No 20 on the very right; 27°40'N 87°22'E). This is interpreted as a classic subglacial meltwater form, created by hydrostatically-confined water under the glacier crevasses. These crevasses form where the ice flows over a roche moutonnée. The Arun ice stream was also an outlet glacier of the South Tibetan ice sheet (cf. Fig. 23). Photograph: M. Kuhle.

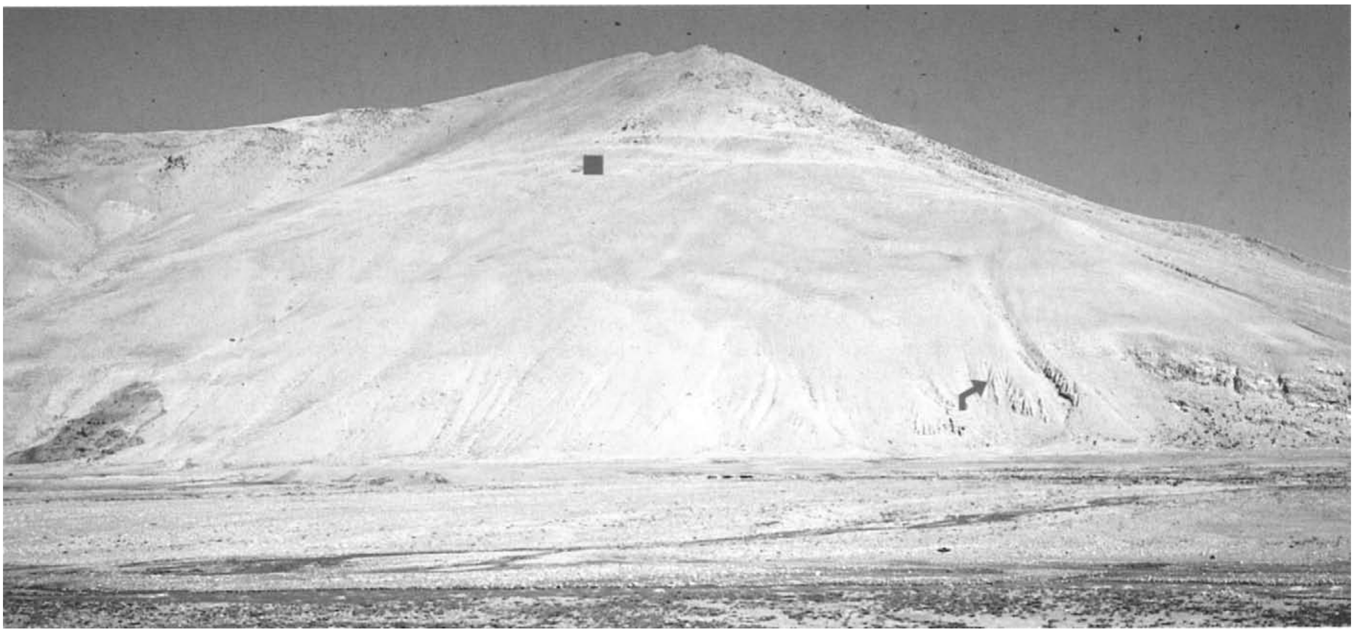


Fig. 25. On the flank of the upper Bo Chu valley in southern Tibet, north of the Himalaya (Fig. 1 No 5; 28°27'N 86°11'E, 4310 m a.s.l.), tens of metres thick till (■) has been preserved right up to the summit. At the foot of the slope it is exposed in the form of earth pillars (arrow). This gives evidence of a representative example of an outlet glacier discharging from the Tibetan south margin through the Himalaya main ridge. Photograph: M. Kuhle.

Fig. 26. Taken from 6050 m a.s.l., the photograph shows 6000 m-high mountains in central Tibet smoothened by the inland ice (----) (Gladongding Massif in the Tanggula Shan; Fig. 1 No 10; 33°30'N 91°E). The present-day thin glacier cover again sharpens the mountains by selective discharge (⇓). The rounded surfaces confirms a Pleistocene glacier level at an altitude above 6000 m and thus a local inland ice thickness of at least 1000 - 1200 m. Photograph: M. Kuhle.

Additionally, the insignificant proportion of lustrous (fluvial) grains speaks against a fluvial origin. Figure 15 shows the morphometry of 11 glacigenic sediment samples from Tibet taken along a transect from north to south across the high plateau between 4000 and 5300 m a.s.l. The density of the till samples is significantly higher than that of corresponding fluvial sediments. Additionally, fine structures indicative of pressure and movement are found in the alignments of clay minerals and silt grains (Fig. 17). Shear planes, flexures and folds that are characteristic of sediments overridden by a glacier have been observed in till samples from many places. In places, their dip directions can help to identify the flow direction of the ice. Some of these minute indicators can only be analysed by using a scanning electron microscope.

Taken together, these features are unambiguous indicators of the extent of a former ice cover. By comparing the lowest positions of the former ice margins in valleys that are still glaciated today, the approximate corresponding

Fig. 27. Metre-sized erratic granite boulder on a very flat pass at 4200 m a.s.l. It is supposed to have travelled over at least 60 km from the Bayan Har Mountains, its source area in the south-west. The Bayan Har Mountains are completely unglaciated today (34°39'30"N 98°02'40"E; Fig. 1 No 3). The boulder lies in a very clayey till matrix on metamorphic sedimentary bedrock. Its position documents a glaciation extending over the entire high plateau (----). Photograph: M. Kuhle.

