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Subtropical Mountain- and Highland-Glaciation as Ice Age Triggers and the Waning of the Glacial Periods in the Pleistocene*

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In the course of the past decade the author has been able to collate findings of deep morainic deposits in the circum-Tibetan mountains which prove that the largest highland region of the earth has been subject to more glaciation during the Ice Age than had previously been thought possible on account of its sub-tropical situation. It was, however, the very fact of the low latitude and the extreme height above sea-level of this former area of inland ice in Tibet that was able to initiate a global cooling process of significant proportions, considering the size of the area involved - according to the author's reflection and outward radiation measurements on present-day glaciers the extremely high insolation energy was reflected up to 95 %. This cooling process was then intensified by the successive growth of glaciers in other highland and mountain areas of the earth as a result of chain reactions. In the Tibetan inland ice the principle of a sub-tropical, and therefore high altitude, cooling surface has been realised; at the moment such plateau has emerged it is capable of turning minor planetary cooling into major glacial epochs. Tectonic uplifts of the crust followed by glaciation, which occurred in situations favourable to radiation, might have had the effect of repeated progressions of cooling in the course of earth history.

The reverse process of late- and post-glacial warming emanated from plains in high latitudes, where a slight rise in the equilibrium line leads to very considerable losses of glacier surfaces. Sub-tropical plateau ice by contrast - such as the ice of the Tibetan interior - is therefore initially difficult to shift since the tongues of its outlet glaciers hang steeply from the edge of the plateau, thus diminishing the efficiency of a rise in the equilibrium line of about 500 m caused by the initial rise in temperature. This applies to ice shields of high latitudes, the horizontal position of which extends to their margins. It follows that the auto-cycles hypothesis on the genesis and gradual disappearence of ice ages is determined by the relief, with processes of self-strengthening and self-weakening related to the fluctuation of the height of the equilibrium line within any one area of steep or flat relief.

The Equilibrium Line as an Essential Dimension of Definition

The extend of cover by Ice Age glaciers can be calculated by observing the distribution of terminal moraines and similar indicators of the positions of ice margins, such as deposits of gravels and ice-marginal ramps (ramp-like deposits of moraine material and washed-out as well as irregularly laid down debris; cf. Kuhle 1984a). Mountainous countries reveal that a larger expanse of ice also implies a lower position of the glacier-ends. The connection between the dropping of glacier tongues to lower positions and the lowering of the equilibrium line had already been discovered during the last century. The equilibrium line was found to follow the depression of the glacier terminus by about half the amount (v. Höfer, 1879). This opened the way to a palaeo-climatic interpretation of remote moraines which are deposited below present glacier termini. The great value of the equilibrium line is due to the fact that it is one of the few well-definable climatic altitudinal limits of the Ice Age. Its power of prediction is based on its course at about half the height of a glacier's vertical extent. It is a

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kind of dividing line between its accumulation and ablation area - with the feeding of the glacier by snow precipitation predominating above, whilst processes of melting and evaporation come to the fore below and cause the loss of ice down to the terminal glacier.

About 3,000 m high on Mount Blanc in the Alps, 2,500 m on Mount McKinley in Alaska, about 4,600 m on Aconcagua in the Andes (Kuhle 1984b) and even at almost 6,000 m on Mount Everest in the Himalayas (Kuhle 1985a; b) - to name but a few examples - the course of the equilibrium line does permit a world-wide comparison of glaciation favourability in which the climate, in radiation as well as temperature and precipitation in form of snow is manifested (Kuhn 1981; 1983). In this the constitutional importance of temperature for the equilibrium line presents itself through the rise of this altitudinal line from sea-level at the polar caps to about 6,000 m in the sub-tropics as on Mt. Everest, for instance. The additional influence of the amount of precipitation and the cloud-cover, which acts as a screen against radiation, is demonstrated by the slight drop of the equilibrium line from the hot-arid sub-tropics towards the humid equator (cf. Hermes 1965; Messerli 1967); in its vicinity few mountains above 5,000 m have glaciers like Mt. Kenya.

Based on contemporary findings, the reconstruction of the extent of glaciation during the Ice Age and the lowering of the ice margins looks for the lowering of the equilibrium line as an indicator of thermal conditions 20,000 to 40,000 years ago. Beyond this, however, the primary question concerning the transformation of the earth's surface through size and position of the Ice Age glacier area has by no means given up its significance, but acquires renewed and fruitful weight in differing ways which will be examined below.

