Fig 18
Large high glacial cirque on the S slope of the Mount Everest area (Khumbu Himal at 27°48'N/86°37'E). Nupla, a 5,885 m-high peak of the Kongde Shar crest is now able to supply only a small amount of avalanche snow to the NE-facing corrie (xx), so that the concave form is almost completely free from glacier ice. The present orographic equilibrium line is at 5,500 m asl (—). The glaciated floor of the corrie (•) extends far down into the forest to about 3,600 m asl. This proves a drop in the equilibrium line of c. 950 m during the last Ice Age. It is, however, likely that the glacier shifted on to the Nangpo Dzangpo Valley glacier, so that the equilibrium line was some 100 m lower (cf. Fig 19).
Photograph at 3,900 m asl, facing SSW. M. Kuhle, 3.9.1982.

Fig 19
Exposure of lateral moraine material containing rough clasts interfingered with glacio-limnic sands (x) 420 m above the bottom line of the Imja Drangka near the settlement of Trashinga at 3,650 m asl (27°53'N/86°44'E) (▲). These are materials which have been transported over short distances; they range from clays to sands (30-40 % dominance of fine sands with 0.06 to 0.2 mm 0) with a proportion of characteristically poorly-rounded grains of quartz, muscovite and biotite. The microscopic-granulometric analysis confirms glacio-fluvial transport, for the degree of matting that is typical for aeolian transport, is absent. Corresponding sediments, which are typical for lateral valleys of glacier edges, are also found near and above the Namche Bazar settlement, and thus give evidence of ice thicknesses of 600-850 m in the area of the confluence of the Ice Age Nangpo Dzangpo and the Imja Drangka glaciers. At present sands of this kind are being deposited in the lateral moraine lakes of Ngozumpa Tsho, Longporga Tsho and Gokyo Tsho amongst others.
Photograph by M. Kuhle, 6.11.1982.

tradition is concerned. The lowest ice margin sites, proved by moraines and glacial polishing (Fig 7) are on the S slope of the Himalayas at heights of 1,100 to 1,200 m asl, as well as N of the main Himalayan crest in the border region towards the Tibetan Himalayas between 2,580 and 2,800 m asl. Some of them have in the meantime been confirmed by Iwata et al. (1982). From this an equilibrium line at an altitude of about 4,200 m and an equilibrium line depression of 1,530 m can be calculated for the high glacial period (Kuhle 1979/80; 1982a; 1983a). The next higher terminal moraine in the S slope of the Himalayas is situated in the Thak Khola, a transverse valley in the Himalayas at 1,870 m. They have been incorporated as the first-stage retreat during the late glaciation under the name 'Ghasa-Stadium I' (Fig 17). This stage illustrates a drop in the equilibrium line which is still one of 1,190 m. Comparable values, although for the high glacial period, were established by Heuberger (1974) on the S slope of the Cho Oyu region 300 km further E. In 1959 v. Wissmann had postulated a depression of only 600 to 700 m for the last Ice Age, a value which - except for the hitherto missing age datings - must be regarded as too small by about half (see below).

East and North Tibet: Animachin Massif, Kuen Lun, Kakitu Mountains and Quilian Shan 1981. (Fig 13, No. 2)

After the author had tried in vain in 1975 to enter various parts of Tibet and especially the N slopes of Mount Everest through the contacts of the German-Chinese Society, Jürgen Hövermann (Hövermann, J.; Wang Wenying 1982) succeeded in co-operation with the Academia Sinica in setting up the first joint German-Chinese expedition. Besides the leader of the expedition and Horst Dronia, the meteorologist, the author managed to

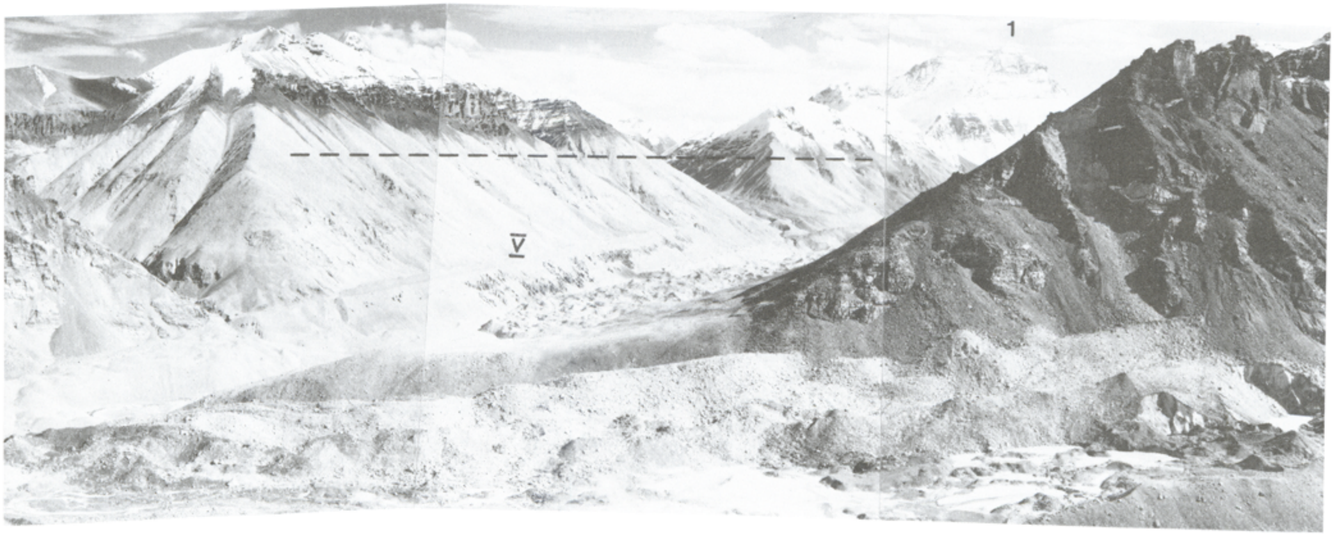


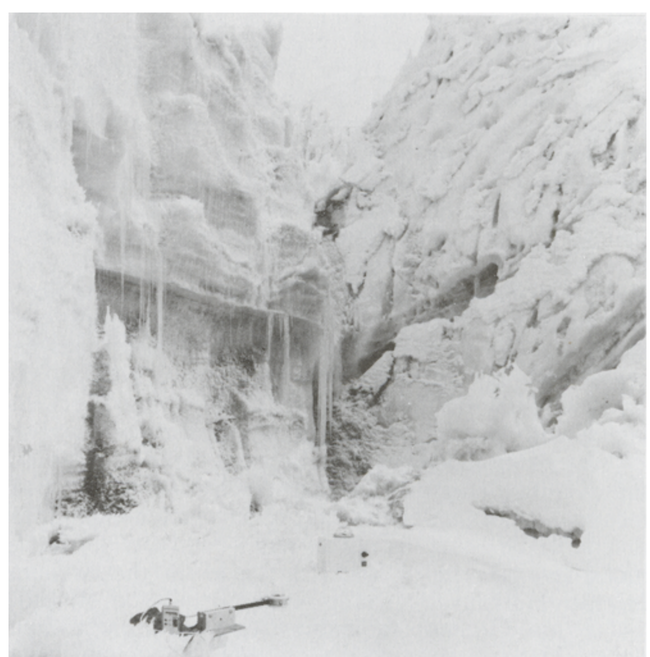
Fig 20
The valley region of the Tibetan Himalayas constitutes a link between the N and Mt. Everest (Chomolungma 27°59'N/86°56'E; 1, 8,848 m). The valley bottom rises from 5,100 to 6,400 m on the left towards the N foot of the mountain 20 km up-valley. The debris-covered tongue of the 17 km-long Central Rongbuk glacier is overlooked by the 180 m neo-glacial lateral moraine terrace which the author has classified as belonging to the "Nauri stadium" (V). In the High Himalayan region the S Tibetan inland ice complex I3 (Fig 27) has dissolved into separate outlet glaciers. ----- marks the south-sloping glacier level of the Rongbuk outlet glacier, which drained towards the S slope of the Himalayas (in contrast to the recent Rongbuk glacier) via the 6,009 m-high Lho La Pass.
Photograph at 5,600 m asl, facing SSE. M. Kuhle.

join this four-month long enterprise which yielded the first insights into the extent of the NE Tibetan glaciers during the Ice Age (Kuhle 1981). With the aid of 43 ice margin localities which in many places were represented by ice marginal ramps the author was able to differentiate an older glaciation (Riss glacial?) with a lowering of the equilibrium line by 1,430 m from a more recent glaciation (Würm glacial?) with a drop of about 1,110 m (Fig 12). During the earlier glaciation, the equilibrium line was at about 3,280 m, and during the more recent one at about 3,770 m asl (Kuhle 1982b; 1983d).