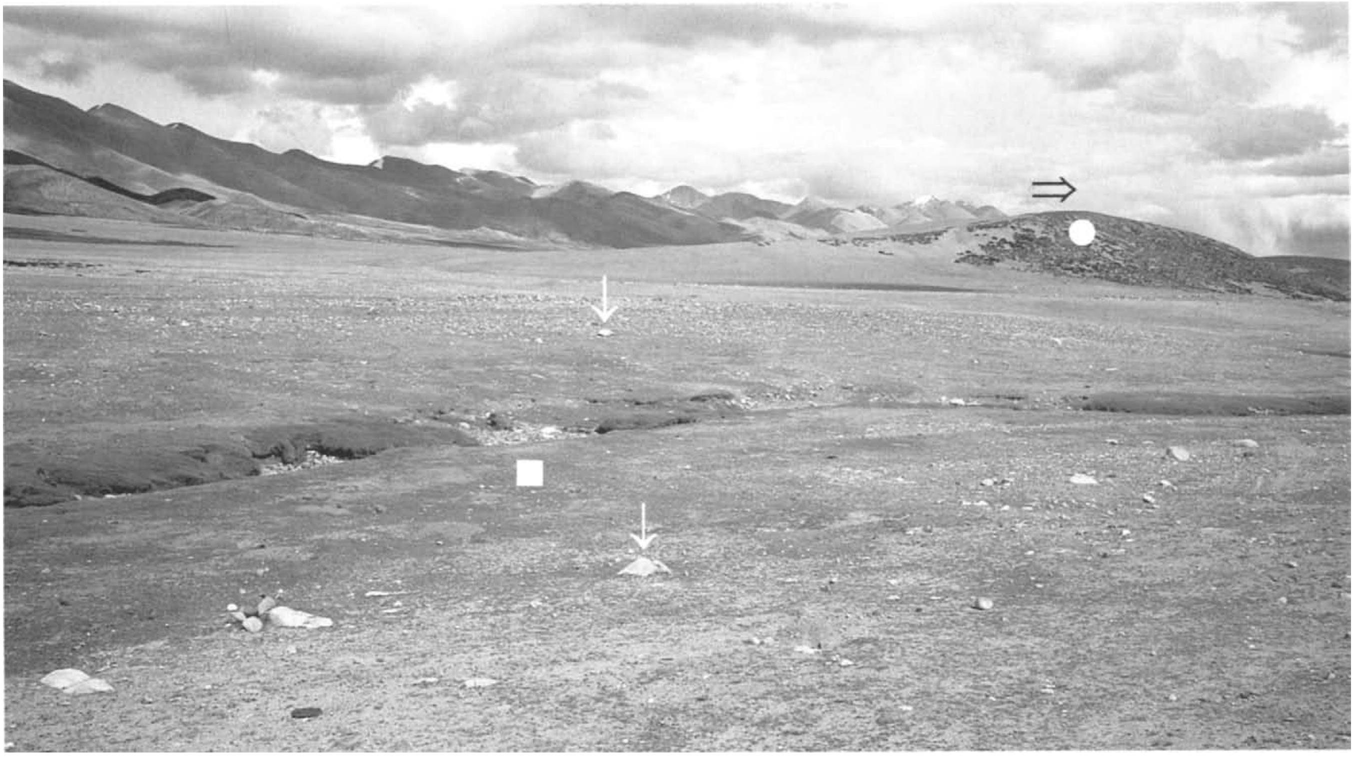


Fig. 28. Till sheet (■) with polymict boulders - including granites (↓) - on sedimentary bedrock in the western part of South Tibet (Fig. 1 No 25, north-west of the Kailas massif, 31°19'30"N 80°38'E, 4700 m a.s.l.). On the right a classic roche moutonnée is to be seen (•), the more gentle, proximal slope of which is mantled by several metres thick till. The flow direction in this area of the ice sheet was from left (north-west) to right (south-east)(⇒). Photograph: M. Kuhle.

Fig. 29. Till exposure (■) in north-eastern Tibet (Fig. 1 No 3 northwest of the Animachin massif, 35°07'30"N 98°53'30"E, 4160 m a.s.l.), overlying calcite-bearing bedrock limestone. The high proportion of fine material in the till is clearly visible. Limestone, phyllite and far-travelled erratic granite boulders (↓) are seen, floating isolated in the matrix. Shear planes (≡) dip against the direction of ice flow. Layer after layer, the internal composition of the till has been torn and sheared off by the overflowing ice. Photograph: M. Kuhle.

Pleistocene snowline depression can be estimated. Taking into account that glaciers from catchment areas rising higher above the snowline tend to reach further down-valley than those from less high mountains, the Pleistocene ELA should have been half of the altitudinal difference between the present-day and former altitude of the glacier termini. This relationship between the average height of the catchment areas and the size of the glacier tongues suggests that the lowest Pleistocene ice-marginal positions can be expected where the highest high plateau and mountain catchment areas are found (Fig. 1, No. 11). They lie approximately the same vertical distance below the ELA as the highest average glacier feeding areas have been situated above it.

At an equal altitude the former ice-marginal positions have been determined empirically by the lower altitude of the former end-moraine positions. Furthermore, the former snowline altitude can be found empirically by using the height of the lateral moraine tops (Fig. 2, No. 13). This can only have been formed when the glacier tongue started melting.

For further methodological and mathematical details of the ELA-determination method applied for the construction of the digital glacier map, see Kuhle (1986d; 1988h).

Overall it should be stressed that the Pleistocene snowline altitudes and depressions shown here are not based on theoretical considerations but on field evidence.

3. References to the empirical database of the glacier map

The field observations of 1973 - 2002, which form the basis of the present glacier map, have been carried out in the areas indicated in Fig. 1. Because they include all key areas