The Previous State of Research into Glaciers and Ice Age, and the Controversy Concerning the Equilibrium line

In the first third of this century A. Penck and F. Machatschek (1944) held the view that the maximum depressions in the equilibrium line occurred in those mountain regions of the earth which had the most precipitation, such as the Alps, where a lowering of at least 1,200 m had been proved for the Ice Age (E. Brückner and A. Penck 1901-1909). The courses of equilibrium lines in arid areas are thought to have been only a few hundred metres lower than at present, thanks to too restricted an amount of snowfall. It has been suggested in this context that these had also formerly been semidesert like areas. Ice Age glaciation was regarded as correspondingly small and insignificant. The suggestive power of this view was effective and the impetus to a better insight which the continuous findings of lower terminal moraines might have given, was stopped in its tracks too early to be capable of saving Ice Age research from a diversion of half a century.

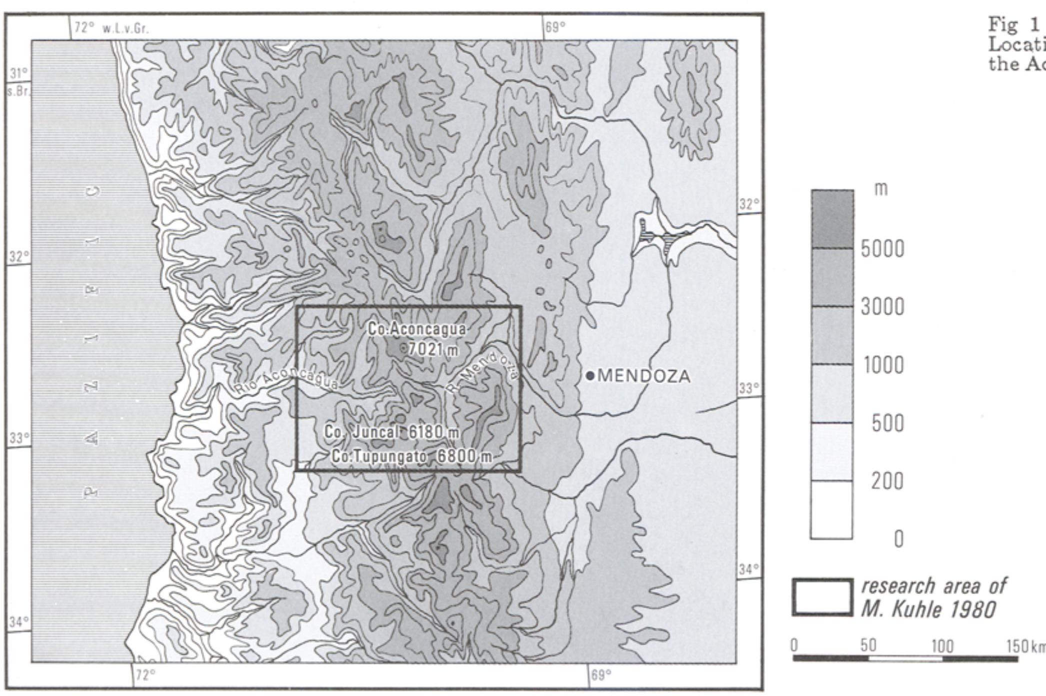


Fig 1
Location of the research area in the Aconcagua massif/Andes

The Aconcagua Group in the Andes

This applies to Tibet and Highland Asia, as well as to the equally sub-tropically arid Andes of the Aconcagua Group, which - situated between 32° and 33° S - attain altitudes of up to 7,000 m asl. In 1980 during the course of four months of investigations in the field[1] (Kuhle 1984b), the author found erratic blocks on the flanks of the large main valleys (Fig 2) of the E slope of this massif (Fig 1). They are evidence of Ice Age glacier thicknesses of at least 1,020 m. Down valley at only 1,870 m asl the corresponding end moraines (Fig 3) were located. In spite of all the present day aridity in this area, these findings, 2,800 m below and tens of kilometres away from the present terminal glaciers, are documents of an equilibrium line which was 1,400 m lower at the time of the Ice Age.

These conclusions are new in the case of the E side of the mountain range, but support those from the W side which Brüggen had published as early as 1929. Unfashionable at the time, they failed to attract a response for more than 43 years until their confirmation in 1972 by Caviedes, and this renewed support by the author a decade later, although both used different approaches. Authors of the intervening years like Salomon (1969) opted for rather lesser ice covers. The formation of valley glaciers extending over 100 or more km (Fig 4) in places where glaciers now rarely exceed lengths of 10 km, required a cooling by about 8.5°C in summer if the aridity persisted, or of 5°C if the summer precipitation areas adjacent to the S extended or shifted N by a mere 50-100 km.