Mount Everest - South Slope 1982 (Fig 13, No. 3)

During the three months of work on the S side of Mt. Everest it was possible to confirm the extent of glaciers which Heuberger had established. These provided the basis for the 900 - 1,000 m values for the lowering of the equilibrium line mentioned above (Fig 18). But data from even lower ice margin sites in the Dudh Kosi, outside the valley of the Luglha (Surke) settlement were collected as well; amongst them sands which had been deposited by ice age waters high up on the valley sides (Fig 19). These glacier indicators at the Namche Bazar, Nyambua Thyang, Chhutawa and Julming settlements (Kuhle 1982c; 1985b) are evidently connected with the former glaciation of this valley down to about 1580 m, as has also been sug-

Fig 21
Arrangement for measuring radiation at 6,040 m asl on the East Rongbuk Glacier on the NE slope of Mt. Everest, in October, 1984 (Fig 22, 23). The instruments are placed between 18 m-high glacier ice walls; in the background - a Thies System actionograph (bimetallic, measuring range 0.3 - 3 um), in the foreground - a Thies System radiation balance indicator (thermoelements, measuring range 0.3 - 60 um).
Photograph by M. Kuhle, 10.10.1984.



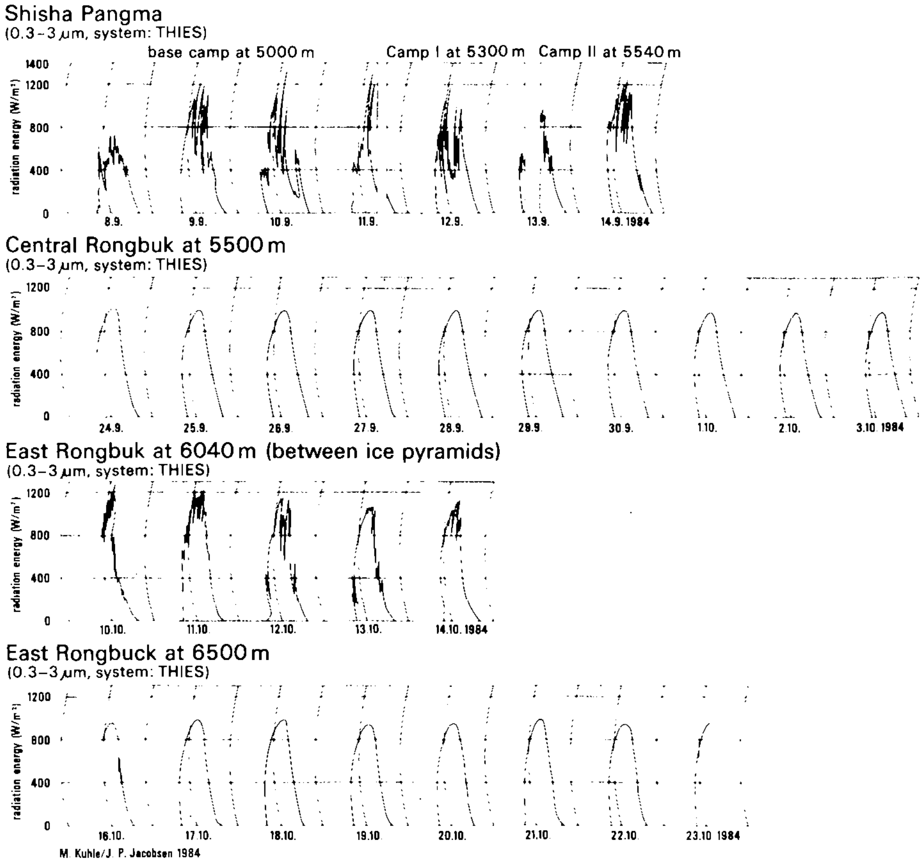


Fig 22
Incoming radiation intensities in S Tibet (Himalayan N Slope) between 28° and 29° N.

gested by Heuberger's most recent investigation (fieldwork in 1984). The results were discussed at the International High Asia and Tibet Symposium held in Göttingen in October, 1985 (Höllermann 1986; Kuhle 1986 b). In 1982 the emphasis of the author's investigations had been on the attempted dating of the states of glaciers from late glacial to historical times. These radio-carbon analyses[6] on samples of plant remains from pre-historic moraine surfaces permitted the author to classify the stage which he termed "Nauri Stadium V" (Kuhle 1979/80) as being about 4,000 years old. That applies to a post-glacial stadium of glaciation which recent calculations associate with a lowering of the equilibrium line by 560 m (Kuhle 1985d; 1986a). This is to be taken as an indication that the lowering of the equilibrium line by about 600-700 m which v. Wissmann supposed to be of a high glacial age applied nearly even 4,000 years ago, and thus belongs to the more recent late glacial period about 10,000 years ago.

According to the present state of knowledge, the 'Nauri Stadium' is followed by another seven terminal moraine echelons and glacier-end sites downhill as far as the really lowest terminal moraines - those of the ice age - on the S slope of the Himalayas (Kuhle 1979/80; 1982a; 1983a). This, too, is an indication of equilibrium line depressions of merely 600 to 700 m being more likely half that of the maximum lowering of the equilibrium line.

South Tibet Expedition: Trans-Himalayas, Tsang-po Depression, Tibetan and High Himalayas with the Shisha Pangma and the North Side of Mount Everest, 1984

As long ago as 1976/77 the author was able to spend eight months extending his investigation to that part of S Tibet which belongs to Nepal. They were the Sangda-, Mul-Lekh-, Muktinath-, Pukhung-, Damodar- and Chulu-Himal mountain groups N of the Dhaulagiri- and Annapurna Massifs (Fig 13, No. 1). They are part of the Tibetan Himalayas, attain a height of 6,636 m, and drain towards the Ganges (Kuhle 1979/80; 1982a). It had been intended to continue research in the Tsangpo region (upper Brahmaputra) N of the watershed in 1984 (Fig 13, No. 4). In this priority was given to visiting the lowest areas and thus also the lowest ice margin sites. However, even this lowest area of S Tibet is nowhere less than 3,800 m high. Moreover, the immediate connection with Mt. Everest, as well as with the Shisha Pangma north slopes, was important; here a high valley landscape with valley bottoms at 5,000 to 6,000 m asl (Fig 20) contrasts with remnants of high plateau (Fig 14), which at

4,800 to 5,600 m are still untouched by valley-forming erosion, thereby illustrating the different extent of the effect by Ice Age glaciers.

In Peking (Beijing) the author had been promised a 50-day full-time working period for the N slope of Mt. Everest. During this time measurements of surface temperatures up to 8,848 m above sea-level, along with measurements of solar radiation and re-radiation (Fig 21, 22, 23), of soil and air temperatures, even atmospheric humidities up to high altitudes above sea-level were to have taken place. In addition it had been planned to extend the geomorphological map, which had been begun for the S flank of the mountain in 1982, across the political boundaries to its N side, in order to complete a representation of the highest area of the earth's crust on one sheet at a scale of 1:50,000.

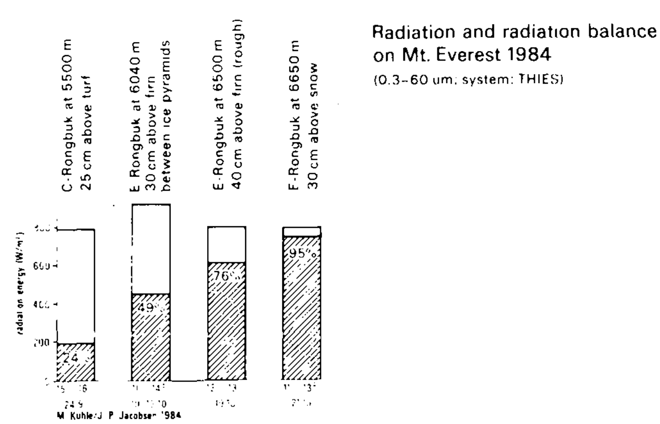


Fig 23
Radiation balances in S Tibet (Himalayan N Slope) between 28° and 29° N.

Organisation, Conduct and Evaluation of the 1984 Expedition

As Chinese territory is involved, the author, after having striven for its realization in a variety of ways over a period of nine years, was able to tackle this project in co-operation with colleagues of the Institute of Glaciology and Cryopedology of the Academia Sinica. In March, 1984, after two years of negotiations, which had the support of the regional government of Lower Saxony (FR Germany), the author was invited to Beijing to discuss details. The outcome was a joint German-Chinese Expedition from the Geographical Institute at the University of Göttingen and the Academia Sinica Institute at Lanzhou, which went to S Tibet and the N flanks of Mt. Everest. The leader on the Chinese side was the geodesist and glaciologist Wang Wenying, and on the German side the author[7]. Automatic-scribing and computer-steered measuring instruments (Lambrecht, Thies, Geodimeter and Raytek systems) which had been made available were important for the complicated breadth of the data which it was intended to obtain. The three German participants were the geographers Jens-Peter Jacobsen, Georg Miehe and the author; together with their Chinese colleagues, who included Wang Wengying, Huang Rongfu, Xi Daoming and Zhening Benxing, along with technical staff, drivers, cooks and assistants, the group started out from Lhasa. Once in the field when moving out from the base camps, and particularly in the Mt. Everest area, the work was supported by Tibetan yak drivers and their pack animals. Sixty three of the in all 87 working days were spent at altitudes above 5,000 m; on 16 days investigations were carried out in the high region at altitudes between 6,000 and 7,100 m asl. In the course of this the E wall of Chang-La, leading up to the N col of Mt. Everest, was climbed (Fig 24).