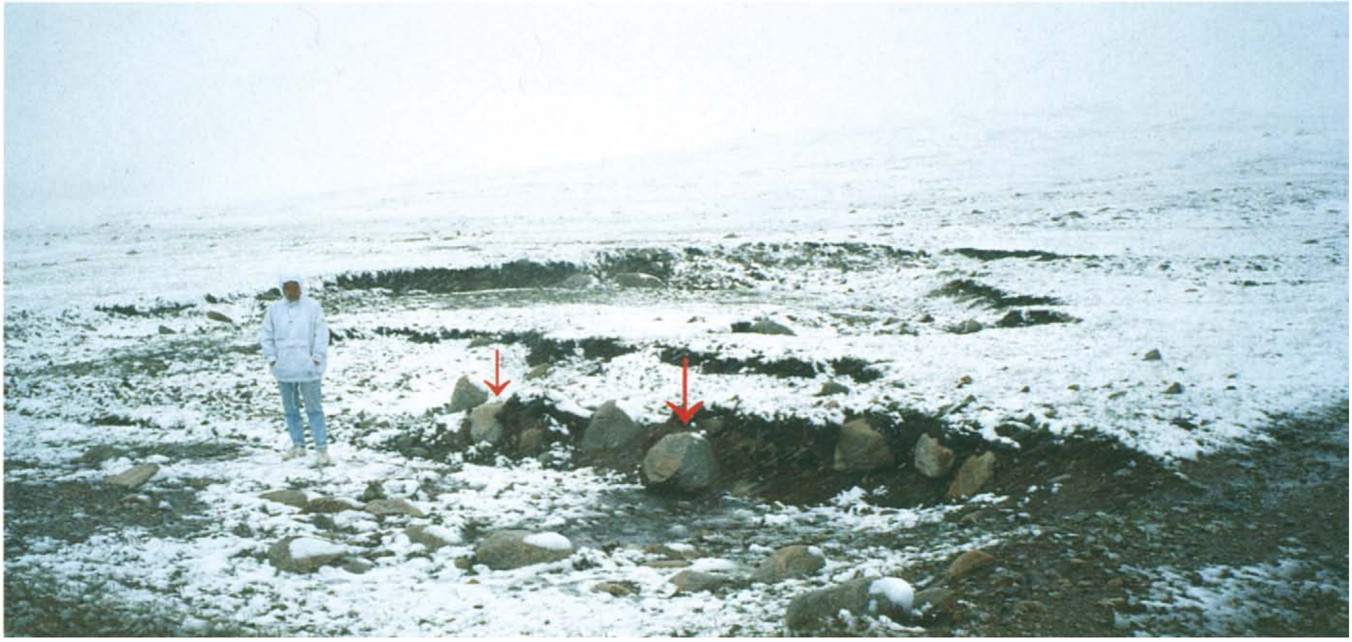


Fig. 30. Till with large granite boulders (↓) in a silty to clayey matrix in central Tibet (Fig. 1 No 10 directly below No 10; 31°35'N 92°10'E, 4670 m a.s.l.). The photograph, taken in mid-August shows, that summer snowfall still remains on the formerly glaciated Tibetan plateau. This reflects the proximity of the highland to the interglacial snowline altitude. Photograph: M. Kuhle.

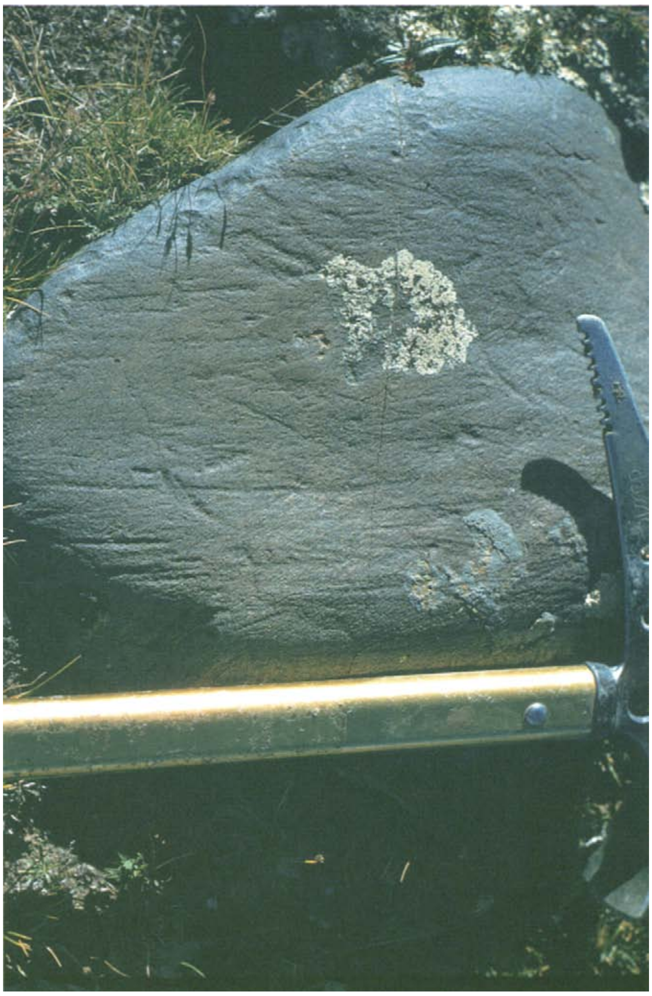


Fig. 31 (left). Striated drift of quartzite on the till surface in the formerly glaciated area of central Tibet (Fig. 1 No 10, 30°08'N 91°32'E, 4650 m a.s.l.). Photograph: M. Kuhle.

of High and Central Asia, they allow very precise interpolations for the regions between that have not been visited.

Some of the mountain areas selected are separate from the Tibetan high plateau and adjoining mountain massifs (Fig. 1 No 1), some are situated in central Tibet (Fig. 1 Nos 25, 5, 10), others right on the western mountain border of Tibet (Nos 4, 7, 9, 10, 24, 25, 26, 31) or on the southern (Nos 2, 18, 20, 21, 22, 28), eastern (No 10 below on the very right, 13, 30, 32, 19 and 3 on the right half) and northern mountain borders (15, 6 and 3 left half).

Test area No 1 lies in the arid to semi-arid Zagros Mountains. It is located SW of the Lut desert, which is one of the hottest parts of central Asia with only winter precipitation. It lies nearly at the same subtropical latitude (27°-30°N) than the Himalaya and the southern margin of Tibet. The test areas there (Nos 2, 4, 9, 10, 18, 20, 21, 22, 27 and 28) rise up to twice the height of the Zagros. They are humid as a consequence of the influence of the monsoon. Their precipitation of up to 6,000 mm/a falls mainly in summer.

The test areas in the Hindu Kush, the Karakoram and the inner western Himalaya (Nos 24, 7, 26, 29 and 31) receive both summer and also winter precipitation.

Whilst in the Himalaya the maximum precipitation falls between 1300 and 2500 m a.s.l., decreasing to well below 500 mm/a in an upward direction, in the Karakoram humidity increases constantly from the desert-like dry valley floors up to the summits, where precipitation can amount up to 2000 mm/a.

Fig. 32. Late Glacial tongue basin (c. 15 ka) into which a tens of kilometres long post-glacial lake has been infilled. It is situated on Last Glacial Maximum (LGM) till in central Tibet (Fig. 1 No 25, 29°29'30"N 86°14'E, 4535 m a.s.l.). Far-travelled erratic boulders, e.g. granites (↓) are found on the shoreline in the foreground. Sedimentary bedrock (schist) lies below. In the same way as the ice sheets of previous glaciations, the LGM (MIS 2; c.32-20 ka) Tibetan ice sheet has further overdeepened the lake basin. This is one example of the numerous Tibetan lakes in glacially overdeepened valleys and tongue basins. Photograph: M. Kuhle.

Fig. 33. In central Tibet slightly metamorphic sedimentary bedrock (•) (dark-grey) is covered with metre-thick till (■) containing metre-long erratic granite boulders (↓)(Fig. 1 No 25, 29°30'N 84°58'E, 4820 m a.s.l.). This is classic evidence of an ice-sheet cover of the Tibetan plateau. Photograph: M. Kuhle.