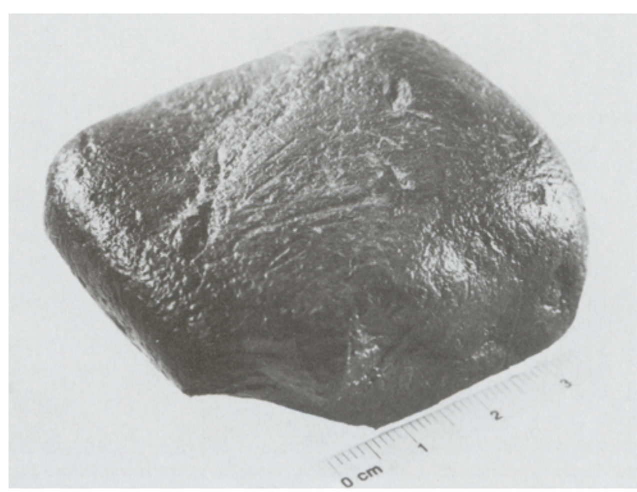
The Zagros Mountains in Iran

Another example of the earlier, and only recently corrected, state of research are the classic investigations by H. Bobek (1937) of the extension of glaciers during the Ice Age and the lowering of the equilibrium line in the desert-like mountain ranges of Iran (Fig 5). Under the impression of the scientific tradition mentioned above, as well as the present-day aridity, terminal moraines, which were not the lowest, but corresponded to an already late glacial stage, when the climate had become milder again, served to locate depressions in the equilibrium line which, though extending to at most 700 to 800 m, were attributed to the coldest period, the peak Ice Age.

In 1967, Jürgen Hövermann voiced a suspicion that the Ice Age glacier margins might have been much lower than had been assumed for this area. Following up this idea, the author, having spent nine months in the field[2] in the Kuh-i-Jupar SW of the Lut Desert at a latitude of 29-30° N, was able to prove that the foreland glaciers had descended to an altitude of 1,900 m during the penul-

Fig 2
Erratic blocks in the Rio de las Cuevas valley in the Aconcagua Group in the semi-arid and subtropical Andes between 32° and 33° S, where peaks rise as high as 7,000 m asl (Fig 4). On the left-hand slope, at an altitude of 3,135 m, there are large, light-coloured granite and granodiorite blocks on shallow banks of Palaeozoic and Cretaceous slates and dark, reddish-brown sandstones which occur here. The solid crystalline rock of the 4.5 x 3.3 x 1.55 m block in the foreground is met only 5 km up-valley. The block is therefore bound to have been transported here along the valleys gradient, but not possibly down-slope. The perspective across and beyond the valley shows that the erratic blocks are found 600 m above the valley bottom. This suggests a minimum depth of the former valley glacier of 600 m. In this cross-section of the valley at the Quebrada Cruz de Caña, the high glacial ice stream was much thicker yet, for the author did find erratic and striated moraine blocks as high as 1,020 m above the valley bottom. A large number of corresponding findings and down-valley moraines permitted the reconstruction of an ice stream network with lengths of constituent glaciers of up to 112.5 km and a lowering of the equilibrium line of about 1,400 m (Fig 4). The present glaciers achieve the size of Alpine glaciers at best.
Photograph by M. Kuhle at 3,135 m asl, facing WSW, on 16.1.1980.

Fig 3
At a distance of about 100 km from the present glacier tongues and on average 2,800 m lower, the author has located glaciated clasts in the mouth of the Quebrada Ranchillos on terminal moraine ranges that rose up to 190 m above the basic altitude of 1,870 m asl (cf. Fig 4 ❾ top right-hand corner). This proves a minimum length of the Ice Age glacier of 112.5 km and a equilibrium line depression of 1,400 m. Laboratory photograph.



timate Ice Age, and to 2,160 m during the last one (Kuhle 1974; 1976). In contrast to traditional opinions, a lowering of the equilibrium line by 1,440 to 1,640 m was thus rendered probable. These results were supported by those of a group of researchers (Hagedorn, H.; Haars, W.; Busche, D. and Förster, H. 1974) working further to the NW in the Shir Kuh Massif at the same time.