The author's proposals for a programme for this expedition, which had originally been submitted to the Chinese Academy, were rather wide-ranging for the very reason that his party was the first one of visiting foreign scientists who were given permission to work in this remote area and on the N side of Mt. Everest. The plan succeeded in so far as some data for ice age research and contemporary glaciology, as well as for research on permafrost, including measurements of shifts in mantle rock, for vegetation geography and for high altitude geo-ecology could be acquired. Whereas the financial scope and the often difficult logistics of the expedition conditions - there was no transport, but everything depended on a small number of excellent porters at high altitudes - tended to restrict earlier Himalayan expeditions to an absolute minimum of equipment, this expedition was even able to experiment with the 'film' medium in respect of its technical action radius in problems of high mountain geography, and make a 16-mm sound film, which was completed in co-operation with the Göttingen Institute for Scientific Film (Kuhle 1985c; 1986d). The results of the S Tibet Expedition of 1984 were debated in Göttingen in October, 1985 on the occasion of the "International Symposium on Tibet and High Asia", at which 54 scientists from 12 countries had come together (Höllermann 1986; Kuhle 1986b). The author has been approached by the Academia Sinica to lead another joint expedition to W Tibet, to the virtually unknown N slopes of the Karakoram Ridge and to the N flank of the 8,611 m-high K2, in order to continue with reconstructions of the ice age. A team of 8 Chinese and 6 German scientists has carried through this expedition from August to November, 1986.

The Results of the Five Expeditions to High Asia

Three kinds of results make up the overall picture of the high glacial conditions in the Tibetan Highland and its mountain systems.

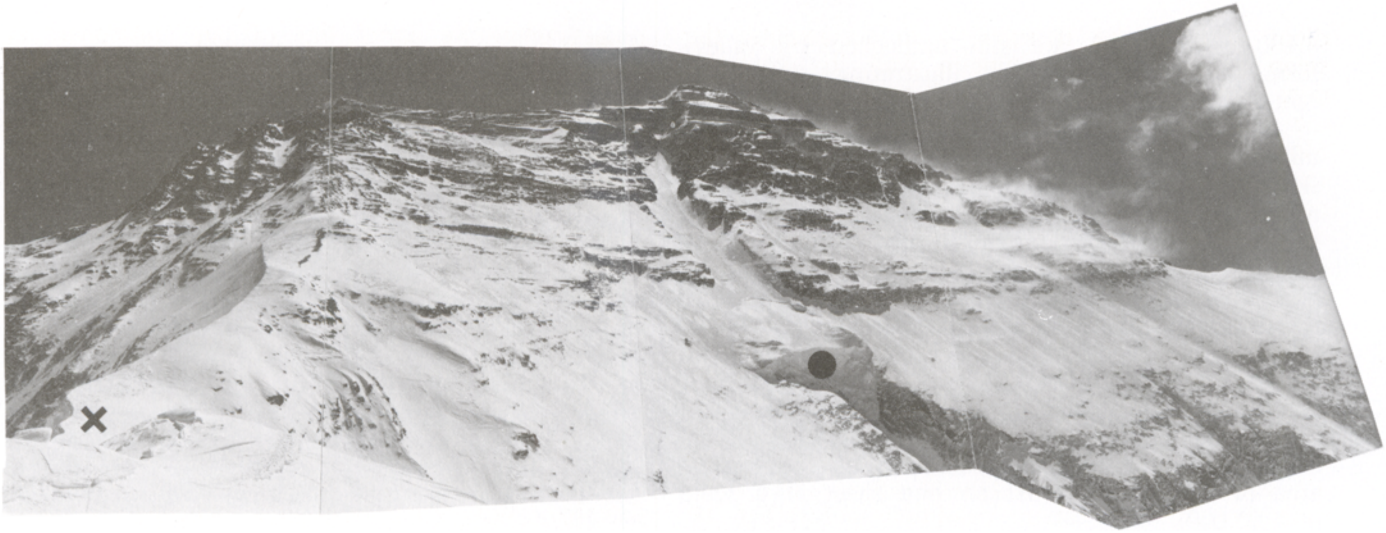


Fig 24
Mt. Everest - NNW Wall, seen from the SSE ridge of the Changtse from a height of about 7,100 m. The upper 1,700 m of the 35-45° steep flank of crystalline slates with quartzite strata and predominant chalk would offer sufficiently low gradients, and thus adequate friction not only for a glaciation of the wall but also for the formation of thicker hanging glaciers, but temperatures at altitudes of above 7200 m are in fact so low that the monsoon snow that falls in summer is super-cooled, i.e. dry and thus incapable of adhering. It is therefore completely blown off during the winter months. As early as the time of taking the photograph, that is 1 1/2 months after receiving the last falls of snow, the outcrops are free from snow. At the time the photograph was taken the process of deflation is lifting snow off the rocks on the W ridge on the right. It follows that the upper limit of glaciation is reached at about 7,200 m, i.e. above this altitudinal line it is too cold for the transformation of snow to ice by temperature metamorphosis, which is normal in the lower glacier regions. Only in stable lee-conditions, where permanent additions of snow through drifting enable tens of metres thick layers of snow to accumulate and thus pressure metamophosis as well as slow molecular diffusion to take place via sublimation, is it possible for glacier ice to form at greater altitudes. This applies, for instance, in the case of ice formation on the lower N spur of Mt. Everest (x) as well as to the ice balcony at 7,250-7,660 m in the Norton Gorge (•). During the Ice Age the upper limit of glaciation was, analogously to the equilibrium line, about 1,200 m lower than it is now.
Photograph taken looking S, 21.10.1984: M. Kuhle.

1. The highest peaks of the earth rise above the altitudinal level of glaciers, for the highest mountains of the Himalayas like Mt. Everest show an upper limit of glacier formation between 7,000 and 7,200 m asl. The author's measurements of surface temperatures - carried out with infra-red thermometres - prove it to be dependent on temperature. The author also observed the cover of firn and ice on 8,000 m peaks to peter out towards the top (Fig 24). That contradicts to the conventional view that glacier formation increases as temperatures decrease with increasing altitudes above sea-level, and that the glacier level is the highest level of the earth.

Two thousand measurements of surface temperatures on a number of mountain faces above 7,000 to 7,200 m show that it is too cold for the formation of glaciers - a result that seems at first sight absurd. It may be explained in the following way: in a correlation and regression analysis the statistical investigation of temperatures on mountain slope surfaces reveals their variations in accordance with height. When observed in sunshine between 11^{00} and 15^{00} the 0°C line never exceeds 7,400 m, and only seldom reaches 7,000 - 7,200 m (Kuhle 1986c). This statement is confirmed by a significant correlation coefficient (-0.835) with a probability of error of less than 1 in 1,000, and a 95 % probability for all future random sample measurements. The measurements establish a decrease in temperature of 1.45°C per 100 m of altitude. Precisely at 7,000 - 7,200 m the bare rock comes to the surface, i.e. the ice cover of the mountains stops (Fig 24). Thus there is an accordance of the upper glaciation limit and the 0°C line. In spite of full solar radiation during the warm season, temperatures of only -46°C to -28°C have been registered in the measurement sections leading up to the 8,800 m summit of Mt. Everest. At 7,000 - 7,200 m 0°C was reached only during a few sunny, calm minutes. The annual mean temperatures are, however, less than -10°C to -25°C here (2,000 m below on dark scree soils, temperatures already reach -15°C). According to observations made by Benson in Greenland (1961) and by Fritz Müller in Axel Heiberg (1962) a very slow settling and sintering, i.e. compression and transformation, is brought about at such temperatures by the formation of ice-bridges between grains of snow, which takes place solely by sublimation and molecular diffusion. This process takes about 20 to 33 times as long as the "normal temperature metamorphosis" near melting-point is estimated to take. This slow process of re-crystallization from freshly fallen snow to glacier ice with a density of 830 kg m^{-3} moreover requires overburden pressure. The necessary pressure is exerted by the burden of snow and firn, which may become 100 m thick in the course of perhaps 100 years. There must not be more than a slight gradient to the slope if snow is to accumulate; the steep gradient of a mountain wall, by contrast, does not allow such deposits, particularly so as the snow is cold and is thus unable to adhere. Moreover, the time necessary for this cold type of ice formation is not available, since the tearing pace of storm at these altitudes blows the cold, dry and therefore non-cohesive fresh snow like drifting sand from the peaks above 7,200 m within a matter of weeks.