The eastern margin of Tibet (Nos 13, 30, 32) as well as the eastern part of central Tibet (Nos 19, 12 and 10)and north-eastern Tibet (3) are comparatively humid (*c.* 500 to over 3000 mm/a) and have summer precipitation. Western central-Tibet (25) up to the northwestern border of the plateau (6) and also including the area of the Pamir plateau to the NW (15) has a semiarid to arid climate. Despite an altitude of over 4000 m the precipitation is less than 100 mm/a. Here most of the precipitation falls in winter.

From the northern margin of Tibet (38°N) to South Siberia (52°N) the glacial histories of five additional test areas have been visited in the Tian Shan, Altai and in the Sayan- and Transbaikalian mountains (Nos 11, 8, 14, 23 and 16). Thus, field data have been gathered from an area that reaches from the Himalaya on the southern margin of High Asia to Lake Baikal in central Asia and from the Iranian mountains in the west to the Setchuan Basin in eastern High Asia. This area extends over *c.* 4,600 km in a W-E direction across various subtropical climate zones, and over *c.* 3,000 km in a N-S direction, i.e. more than 25 degrees of latitude.

The regional results and the corresponding field and laboratory data on which the glacier map and the glacial chronology are based have been published in detail elsewhere (see below). The publications are listed here in relation to the corresponding investigation areas (*cf.* Fig. 1).

No. 1: Kuh-i-Jupar Massif, Zagros, Iranian mountains (Kuhle, 1974; 1976; 1984c; 1987e; 1989a; 1990c; 1991a; 2003 d).

No. 2: Southern and northern Dhaulagiri and Annapurna Himalaya and southern margin of Tibet (Kuhle, 1980;

Fig. 34. Two till sheets (■) dissolved into earth pillars typical of this type of sediment, on the south-western margin of Tibet in the south-eastern Zanskar Himalaya (Fig. 1 No 17, 33°54'N 77°40'E, c. 3800 m a.s.l.). They confirm the complete former glaciation of this presently semi-arid area by an ice stream network. Photograph: M. Kuhle.

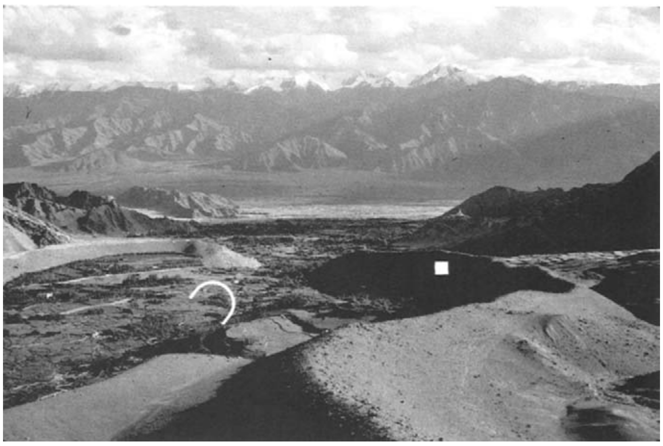


Fig. 35. The tongue basin (∩) of a Late Glacial glacier terminus is fringed by steep proximal morainic slopes (■). In the Leh valley the glacier flowed from the at present semi-arid and completely unglaciated, only 5400 m high south side of the Ladakh Range down to the upper Indus valley in southwestern Tibet to an altitude of 3400 m a.s.l. This would have required a snowline depression of at least 1200 m (Fig. 1 No 17, 34°13'N 77°40'E). Photograph: M. Kuhle.

1982a, c; 1983; 1986°, i; 1987e; 1988c, e, g; 1989b; 1993b; 1998a; 2001b).

No. 3: North-eastern Tibet with Kuen Lun and Animachin in the south and the Quilian Shan in the north (Kuhle, 1982b, c, d, e, f; 1984a, c, d; 1986a, i; 1987b, c, e; 1988c, e, g; 1989b; 1996b; 1997a; 1998a; 1999c, d; 2001a, d; 2002c; 2003a).

No. 4: Southern slopes of the Cho Oyu and Mount Everest-group, central Himalaya (Kuhle, 1984b, d; 1985a; 1986a, i; 1987a, e; 1988c, f, g; 1989b; 1993b; 1998a; 2000c; 2001b; 2002b).

No. 5: Southern Tibet from southern central Tibet up to the north slopes of the Shisha Pangma, Rolwaling, Cho Oyu, Gyachungkang and Mount Everest (Kuhle, 1984b, c. d; 1985a, b; 1986a, b, c, e, f, g, h, i; 1987d, e; 1988c, d, e, f, g, j, k; 1989a, b; 1991b; 1993b; 1998a, b, c; 1999c, d; 2000a, b, c; 2001b; Kuhle *et al.*, 1989; Kuhle & Kuhle, 1997).

No. 6: North-western margin of Tibet down to the Tarim Basin, western Kuen Lun, Aghil mountains, Karakoram north slope with the K2, Skyang Kangri, Broad Peak, Gasherbrum I (Kuhle, 1987d; 1988a, b, e, g, i; 1989b; 1990c; 1993b; 1994a, b; 1996b, c; 1997d; 1998a, d; 1999c;

2002c; 2003e; Kuhle & Kleindienst-Andreé, 1994; 1998; Kuhle *et al.*, 1989, 1997).

No. 7: North-western Karakoram with the Batura- and Rakaposhi massifs; the Nanga Parbat with the Rupal- and Astor valley and the lower Indus valley. (Kuhle, 1988c, j; 1989b; 1990e; 1991a, c; 1993°, b; 1994c, 1995c; 1996a, b; 1997a; 1998a; 2001d; 2002d, e; 2003b, c, e; Kuhle *et al.*, 1989; 1998).

No. 8: The Tian Shan with the Lake Issyk-Kul area including the Terskey Alatau north slope and the Kungey Alatau south and west slopes (Kuhle, 1994a; 1995b; 1998a; Grosswald *et al.*, 1994; Kuhle *et al.*, 1997; Kuhle & Schroeder, 2000).

No. 9: Southern margin of Tibet, eastern part; Kangchendzönga north, west and south slopes (Kuhle, 1990b; 1998a; 2001b).

No. 10: The central Tibetan plateau with the Gladongding massif and Tanggula Shan; cross profile of Tibet between Tanggula Shan and Nyainqentanglha; west-east profile of the Gangdise Shan up to the Namche Bawar at the Tsangpo Gorge, and the meridional stream furrows (Kuhle, 1990d; 1991b; 1993b; 1994c; 1996b; 1997a; 1998e; 2001a, b, d; 2002c; Kuhle, M. & Kuhle, S., 1997; Kuhle & Xu Daoming, 1999).