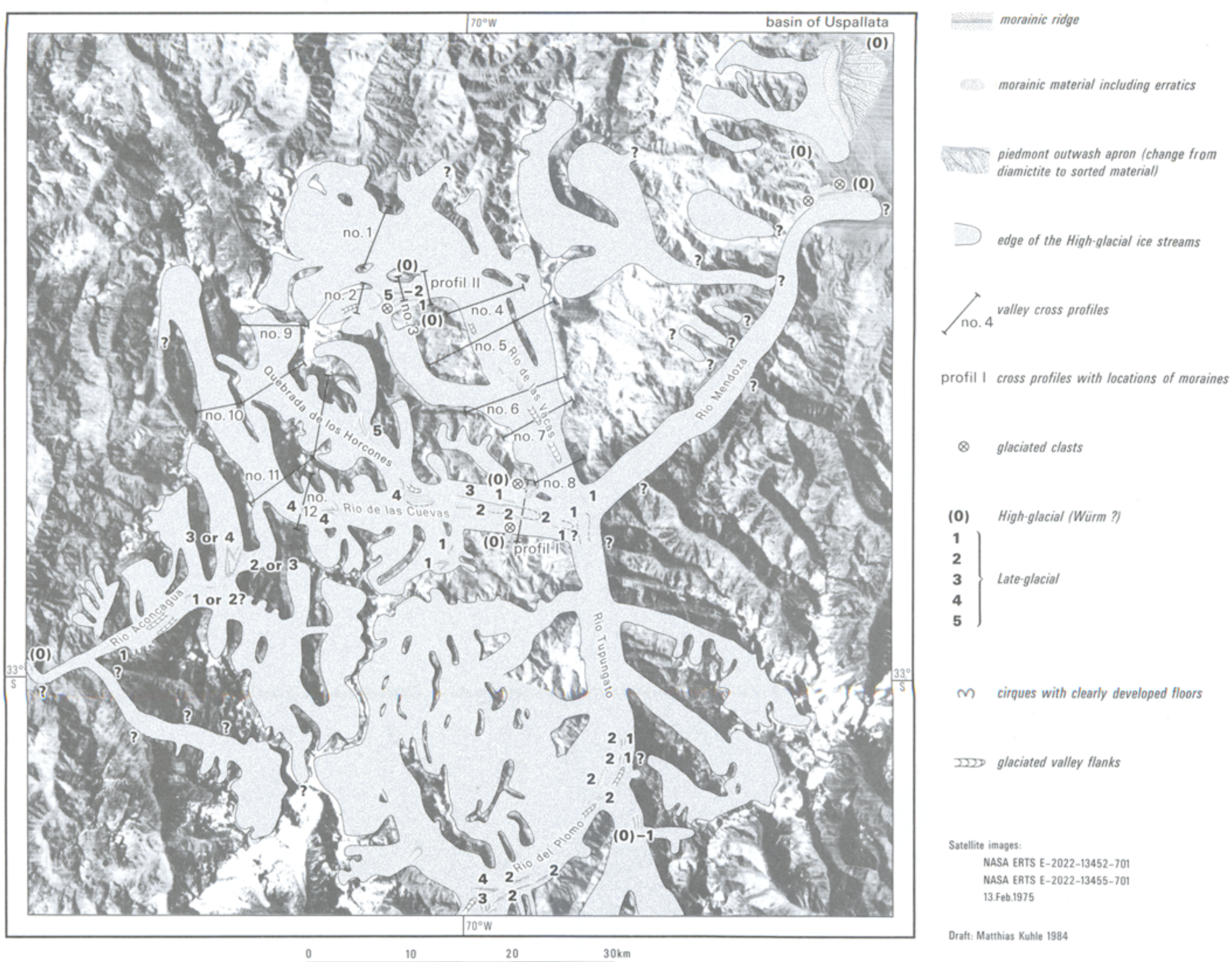
No higher than 4,465 m, these hot and arid mountains of S Persia rarely have snow patches which last through the summer, and glaciers are altogether absent, so that valley glaciers up to 500 m thick and 17 km long, extending to the foreland of the mountains (Kuhle 1976) make great demands on the imagination (Fig 5 and 6).

High Asia and Tibet

Until about 1935 the diagnosis of moraines required for the reconstruction of Ice Age conditions and their localization on sketch maps had been carried out by several researchers travelling in Asia. Their routes largely followed those of caravans. For political reasons access to some areas, as for example the Nepalese section of the Himalayas, was granted only after 1950. The collective observations made in the field, including equilibrium line depressions calculated from the data, have been presented by v. Wissmann (1959) in a book which is a model of its kind. This work based on the literature endeavours to present a harmonious panorama of the last Ice Age glaciation of High Asia.