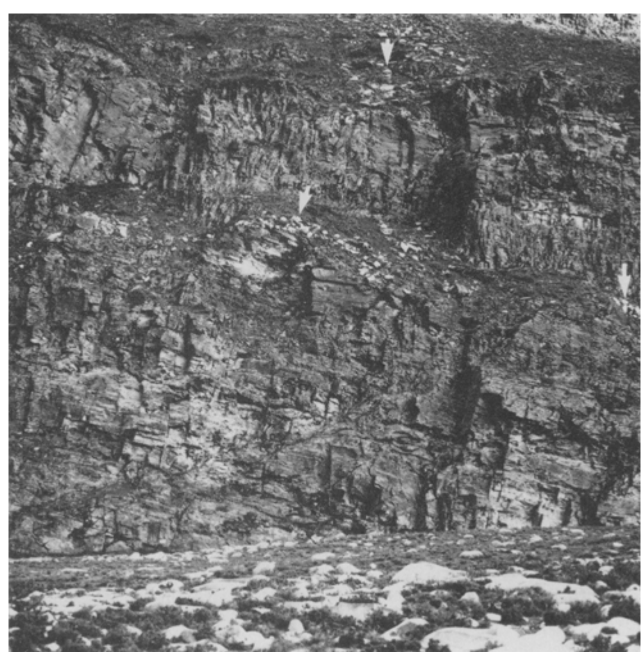
Neither steepness nor wind velocity are the primary causes of an upper glacier limit. This is borne out by the fact that mountains exposed to wind but less than 7,200 m high carry ice that is several metres thick on their steep walls; it covers the entire surface and ice balconies which are tens of metres thick appear up to their summits (Fig 24 X). Primary conditions are rather the very low temperatures, which do not allow the snow to cohere; aided by gravitation, they enable the wind to shift it within a year, so that never more than a thin layer remains. Not unlike those down in the valleys, the rocks up there are seasonally free from snow, though not in summer, but during the cold season, which is windy here and lacking in precipitation.

There is therefore a second, highest altitudinal level of rock and scree, the weathering of which does not, however, take place as congelifraction as is the case on the lower level of frost scree. That fracturing alternation from liquid to frozen water is absent there. On the other hand that highest level is characterized by a 'pergelide', a permanently frozen environment. Weathering consequently is purely an effect of temperature on the negative spectrum, which breaks up rock without any humidity, but merely through differences in the expansion of the minerals. Thus conditions exist on a few of the earth's high peaks as can probably be assumed for large areas of Mars, for example.

This peculiar reflective symmetry of a glacial zone, which peters out above and below the equilibrium line presents exceptions above 7,200 m in places where shallow niches in the rock wall are continuously supplied with drifting snow by the wind. Here in a stable leeward situation, compaction through pressure and re-crystallization can transform permanent deposits of snow and firn into small hanging glaciers and ice-balconies even at the highest altitudes (Fig 24 •). Restricted to specific locations, these occurrences do not, however, constitute a modification of the conformity (with natural law) sketched-out above.

2. The values of solar radiation which were registered at altitudes between 5,000 and 6,650 m appeared to be of fundamental importance. In spite of the advanced season they reached 1,000 to 1,200 watts per sq. metre on cloudless days (Fig 22). In theory on September 21st - at the time of the average position of the sun during the expedition - a maximum of 1,180 watts per square metre impinges upon the upper line of our atmosphere at this latitude of 30°N. This comparative value demonstrates that the recorded radiation intensities are approximately equal to the solar constants. Global radiation being dependent on the angle of radiation, it is three times as great in the sub-tropical areas of Tibet as in the higher latitudes of, for instance 60° to 70°. This can be gathered from Bernhardt and Philipps' (1958) interpolated radiation maps, and has also been suggested by the measurements carried out in the field. Thanks to the permeability of the thin mountain air however, the radiation favourableness of Tibet exceeds even that. This is the reason why energy inputs are four times as large as at altitudes 3,000 to 5,000 m lower in Scandinavia, like those where the N European inland ice lay during the Ice Age. Reflection and outgoing radiation measured in the glacier basins above the equilibrium line were about 76 to 95 % of the radiation

Fig 25
Erratic granites on basaltic bed rocks in S Tibet (28°50'N/87°20'E; Tibetan Himalayas). The Lulu Valley is set in bed rock basalts. Between 4,400 and 4,950 m asl the floor of this valley is covered by ground- and lateral moraines containing numerous blocks (foreground). The largest ones of the light coloured granite measure up to 4.3 x 2.6 x 2.2 m and have well-rounded edges. The blocks are isolated from each other by a loamy material. Erratic blocks of granite were found on the sills of valley flanks up to at least 250 m above the bottom of the valley (the light-coloured, rounded blocks on dark basaltic rock ⇩⇩). The basalt is hydrothermally decomposed; the x-ray diagram shows pseudomorphotic substitution of the pyroxenes by chlorite and dolomite. The two varieties of granite which occur here differ in their respective proportion of mica and also in the fact that biotite granite contains K-feldspar. The erratic material must have been transported by a big ice stream over distances of tens of kilometres from the highland region of Latze (Latzu), as acid plutonic rock does not occur here in the effusion area of basalt.
Photograph by M. Kuhle at 4,950 m asl; 31.8.1986.



quoted above. These rates apply approximately to all areas of firn and snow on the earth (Fig 23). On the other hand, Tibet's scree and rock surface without its glacier covering attains an albedo and outward radiation of about 20 % (Fig 23). It follows that during the Ice Age up to three quarters of the four-times greater radiation - as compared with lowland areas much further north - were reflected back into space. They were lost to the earth's heat economy as a result of Tibet's high glacial ice cover.

3. In the area under investigation during the 1984 expedition (28°-29°50'N/85°24'-91°13'E) the author defined a mean equilibrium line altitude of 5,900 m on the present glaciers of Mt. Everest, Shisha Pangma and the mountain groups of the Tibetan Himalayas and the Transhimalayas (Kuhle 1985a). This was done by going over the glaciers and by observing the uppermost scree particles as they were released by the thawing ice. For the definition of the high glacial equilibrium line the lowest sites of terminal moraines were registered. The reconstruction is based on the fact that the equilibrium line, as has been mentioned earlier, runs half-way between the crest frame of the glaciers' feeding area and the lowest end of the glacier. On the other hand there is the possibility of halving the altitudinal difference between the Ice Age site of the terminal moraine and its present one

$$(ELA_{Depr.} = \frac{t_p - t_i}{2} \text{ m asl})$$

in order to establish the equilibrium line depression and thus define the former level of the equilibrium line above it

$$(ELA_i = ELA_p - ELA_{Depr.} \text{ m asl}).$$

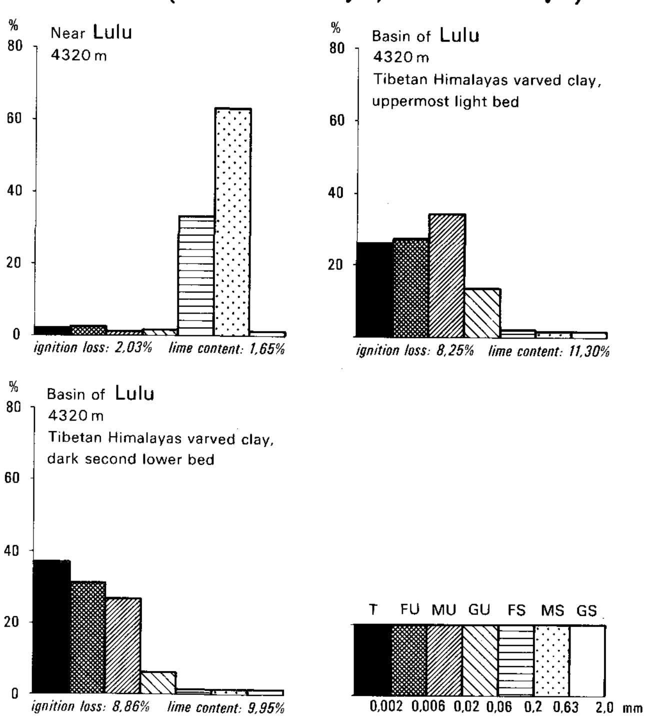
At present there are numerous small individual glaciers in the S Tibetan area under investigation in 1984, where these were merely eight glacier ends at the time of the high glacial period for which there is evidence in the form of moraines and other appropriate indicators. The reason is that the very extensive, compact ice complexes sent but few outlet glacier tongues down to the lowest valley regions. Such valleys occur more frequently in the marginal areas of the plateau in the investigation areas 1-3, which fall away to the plain (Fig 13).

There is evidence of the deepest glacier traces in the Tsangpo area with its tributary valleys in a S parallel valley in the Lulu Basin (Fig 25 and 26) and in the Bote Chu (Sun-Kosi) a Himalaya-transverse valley E of the Shisha Pangma massif, to name only a few examples. These data provided a basis for calculating the altitude of the high glacial equilibrium line to have been at 4720 m, thereby implying a depression of about 1180 m as compared with the present level of the equilibrium line (Kuhle 1985b).

The course of the equilibrium line is coupled to temperature; rather to the temperature of the warmest month (Kuhn 1981) than to the annual mean temperature, so that the Ice Age lowering of the summer temperature can be derived from its depression. Assuming a change in temperature of 0.6 to 0.8°C per 100 m of altitudinal difference, it amounted to 7.1 to 9.4°C in S Tibet (0.6 x 11.8 (1180 m) - 0.8 x 11.8). The equilibrium line depression which was recorded in the central area under investigation in south Tibet (Fig 13, No. 4) fits into the context of investigations carried out since 1976. It confirms the Ice Age depression values of 1,110 to a maximum of 1,430 m for NE Tibet (Kuhle 1982b; 1983d) (Fig 13, No. 2; Fig 12) and between a mimum of 1,150 and 1,530 m in the W High and Tibetan Central Himalayas (Fig 13, No. 1; Fig 8, 7 and 17) as well as the S slope of Mt. Everest (Fig 13, No. 3; 18 and 19) (Heuberger 1974; Kuhle 1979/80; 1982a; 1982c; 1983a).