No. 11: The Tian Shan plateau between Kokshaal Tau with the Pik Dankowa and Terskey Alatau; massifs of the Pik Pobedy and Han Tengri; Kirgisen Shan (Kuhle, 1994a; 1995b, c; 1996b; 1998a; Grosswald *et al*, 1994; Kuhle *et al.*, 1997; Kuhle & Schroeder, 2000).

No. 12: Northern central Tibet between the central Kuen Lun and Tanggula Shan Mountains (Kuhle, 1993a; 1995a; 1998a; 1999c, d, e; 2001a, c; 2002a; Kuhle & Kuhle, 1997; Kuhle & Xu Daoming, 1999).

No. 13: Eastern margin of Tibet including the Datou Valley and the eastern foreland, west of Chengdu (Kuhle, 1993a; 1995a; 2001b).

No. 14: Eastern Tian Shan: Bogdo Uul and the massifs south of Urumqui adjoining to the west (Kuhle, 1998a).

No. 15: North-western Karakoram: west slope of the Rakaposhi group, south and north slopes of the Batura group, north slope of the Distaghil Sar group (Shimshal), Shimshal Pamir, north slope of the northwestern Karakoram, East-Pamir plateau: Muztagh Ata, Qungur Tagh, Kara-Bak-Tor, Oytag valley (Kuhle, 1988c, j; 1989b; 1991c; 1993b; 1994c; 1995c; 1996b; 1997a, b; 1998a, f; 1999a; 2001b; 2002d, e; 2003b, c; Kuhle *et al.*, 1998).

No. 16: Eastern Sayan Mountains and Transbaikalian Mountains in southern Siberia (Kuhle, 1995b, c; 1998a; 1999a; Grosswald & Kuhle, 1994).

No. 17: South slope of the Ladakh Range and middle Indus valley; West-Himalaya profile from Nun Kun (Zanskar Himal) in the north-west to Manali and Dharamshala (south slope of the Himalaya) (Kuhle, 1994c; 1995c; 1996b; 1998a; 1999a; 2001b; Kuhle & Kuhle, 1997).

No. 18: Western central Himalaya: Garhwal (Chamoli) Himalaya with Kamet, Nanda Devi and Trisul massifs (Kuhle, 1994c; 1995c; 1996b; 1997a; 1998a; 1998e; 1999a; Kuhle & Kuhle, 1997).

No. 19: North-eastern central Tibet from the Bayan Har Mountains up to Chaling Hu (source lake of the Hoang Ho River) (Kuhle, 1982b, c, d, e; 1985a; 1986i; 1987b, c, e; 1988c, e, g; 1989b; 1993b; 1995c; 1997a; 1998a, e; 1999a, c, d2001; 2002c; 2003ad; Kuhle & Kuhle, 1997).

No. 20: Central Himalaya; Makalu massif; catchment areas of the Barun and Arun valleys (Kuhle, 1991b; 1995c; 1997a; 1998a, e).

No. 21: Central Himalaya with west, north, south and east side of the Manaslu; south side of the Lamjung and Annapurna (Kuhle, 1995c, 1997a; 1998a, e; 2001b).

No. 22: Western part of the Central Himalaya with the west and north-west side of the Dhaulagiri Himal, Dolpo, Kanjiroba (Kuhle, 1997a; 1998a, e).

No. 23: Altai Mountains with the Belucha massif, southern Siberia: unpublished.

No. 24: Hindu Kush: from the Gilgit Valley across the Shandur and Sani Pass through Chitral to Mirkhani, lower Indus valley and the Nanga Parbat north slope (Kuhle, 1988c, j; 1989b; 1991c; 1993b; 1996a; 1997a; 1998a; 2001b; 2003b, c, g).

No. 25: (1) Profile of central southern Tibet from the central Himalaya (Shisha Pangma and Cho Oyu north slopes) via the Tsangpo depression and the Gangdise Shan up to Central-Tibet (Chang Tang) and central western Tibet. (2) Profile from western South Tibet from the Gurla Mandata and Manasarowa (Kailas in the Transhimalaya) via Aksai Chin (West Tibet) up to the western Kuen-Lun (Kuhle, 1998a, b, c, d, h; 1999a, b, c, d, e; 2000a, b, c, d, f; 2001a, c, d; 2002a, d; 2003f; Kuhle & Kuhle, 1997).

No. 26: Muztagh Karakoram: from the K2 Broad Peak and Masherbrum across the Baltoro and Biafo glaciers into the Braldo and Shigar valley; from the basin of Skardu towards the Deosai plateau and down the middle Indus valley (Kuhle, 1999a, b, e; 2001b; 2002d, e; 2003b, c, g).

No. 27: Southern side of the Central Himalaya: Langtang, Annapurna and Rolwaling Himal (Kuhle, 2001b).

No. 28: East Himalaya: Kangchendzönga south slope with Yalung- i.e. Simbua Khola. (Kuhle, 1990b; 2001b).

No. 29: Central Karakoram: the Hispar Muztagh with the Spantik west slope, Distaghil, Kunjang Shish and Kanjut Sar south slopes (Kuhle, 2001b; 2003c, g).

No. 30: East Tibet between Daocheng and the Minya Konka east slope with the Datou Valley (Kuhle, 2001b).

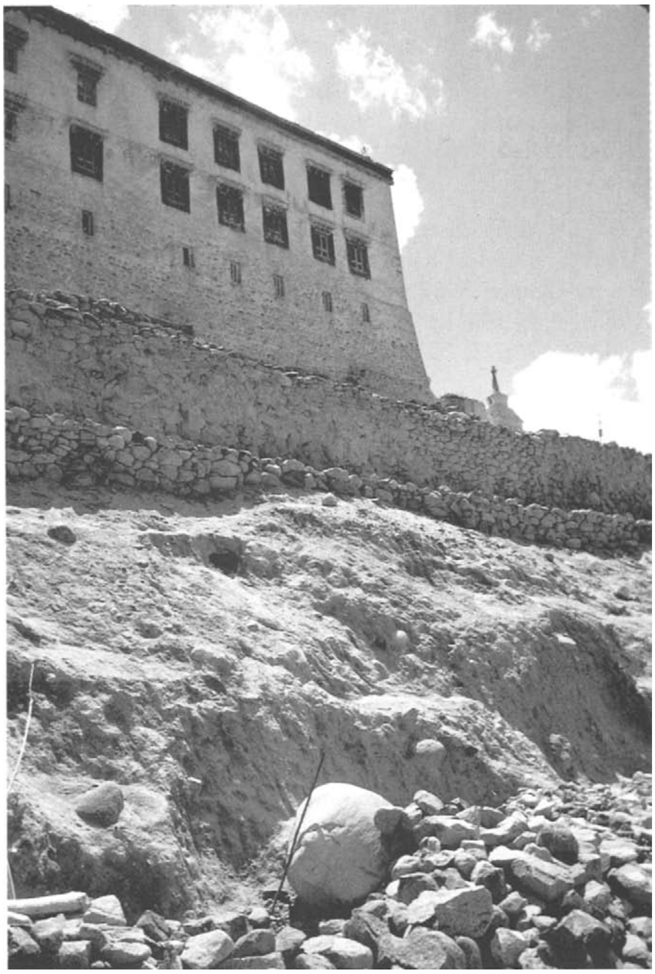


Fig. 36. Classic Late-glacial end moraine (■) in the Stok valley, the WNW valley parallel to the Leh valley (see Photograph 35) in the south slope of the Ladakh Range (Fig. 1 No 17, 34°14'N 77°22'E, 3300 m a.s.l.). A Lamaistic monastery has been erected on the end moraine. Facetted and in part also striated (↓) isolated polymict block-sized boulders are contained in the clay- and silt-rich till matrix. (stick in the foreground: 150 cm). Photograph: M. Kuhle.

No. 31: Karakoram: Haramosh-Malubiting group with the Barpu and Chogolungma Glacier; Deosai plateau; Batura south slope: Bar Valley with Kukuar and Baltar Glacier (Kuhle, 2001b; 2002d, e; 2003b, c, g).

No. 32: Xuebao massif in eastern Tibet and Miriang Valley system; unpublished.

By interpolation the investigations have been extended to those parts of High Asia which lie between the test areas (Fig. 1) that were investigated in the field. In this case the climatic and orographic-topographic conditions have been taken in consideration, including comparable latitude and meridian positions and windward or lee-side positions. The interpolations are based on the orographic and climatic snowline (ELA) determined by field data in the test areas. It is a climate-controlled altitude which allows inter-regional comparison. With such an interpolation, reliable information can be obtained about the former glaciation there. For that the Pleistocene snowline depression, found out empirically in the test area is transmitted to the appropriate comparable area. According to the fact that the ELA runs halfway between the average altitude of the catchment area (= fringing mountain ridge with summits

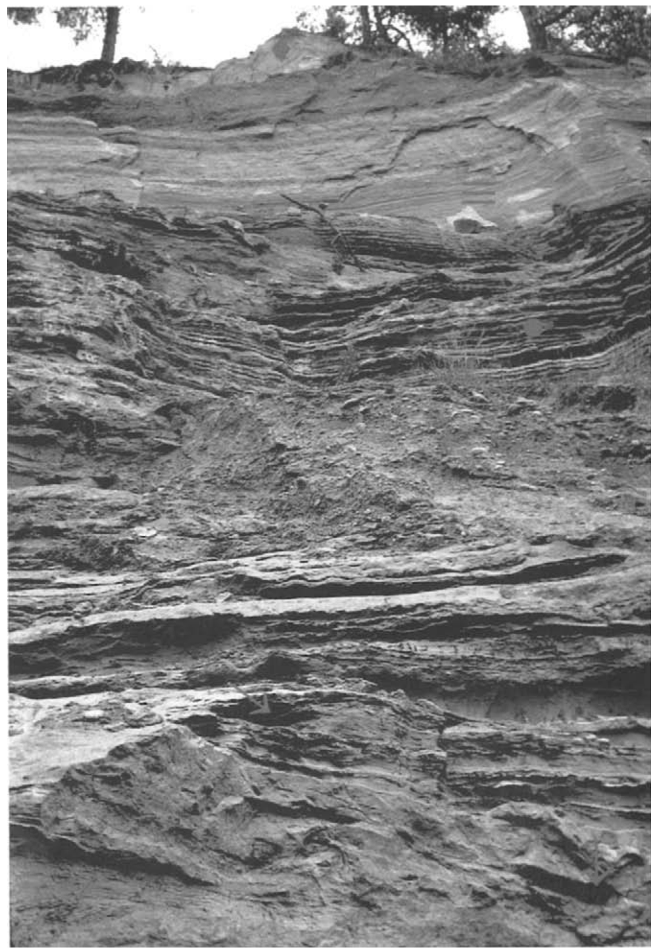


Fig. 37. Radiometric dates confining the age of the LGM glaciation in High Asia: view at the 80 m-high exposure on the right-hand side of the Tsangpo valley near the mouth of the Nyang Qu and 'Ganga Bridge' in south-eastern Tibet, 60 m above the present Yarlung (Tsangpo) River level (Fig. 1 No 10 west of the Namche Bawar; 29°18'N 94°21'E, base altitude 3060 m a.s.l.). On the top poorly stratified aeolian sands, partly with gravels (♦); below 8 m of varved clays (≡) above the sand (•), which have been ^{14}C-dated in the lower 32 m of the exposure. The varved clays (≡) are related to the deglaciation, i.e. to the Late-glacial. The original position of several of the dated coniferous tree trunks (↓) is indicated. Eight of the trunks sampled from different heights within the exposure, have been dated. Their radiocarbon ages mostly lie between 48,580 + 4660/-2930 years BP and 16,350+/-580 years BP. The younger lake evidenced by the varved clays higher up-section, had been dammed by the Nyang Qu Glacier, an outlet glacier of the central Tibetan ice sheet. Consequently it post-dates the LGM. Those trunks which are older than 20,000 years BP must have been overrun by the ice sheet. Photograph: M. Kuhle.