Field work carried out over the past ten years thus led to the emergence of the following overall picture of glaciation in High Asia during the Ice Age: at the time of the last Ice Age the equilibrium line dropped below Tibet's mean plateau altitude of about 5,000 m asl by falling to 3,770 in the N, to 4,720 m in the central and S areas, and to below 4,000 m on the S slope of the Himalayan main crest (Fig 27). The cogent result was the build-up of a large sheet of inland ice, extending over 2.0 to 2.4 million km² (Fig 27), which must accordingly have been larger than the present Greenland ice (1.7 million km²; in contrast

Fig 26
Glaciofluviatile sands (above left hand); rhythmite (above right and below left hand) which shows characteristic attributes of varves (above summer layer, below winter layer).



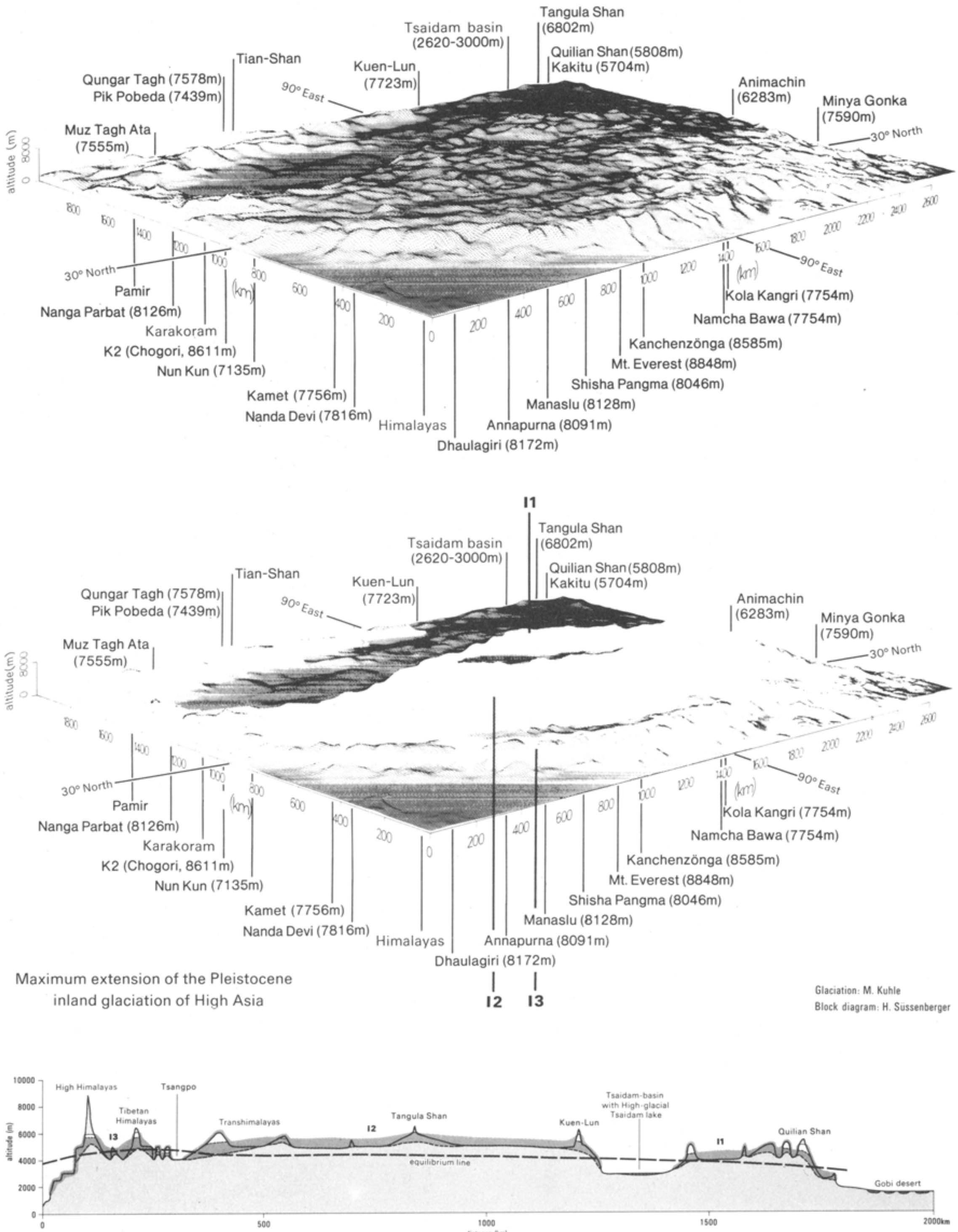


Fig 27
above: Tibetan highland and bordering mountain chains under presentday conditions without glaciation (exaggeration 15-times).

middle: the 2-2.4 mill. km^2 inland ice (ice sheet) on the Tibetan highland with its centres I1, I2, I3. Only peaks reaching more than 6,000 to 6,500 m project above the glacier surface (exaggeration 15-times).

below: the cross section of Tibet from SW to NE shows the ice sheet with its centres I3, I2, I1 attaining thicknesses of at least 700 to 1,200 m and up to 1,600 m in the valleys (exaggeration 30-times). Mountain slopes above 6,000 to 6,500 m remained unglaciated. I3 and I1 partly were of the ice stream system type. To some extent the Tsangpo valley and the Tsaidam-basin remained unglaciated.

the "climap"-group, [coordination: A. McIntyre; ed.: R. Cline 1981] assumed only a very slight glaciation of High Asia during the last Ice Age). Its compact ice cover attained a thickness of at least 700 to 1,200 m - probably considerably more, however. In some Himalayan valleys, which served as run-offs for outlet glaciers, it was up to 1,600 m.

In the central plateau region, for instance in the Transhimalayas and in the Tibetan Himalayas, too, the author was able to prove these minimum thicknesses in the light of erratic moraine blocks. They were found on top of other types of rock on slopes up to 1,200 m above the valley bottoms, and had thus to be diagnosed as substratum that had been transported by the glacier over some distance (Fig 28, 29, 30). The former glacial level is revealed by knick-points too, along with glaciated surfaces and grooves.

The inland ice consisted of three complexes: I1, I2 and I3 (Fig 27). The I1 centre was in the Kakitu Mountains at 38°N. It was separated from I2, the largest ice complex, by the glacial Tsaidam lake (for analysis of lake sediments: Hövermann 1982) (Fig 27). The centre of I2 was in the Tangula Shan, a mountain range at 33°N, which rises from the Tibetan basal area of 5,000 to 5,500 m to 6,500 m. The dividing line to the most southerly glacial unit I3 of the ice stream system follows the Tsangpo depression from E to W (Kuhle 1982a; 1983a; 1985a; 1985b). Ice stream systems are glacier areas which are broken up by peaks and ridges, but alternate with a totally covering inland ice wherever high mountains give way to flat plateau relief. Such mountain ranges, like the Kuen-Lun and Quilian Shan in the N, or the Tibetan and High Himalayas in the S increasingly channelled the ice run-off towards the edge of the highland (Fig 27: cross-section of Tibet).

Reconstructions of the lowest sites of ice margins in the Tsangpo area (Fig 13, No. 4), on the boundary of I2 and I3 led to the conclusion that the outlet glacier tongues of the large ice fields of the Transhimalayas in the N and of the Tibetan Himalayas in the S just missed reaching the Tsangpo Valley bottom at 3,800 - 4,000 m asl. One will therefore have to imagine a 'river oasis' between the two ice regions, which was crossed by meltwaters, where the remnants of the pre-Ice Age flora had retreated as in a refuge centre. According to the established lowerings of the equilibrium line, contact between the two ice systems I2 and I3 probably only existed W of 85° to 84° E lat., where the upper course of the valley bottom exceeds 4,300 m.

How conclusive and cogent the inference of covering inland ice sheets and ice stream systems is, which resulted from the reconstructions of equilibrium line depressions, is demonstrated by a comparative glance at the Alps: the lowering of the equilibrium line in the W Alps to about 2,000 m during the Ice Age (A. Penck 1901) has led to the complete glacier in-filling of the valleys there. That applies to valleys the bottoms of which were but a few hundred metres above sea-level, and thus 1,600 m lower than the equilibrium line - as, for instance, in the case of the vast Rhone valley. The lowest valley bottoms of Central

Fig 28
Granite erratics (○○○) on the 5300 m-high Chalamba La (a pass in the Transhimalaya at 29°41'N/90°12'E). The large, rounded and light-coloured granite blocks occur on the slopes (dark rhyolitic rock) up to about 200 m above the pass depression. The mineral compositions of the acidic rocks concerned are to be found in Figs 29 and 30. These findings of erratics prove a prehistoric glaciation of the Himalayas with an ice stream network the surface levels of which covered watersheds at 5,500 m asl at the lowest, and attained thicknesses of at least 1,200 m in the valleys.
Photograph: M. Kuhle, 24.8.1984. 5,350 m asl, facing W.

Tibet whose glaciation has been reconstructed are, on the other hand, only 300 to 500 m, and at most 800 m, lower than the equilibrium line at the time of the Ice Age. This discrepancy of one third to one half the depth of the infilled Alpine valleys underlines the problem-free built-up of a compact Tibetan inland ice. This considerable difference in the infilled valley depth below the equilibrium line may even compensate for the greater aridity in Tibet during the Ice Age by comparison with the Alps.

To sum up: it is evident from these new research findings that High Tibet from the Gobi Desert in the N to the S slope of the High Himalayas was much more heavily glaciated during the high glacial stage than v. Wissmann and, following this tradition, the geomorphologists Shi Ya-feng and Wang Jing-tai (1979) and others (Climap Projekt; Cline, R. 1981) sketched out. Even in 1982 Flohn still speaks of merely a 20 to 30 % glacier area.

Climatological Consequences and an Ice Age Hypothesis

In terms of geological ages, the ice ages were just short-term climatic deteriorations. They occurred during the past one or two million years. Thus long-term development factors are eliminated as primary causes. The location of continents on a pole, for instance, cannot have played a causative role, for the Antarctic had already taken up its position many millions of years ago and maintained it throughout the intermediate warm ages of the past millenia. This does not call into question the cooling effect of the inland ice, which can only accumulate on a continent that is situated on a pole, but its causative influence on the recent ice ages is out of the question.

Some authors (cf. Schwarzbach 1974; Imbrie and Berger 1984) regard the reduction in primary radiation from the sun and the radiation graphs in Milankovic's sense (1941) as an inducement for the necessarily short-term drop in temperature. One case is a matter of a deterioration of the energy efficiency of the sun or of the energy-absorbing effect of cosmic or volcanic dust, and the other a matter of cyclic variations in the geometry of the earth's orbit and in the tilt of the earth's axis, changes which enhance one another in their effects. The proof of Milankovic's theory depends on the precise determination of the time of the maximum extensions of glaciers and on the problem of their synchronicity with the phases of diminished energy input. But even proven temporal synchronization remains dubious, since all the necessary amplification factors can have induced a glaciation only after a time-lag of little-known extent.

Whatever the causes, there is nonetheless agreement that such a planetary drop in temperature reached 3° to 4°C at the most. A fully grown ice age with a reconstructed impact throughout the world, would require a drop of about 7-11°, and thus a self-induced amplification process. The so-called autocyclic hypotheses, which try hard to find positive feedback mechanisms of that kind are summarized by Schwarzbach: "An automatically proceeding cyclical process appears to be the most obvious explanation for repeated climatic changes in the Quaternary. But the autocycle hypotheses developed so far fail to satisfy" (1974, p. 312; see also Liedtke 1986, p. 412).

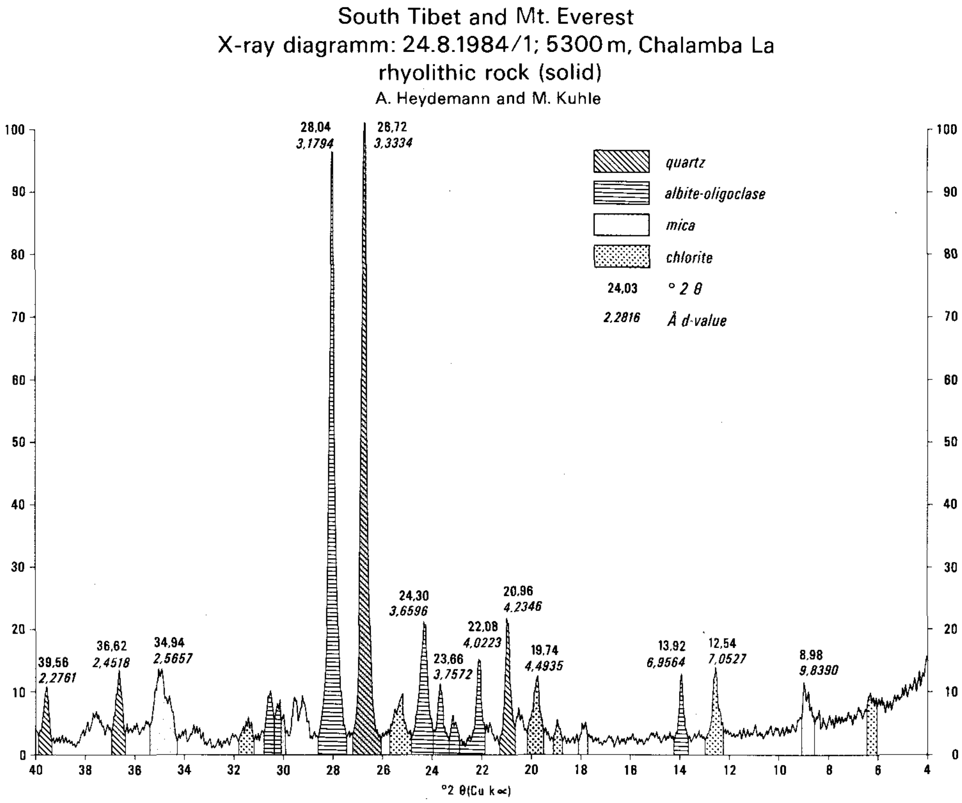
The new findings from High Asia, which form the basis of a reconstruction of a Tibetan inland ice (Kuhle 1985b) offer a more satisfactory autocycle hypothesis for the Ice Age. It is based on three factors:

1. the extreme altitude of the vast 2-2.4 million km^2 Tibetan plateau and its system of mountain ranges near the equilibrium line,
2. the sub-tropical latitude together with an extreme radiation transparency of the atmosphere at a high altitude with about 3 to 4 times the radiation of higher latitudes like Scandinavia or Greenland,
3. a reflection and outward radiation on snow, firn and firn ice of 76 to 95 %, in contrast to a value of 20 % in the case of surfaces of rock and scree (see above).

An initial drop in temperature of perhaps 3 to 4°C, caused by a reduction in primary solar radiation or a change in radiation conditions, resulted in a lowering of the equilibrium line by 500 m (3.5°C drop in temperature where the gradient is 0.7°C per 100 m = 500 m). That implies that the glaciers then reached down 1,000 m further than now (see above). Conditioned by the relief, a change took place within this altitudinal span of 1,000 m; in this glaciers, which flow from steep mountain slopes and are there of moderate extent, such as can also now be found again, became piedmont glaciers which did not lose much in height but spread widely across the Tibetan plateau. The enlargement of the glacier area per metre of descent is greatest below the angle of the foot of the mountain slopes with the Tibetan plateau (Fig 14). This accounts for the causative qualitative jump under conditions of a continuous glacier descent. The firn and snow fields of the feeding grounds experienced a considerable areal expansion. On the one hand they made a 500 m descent from the mountains down to the flat areas, and in addition a damming-back which had the effect of a rise of the ice surface set in together with a levelling of the upper courses of the glaciers.

It is the author's opinion that, increasingly raised by the 'sub-tropical latitude factor' and the "... massive elevation of the huge Tibetan highland, which increases the temperature of the free atmosphere in summer more than in any other place on earth (as Flohn wrote in 1959, p. 323), the enormous increase in glacier areas becomes the trigger of further drops in temperature. Now some

Fig 29



of the Tibetan areas of scree and rock, which had returned only 20 % of the radiation energy and provided most of it for the warming up of the atmosphere, became coated by ice and firn. Suddenly they had changed from being a heating area to acting as a cooling area, which returned up to 95 % of the energy. The difference of approximately 75 % was reflected completely into space because - by comparison with atmosphere in low altitudes - extreme radiation transparency began to be effective again in matters of reflection and outward radiation as well as insolation. Having passed off in this way, the effect of positive feedback was comparatively rapid because the suddenly increased percentage of outward radiation concerned the 3 to 4-fold radiation in higher latitudes. In Tibet this process was to build up a 2.0 to 2.4 million km^2 area of inland ice which caused the same heat loss of the earth as a low-lying N or S inland ice of at least 6, and more likely of 9.6, million km^2 - i.e. half to three-quarters of the dimensions of the Antarctic - can cause in the vicinity of the poles. The Scandinavian inland ice of the Ice Age that reached as far as NW Germany was at best twice as large as the Tibetan area, which implies that the Tibetan ice must have had a disproportionately greater cooling effect around twice the size.