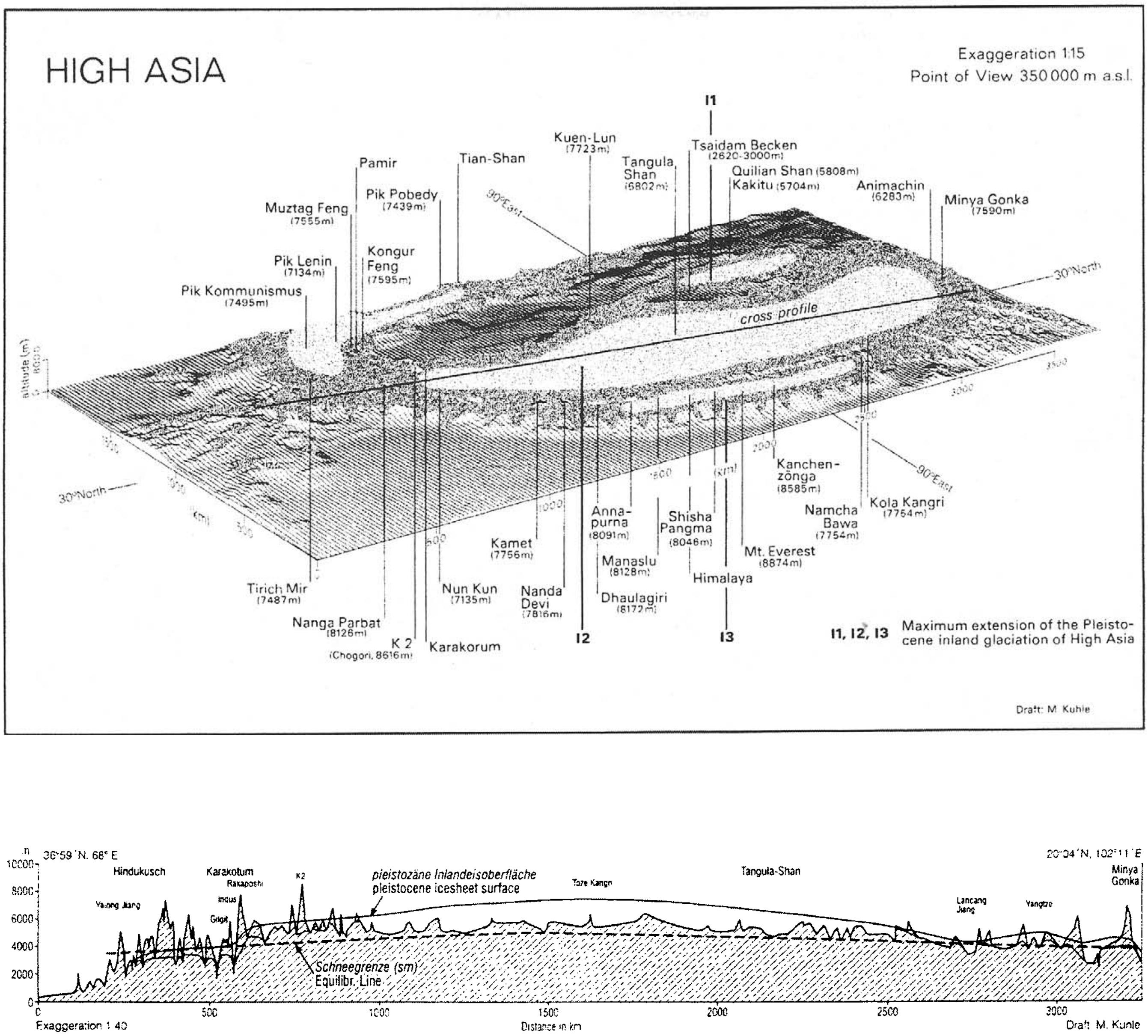


Fig. 38. (above) The reconstructed 2.4 million km² ice sheet, or ice stream network, covering the Tibetan plateau, with the three glaciation centres I1, I2, I3. Only peaks higher than 6000 m rise above the ice surface.
(below) Cross profile of the central ice sheet from the Hindu Kush in the west to the Minya Gonka in the east.
A synthesis of the author's empirical data supplementary to the digital glacial map of High Asia.

and notches) and the altitude of the glacier terminus – which corresponds to a ratio of approximately 2:1 between feeding and ablation area - , the extent of glaciation can be extrapolated from the projected ELA. The accuracy of the glacier reconstruction allows an inclusion in the mapping project of the very remote High Asian areas which are difficult of access. For this purpose an exact base like the Digital Chart of the World (DCW) is fundamental (Kuhle, 1997a).

Comparison of Figures 3 and 38 may serve as an example. The Pleistocene ice cover of the Tibetan plateau (Fig. 38) has been reconstructed primarily based on the observation of glacial landforms and deposits in the Tibetan test areas (Fig. 1) and secondarily by interpolation between them. This is based on the fact that the Pleistocene snowline over vast areas lay below the plateau surface (Fig. 3). It is methodologically inadmissible to interpolate an appreciable difference in LGM snowline altitude between two immediately adjacent, climatically comparable test areas at the same latitude.

The data suggest an average LGM snowline depression of 1,100-1,200 m as compared to the modern snowline altitude. Additionally, a longitude-parallel snowline incline of 100 m over a distance of 100 km could be observed between High and Central Asia (Fig. 3) which was approximately parallel to that at the present-day. The

Table 1: Glacial stages of the mountains in High Asia, i.e. in and surrounding Tibet (Himalaya, Karakoram, E-Zagros and Hindu Kush, E-Pamir, Tien Shan with Kirgisen Shan and Bogdo Uul, Quilian Shan, Kuenlun with Animachin, Nganclong Kangri, Tanggula Shan, Bayan Har, Gandise Shan, Nyainquen Tanglha, Namche Bawar, Minya Gonka) from the pre-Last High Glacial (pre-LGM) to the present-day glacier margins and the pertinent sandar (glaciofluvial gravel plains and gravel terraces) with their approximate age (after Kuhle 1974-2003).

glacier stage		gravel field (sandur)	approximate age (YBP)	ELA depression (m)
- I	= Rissian (pre-last High Glacial maximum)	No. 6	150 000 - 120 000	c. 1400
0	= Würmian (last High Glacial maximum)	No. 5	60 000 - 18 000	c. 1300
I - IV	= Late-glacial	No. 4 - No. 1	17 000 - 13 000 or 10 000	c. 1100 - 700
I	= Ghasa stage	No. 4	17 000 - 15 000	c. 1100
II	= Taglung stage	No. 3	15 000 - 14 250	c. 1000
III	= Dhampu stage	No. 2	14 250 - 13 500	c. 800 - 900
IV	= Sirkung stage	No. 1	13 500 - 13 000 (older than 12 870)	c. 700
V - 'VIII	= Neoglacial	No. -0 - No. -2	5 500 - 1 700 (older than 1 610)	c. 300 - 80
V	= Nauri stage	No. -0	5 500 - 4 000 (4 165)	c. 150 - 300
VI	= older Dhaulagiri stage	No. -1	4 000 - 2 000 (2 050)	c. 100 - 200
'VII	= middle Dhaulagiri stage	No. -2	2 000 - 1 700 (older than 1 610)	c. 80 - 150
VII - XI	= historical glacier events	No. -3 - No. -6	1 700 - 0 (= 1950)	c. 80 - 20
VII	= younger Dhaulagiri stage	No. -3	1 700 - 400 (440 resp. older than 355)	c. 60 - 80
VIII	= stage VIII	No. -4	400 - 300 (320)	c. 50
IX	= stage IX	No. -5	300 - 180 (older than 155)	c. 40
X	= stage X	No. -6	180 - 30 (before 1950)	c. 30 - 40
XI	= stage XI	No. -7	30 - 0 (= 1950)	c. 20
XII	= stage XII = recent resp. present glacier stages	No. -8	+0 - +30 (1950 - 1980)	c. 10 - 20

Fig. 39. Typical exposure of an 8 km long and 450 m high lateral morainic (■) terrace near the settlement of Bayizhen (Baji) in the lower Nyang Qu (valley) c. 100 m above the moraine base in central southeastern Tibet (Fig. 1 No 10 west of the Namche Bawar, 29°40'N 94°23'E, height of the lowest moraines: 3200 m a.s.l.). The exposure shows up to several metre-long polymict boulders floating isolated from each other in a silty (74,7%) and clayey (6.3%) matrix (■). These are quartzite-(↓) and granite (⇓) boulders. Photograph: M. Kuhle.