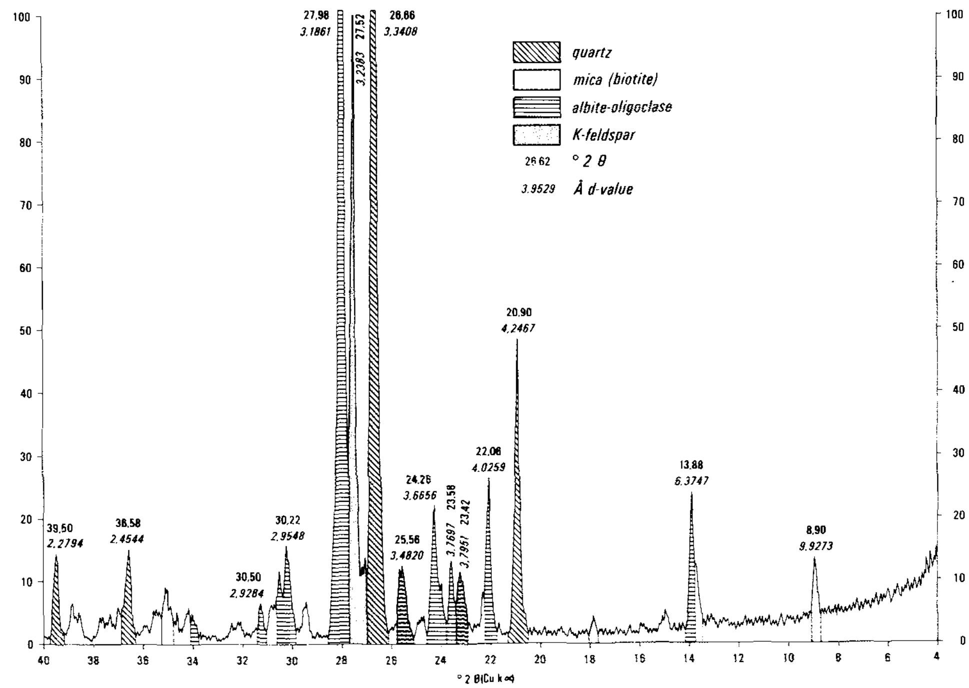
This touches upon an important point, and the difference between amplification influence and trigger potential is to be illustrated by the following example. Even when assuming an equal increase in glacier area in the Scandinavian mountains and their forelands, the resulting drop in temperature would only be increased by about a quarter of the radiation that is available in High Tibet for reflection and outward-radiation as the cause of an ice age. The potential for causing an ice age is consequently four times greater in Tibet. Ushered in by an increase in glacier area, the drop in temperature due to increased outward-radiation resulted in a further lowering of the equilibrium line, increase in the glacier area etc. etc. until the build-up of ice found its limit at 2-2.4 million km^2, thanks to the extent of the highland and its mountain ranges. Another superimposed effect of amplification and build-up of ice was brought about by the accumulation of snow, firn and ice which raised the inland ice surface to a shallow dome. The decrease in temperature as a result of greater height increased the annual mean supply of solid precipitation - snow precipitation - that is, the glacier feeding area from the centre to the periphery of the inland ice.

The entire system kept expanding until the outlet glaciers of the inland ice flowed through the mountain fringe of the highland into the lower altitudes of intensive melting and balanced the central supply of snow.

Besides the amplifying factors the author claims a stabilizing effect for the build-up of inland ice in High Tibet, to which Shumskii (1964, p. 408) had already drawn attention in general

Fig 30

South Tibet and Mt. Everest
X-ray diagramm: 24.8.1984/2; 5300 m, Chalamba La
Erratic clast: Granite (tectonometamorphic)
A. Heydemann and M. Kuhle



terms. Warm advective air masses, i.e. those which pass horizontally over such ice masses and could be of greater significance in sub-tropical than in cooler latitudes, only affect the fringes without consuming much glacier ice. Even the rather minor processes of melting and evaporation they produce cause them great heat-loss, so that they, having cooled down to 0°C over a short distance, do not do any harm to the ice. The larger the plateau ice dome is, the more this proportionally applies.

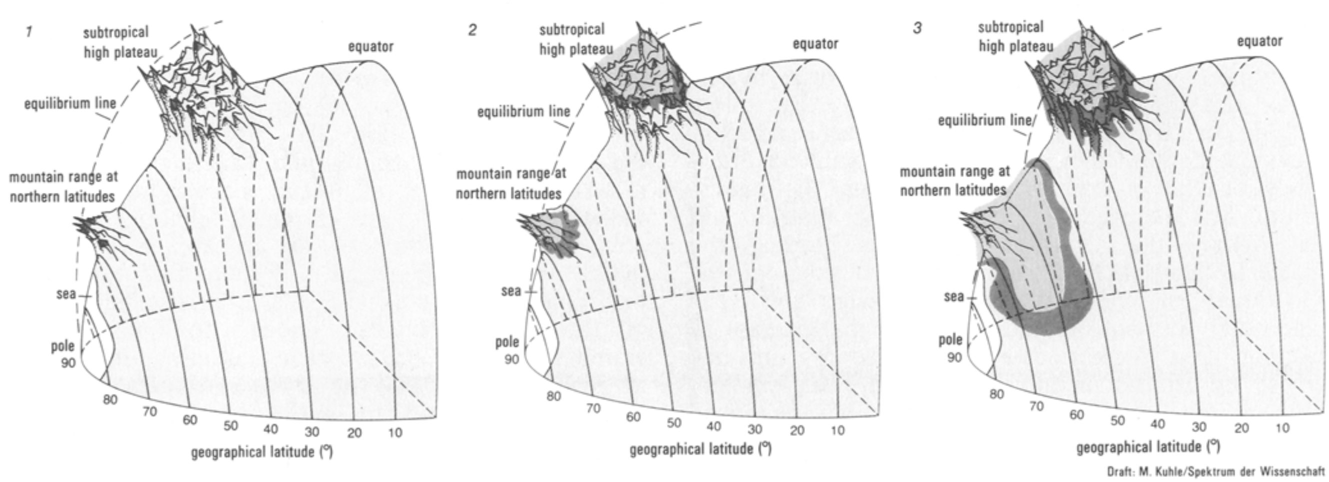
Established through research in the Himalayas during the past decade and presented above, findings concerning the climatic upper glacier limit (Kuhle 1985b; 1986c) add another aspect to the overall picture of this sub-tropical inland ice. In the first phase of the build-up of the Tibetan ice the glaciation, together with a descending equilibrium line, proceeded from the high mountains. Hanging and valley glaciers, like those still in existence today, flowed further and further down until they reached the mountain forelands or the plateau areas. But when the equilibrium line reached the level of the plateau and fell below, the significant share in feeding the glaciers changed from the mountain sides to the flat areas of the forelands. However, this displacement was not only advanced by the increase in feeding area further down, but also by its decrease up in the mountains. As had been demonstrated, the present upper glacier limit is linked with the 0°C line at an altitude of 7,000 to 7,200 m. The temperature-related lowering of the equilibrium line must have been accompanied by a lowering of the upper glacier limit by a corresponding 1,200 m to about 6,000 m. This height was within the domain of the ice dome surface so that an inland ice and ice stream system must be envisaged, which was not overtowered by glacier-clad slopes and walls, but at best by seasonally snow-covered, though otherwise dry rocky summits (Fig 27: cross-section of Tibet). In contrast to the formation of ice-marginal ramps (see above) imagination is aided here by the principle of uniformitarianism. Comparable conditions exist now in the 5,139 m-high Vinson massif at about 80°S (recrystallization zone acc. to Shumskii 1964, p. 409). As can be recognized in aerial photographs taken by the Geological Survey in 1959, bare unglaciated rock walls rise there above the Antarctic inland ice from about 3,600 m asl.

To sum up so far: the chance location of the Tibetan plateau within the altitudinal scope of the Early Ice Age equilibrium line depressions led to a complete cover of inland ice and thus to the sudden change from an extremely effective heating area of the atmosphere to an area of cooling (Kuhle 1985b). The result, in simplified terms, is the following hypothesis: the considerable extent of the Tibetan plateau under conditions of an extreme radiation transparency of the atmosphere at high altitudes and at the sub-tropical latitude made the highland to initiate a probably global feedback reaction of temperature decline which influenced the other glaciation areas of the earth and thus became the true trigger of the Ice Age. But that would be too crude to make my approach plausible, and the term "global feedback reaction" requires explanation.

Tibet Initiated a Global Temperature Decline - other Mountain Ranges with Forelands Reacted to it and Amplified it in Turn (Fig 31)

Presented for the case of Tibet and its mountain ranges, the principle of the enormous increase in glacier areas through the lowering of the equilibrium line, which allows ice streams to advance as far as the flat areas of the mountain forelands, applies to all mountain areas on earth. That was also the reason for the North European inland ice to establish itself from the direction of the Scandinavian mountains. Today, to quote one example, the equilibrium line runs in the S of the Skandinavian mountains, in Jotunheimen, at an altitude of 2,100 m, and the flat valley bottoms and foreland areas lie at 900 to 700 m, even lower, so that the lowering of the equilibrium line must be 700 m before larger areas are overwhelmed by ice. Similar conditions prevail in the Sarek area in the N, where the equilibrium line runs at about 1,400 m and the mountain forelands begin only at about 300 m asl. To attain such lowering of the equilibrium line there must be a decrease in temperature of more than just 3.5°C which was sufficient in Tibet. What is necessary are at least 5°C. Thanks to its shorter distance to the level of the initial equilibrium line, substantially larger glacier areas would at the same time have already existed on the Tibetan plateau than would have been able to begin their build-up in Scandinavia now, even if an initial drop in temperature by this amount had been caused by primary planetary factors.

Fig 31
Strongly schematized presentation of the principle of the relief-related origin and termination of ice ages. The causative intensification of the cooling-down process emanates from a subtropical high plateau (such as the Tibetan High Plateau) due to the fact that the initial lowering of the equilibrium line by c. 500 m leads to the glaciers descend by 1,000 m from the mountains, thus suddenly glaciating large plateau areas (Step 1 to 2). Mountain chains at higher latitudes experience the same amount of equilibrium line lowering as a result of the cooling-down by 3.5°C during that change in the parameters of the earth's orbit. But, since the altitudinal distance of the present glaciation to the height of the foreland areas is too great, glaciation has as yet had little effect on area and thus on reflection (2). As the subtropical high plateau has undergone large-scale glaciation and the transformation of a formerly very effective "heating panel" into an area of reflection, the further cooling down of the atmosphere caused in this way leads to a renewed lowering of the equilibrium line. The consequence is a chain reaction-like, worldwide enlargement of glacier areas. This particularly advanced very fast in all those places where the lowering of the glaciation line reaches the flat mountain forelands (Step 2 to 3). The sequence of additions of mountain foreland glaciations depends on the particular altitudinal distance of pre-Ice Age hanging glacier ends from the altitudinal level of the foreland. Although, due to the conditions of radiation, the cooling effect per glacier area is greatest in the sub-tropics, the areal gain of glaciers increases significantly with the decreasing equilibrium line at higher latitudes (3). The reason for this is the fact that the equilibrium line dips towards the polar regions, and that starting point of equilibrium line heights comes progressively lower towards the lowlands. In the end the ice areas of the high latitudes outnumber those of subtropical high plateaux and mountains by approximately 12:1, by which time their cooling effect has increased around threefold.
Nonetheless, such far-reaching glaciation would not have occurred without the impact of the subtropical inland ice. The cooling, which reacts upon the subtropical plateau ice as well can hardly result in any further increase of the area of ice there because the glaciers cannot reach the lowlands when flowing over the edge of the plateau (Step 2 to 3). In a reverse process (3⟶1) the end of the Ice Age begins in the N and S lowland plains: on the return to normal values of solar radiation and a rise in temperatures by those initial 3.5°C the corresponding rise in the equilibrium line by 500 m and the rise in the glacier ends thus by 1,000 m becomes particularly effective for areas of flat lowland glaciation (Step 3 to 2). Whilst lowland ice areas experience extreme reductions, thus forcing a global warming-up, the surface areas of the subtropical highland ice will remain almost constant, because only the steeply descending outlet of glacier tongues on the margins will become shorter on the initial upward move of the equilibrium line, whereas the reduction in glaciation is far from reaching the flat plateau ice proper (Step 3 to 2). Only when the further warming-up of the earth has been initiated and progressed through the disappearance of lowland ice, will the subtropical highland areas also be freed from ice (Step 2 to 1).
Design: Spektrum der Wissenschaft / M. Kuhle 1986



But it is not only the shorter equilibrium line distance of the Tibetan expanses that accords them priority as a trigger of ice ages over Scandinavia and its forelands, but above all the highland is affected by a radiation that is four times greater (see above). Similar ice age performances have only taken place in other sub-tropical highlands and mountain areas such as the Altiplano in the Andes and its adjoining areas, though to a much smaller extent than in Tibet and its mountains, which is the largest sub-tropical highland on earth. In the extreme S of the Andes, in Patagonia, conditions during the Ice Age were again similar to those in Scandinavia or in the N outliers of the North American Rocky Mountains in Yukon and Alaska. The foreland ice did not reflect 75 % of sub-tropical radiation energies here, but comparatively less.

At this point at the latest the statement which introduced the distinction between the ice age potential for amplification and triggering the development process of a coming ice age becomes clear. The greatest possible amplification of an initial drop in temperature and lowering of the equilibrium line requires one or more sub-tropical highland and mountain areas. There are other N and S foreland regions and areal expanses which achieved an increase in glacier area with an initial drop in temperature by 3.5°C, which in turn furthered the cooling process through reflection and outward radiation; but at first it remained proportionately small, comparatively speaking. Only when the global drop in temperature reached 5°C as a result of the energy loss caused by Tibet's and corresponding sub-tropical glacier areas did the Scandinavian and other ice areas expand. The worldwide increase in glaciers which emanated from the mountain areas as its "crystallization cores" overtook the Tibetan area and, through its own volume, contributed increasingly to the intensification of the cooling process. This in turn affected Tibet itself and let the Tibetan ice grow gradually to the limits of the highland base. In the end in spite of their multiplier effect the global cooling influence of the remaining 41 million km^2 Ice Age glacier areas of the earth considerably - about 3-fold - outpaced the influence of Tibet and other sub-tropical glacier areas by way of energy reflection and outward radiation, but that did not diminish their pre-eminent 'triggering' function.

We must therefore imagine a chain reaction of the cooling process, emanating from a 2 to 2.4 million km^2 Tibet and other highlands and mountain areas of the earth that are favoured by radiation - altogether covering about 3.5 million km^2 - took effect world-wide in mountains and mountain forelands by way of intensified depressions of equilibrium lines, and finally led to the formation of large inland ice masses even in low-lying countries.

It can easily be calculated from the altitudinal difference of their present equilibrium line or glacier ends to their forelands in which sequence the mountain ranges and their forelands were included in this cooling process.

Step by step the glaciation descended from the mountains and highlands and received its strongest impulses in the sub-tropics, especially in Tibet. A question which follows on from this ice age hypothesis is: were there noticeably sub-tropical mountain range formations at other glaciation periods of the earth's history, such as in the Permo-Carboniferous?

Reduction of the Ice towards the End of the Ice Age

Though these arguments have drawn particular attention to the build-up of ice on earth, they must not lose sight of the fact of its reduction during the late glacial stage. This model therefore includes that angle as well. In this the world-wide reduction of glaciers is to be presented as a kind of processive reflex symmetry, which was not started by the sub-tropical highlands but by the disappearance of the vast nordic lowland areas of ice. The impetus was given by the retrogression of the initial drop in temperature by those 3.5°C. Thus the pre-Ice Age radiation conditions were re-established together with a rise in the equilibrium line by those initial 500 m.

That this reverse process was influenced by the dwindling of the Tibetan ice in a subordinate and not a forcibly intensifying way once again has its cause in the relationship between steep and flat relief - entirely in conformity with the constitutive mechanism of amplification previously put forward. To recapitulate: the Tibetan ice had built up as far as the fringes of the plateau and the lowest moraines of its outlet glaciers had been deposited in the steeply descending valleys of the escarpments as far down as 2,300 m on the N fringe and 1,100 m on the S fringe. This explains why a 500 m rise in the equilibrium line can have shortened the outlet glacier tongues, but not reduced the area of plateau ice actually. A rise in the equilibrium line by 500 m only made the outlet glacier ends recede in an upward direction by 1,000 m, being narrow valley glacier tongues with little surface area, but nonetheless they still remained below the mean altitude of the Tibetan plateau. The initial rise in the equilibrium line was accordingly checked by the marginal escarpment of the highland with only a small loss of area.

This did not apply to the glaciated lowlands. They lacked a barrier in the form of a peripheral escarpment and the smallest rise in temperature, or in the equilibrium line was immediately transformed into a huge loss of area. This areal loss of the North European, North American and Siberian inland ice by far outstripped the effect of the small areal loss of the Tibetan inland ice.

In order to present in a few sentences the principle of this relief-specific autocyclic hypothesis for the genesis of the Ice Age, this self-intensifying, accumulating and then self-reducing, diminishing development it could be summarised as follows:

The steep relief hinders the accumulation of ice as well as its reduction, since it does not allow the shift in the level of the equilibrium line to become effective for the area in either direction. The flat relief on the other hand forces both of them, since both the feeding of the glaciers and the process of its melting off become most effective in it. A cooling impulse as well as a heating impulse therefore acts upon the flat highland and the flat lowland. Favourable to radiation, the spatial limits of the highlands as contrasted by unlimited lowlands which are less favoured by radiation, take precedence for the triggering of an ice age, whereas the recession of glaciers, the end of an ice age, begins in the lowlands.

The Ice Age descended from the sub-tropical highlands, and the change for warmer temperatures proceeded from the glaciated lowlands.

Footnotes

1) The expedition was financed by the German Research Society (Deutsche Forschungsgemeinschaft)

2) These two research trips were financed by Göttingen University

3) The effect of subglacial meltwater run-off and the existence of V-profile valleys in glaciated landscapes was described earlier by Tietze 1958, 1961 and 1973

4) The two Himalayan and South Tibet expeditions were financed by the German Research Society (DFG)

5) The same applies to plate tectonics: the parallel coastal outlines of South America and Africa shown on a world map inspired Alfred Wegener's hypothesis of continental drift.

6) These were carried out by M.A. Geyh in the Soil Research Authority at Hannover, FR Germany (Landesamt für Bodenforschung).

7) Basic finance came from the German Research Society (DFG), the Academia Sinica, the Max-Planck Society and the University of Göttingen.

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