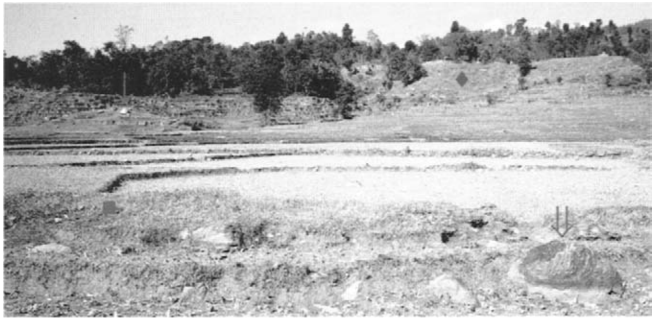


Fig. 40. End moraine hill (♦) and till material (■) in the southern Himalaya foreland in the area of the lower Marsyandi Khola (Fig. 1 No 21; 28°11'N 84°25'E, 620 m a.s.l.). In the clayey, silty, sandy matrix isolated metre- to hut-sized polymict boulders are included (↓). Among them are far-travelled augengneiss boulders (↓) which outcrop in the Himalaya main ridge at a distance of at least 35 km. The lowest ice-marginal position of this outlet glacier from South Tibet reached the settlement of Dumre at a mere 460 m a.s.l. It is the lowest known former (LGM) ice margin identified so far in High Asia. Photograph: M. Kuhle.

regional divergences are lower than the author had expected when he started with his field investigations three decades ago. Nowhere did the ELA depression amount to less than 900-1000 m and only in the Iranian highland (Zagros), on the Himalaya south slope and by Lake Baikal it exceeded 1400 m. Only regionally may the gradient of the snowline altitude have approached 125 m/100 km. However, this contradicts to the proportional increase in relative humidity in accordance with the glacial lowering of temperature. Compared with today this might have caused a better-balanced and thus over large parts more uniform climate.

Considering the manifold small- and large-scale relations and connections between the findings, mistakes could be kept to a minimum. This allows for the first time to attempt a complete glacier reconstruction for High Asia at a scale of 1:1,000,000. However, with regard to many details this draft map is bound to be only valid for the time being.

4. Climatic-ecological consequences of the Pleistocene glaciation in High Asia

The chronological classification of the mapped glacier area can be seen from Table 1, where it is indicated as 'Glacier stage 0' (= Würmian = Marine Isotope Stages 4-2 = Last High Glacial Maximum) (Kuhle, 1997a). The chronological classification of the mapped LGM ice margins (moraines), which in all cases are only locally valid, is confirmed by the corresponding ELA determinations (Kuhle, 1974; 1982a; 1983; 1986a, d; 1987a; 1988h) and relative - i.e. geomorphological - and absolute radiocarbon and thermoluminescence dates (Kuhle, 1987a, c; 1997a; 1998a) of younger, i.e. Late-glacial, Neoglacial and historical glacier positions.

This glaciation corresponded to a lowering of the snowline by some 1200 m. For the LGM this suggests a depression of the average annual temperature by 7 to 8°C combined with lower precipitation than today (Kuhle, 1998a). Owing to this drop in temperature a supposed drier climate has partly been compensated with regard to the glacier feeding by a minor evaporation and an increased relative humidity.

Due to its great extent this glaciation of the subtropics was the most important 'climatically foreign' element on earth. With an albedo about 80-90% this ice area of Tibet has reflected at least 4 times greater global radiation energy per surface area into space than the other ice masses (Kuhle, 1985a, b; 1986f, h, i; 1987e; 1988a, f; 1989b; 1991c; 1998a; 2000b, d, e; 2001a; 2002a). Thus at that time the area which at present, under interglacial conditions, is the most essential heating surface of the atmosphere, was the most important cooling surface. The present annual thermal low-pressure cell over Tibet which drives the summer monsoon, was lacking. The glaciation thus caused an interruption of the summer monsoon with serious consequences for global climate, including pluvials in the Sahara, the expansion of the Thar desert, the heavier dust influx into the Arabian Sea etc. It also caused a lowering of the treeline and all other vegetational belts of the alpine-boreal forests right down to the semi-humid Mediterranean forest which then had replaced the interglacial tropical monsoon forests on the Indian subcontinent. But also the migration of stags like *Java rusa* far into South Asia are a consequence of this glaciation.

Despite the high evaporation and ablation rates caused by the strong insolation, meltwater discharge from the glaciers into the Inner-Asian basins was sufficient for the creation of extensive meltwater lakes in the Tsaidam and Tarim basins and the Gobi. The simultaneous drop in temperature favoured their development. Thus, the clay fraction produced by the scouring and grinding of the ice sheet got available for erosion. Deflation of the limnite deposits and aeolian long-distance transport were connected to the katabatic winds. Accordingly, the High to Central Asian glaciation discussed here was the actual cause of the enormous loess production and the eastward transport of the material into the Chinese uplands and lowlands (Kuhle, 2001a; 2002a). During the Ice Age the katabatic circulation for which the name 'winter monsoon' is not quite correct, blew all year round.

The enormous uplift rate of Tibet of approximately 10 mm/a measured by triangulations since the 19th century have been confirmed by glacial geomorphological as well as seismological investigations of the uplift of the Himalaya. However, these amounts of uplift far exceed any conceivable primary tectonic uplift of the high plateau based on epirogenetic processes alone. Actually, they are much easier explained if a superimposed glacioisostatic compensation movement of Tibet about 650 m is taken into account (Kuhle, 1989b; 1993a; 1995a; 1997a; 1999b; Kuhle & Kuhle, 1997).

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