Alternative interpretations of some of the recorded findings, which seemed to be out of place, served to avoid contradictions. This applies, for instance to the observations made by Weng and Lee (1946) from the N slope of the Quilian Shan on the N edge of the Tibetan Plateau; to those made by Odell (1925) in respect of its S edge, and to those carried out by Wiche (1958) in the Gilgit Karakoram in the W - to name but a few. According to v. Wissmann the drop in the snow-line

Fig 4
Satellite image: Pleistocene glaciation (Würm?) of the Aconcagua group/Andes



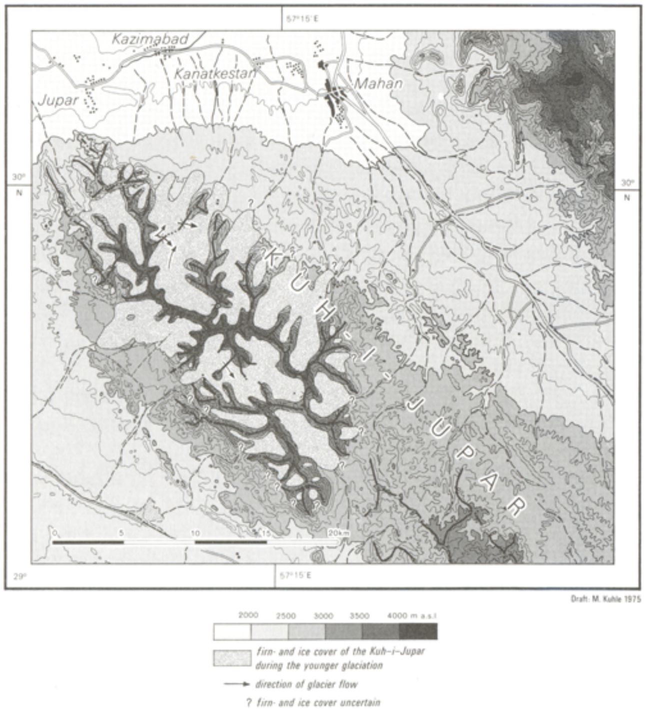


Fig 5
Firn- and ice cover of the Kuh-i-Jupar during the younger glaciation (Würm)

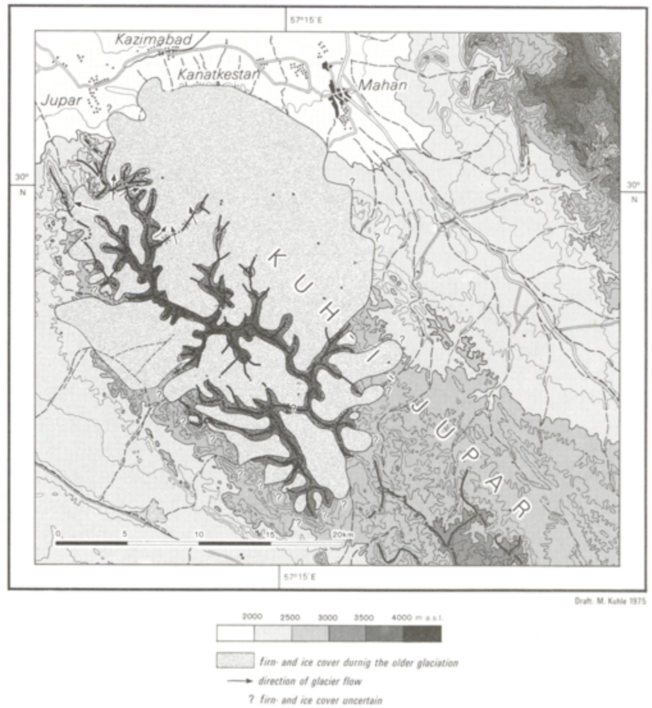


Fig 6
Firn- and ice cover of the Kuh-i-Jupar during the older glaciation (Riss)

(here used synonymously with "equilibrium line") in W Tibet was merely 200 to 300 m, and 700 to 1,000 m in the extreme E of the highland.

With the traditional reference to the extraordinary aridity of the areas concerned, Flohn (1959; 1982) supported v. Wissmann's view of an unusually small drop in the equilibrium line during the last Ice Age - the Alps, in comparison, experienced a drop of at least 1,200 m, as has been mentioned above.

Comment in the Light of the Theory of Science

Thus it were no longer the findings themselves and their interpretation, but the usefulness of an attempt for related disciplines which decided its tenability. Particularly susceptible to such a development are fields of research, which are not accessible to well defined experimental arrangements producing repeatable measurements under fixed conditions. Here, either contradictory or confirmatory evidence can arise solely from one or more expensive expeditions into areas access to which is sometimes difficult. The interpretation of a proof also depends on the level of integration, i.e. the possibility of isolating marginal effects, and thus the unambiguousness of findings as well as their spatial and temporal transferability. At a later stage this will be discussed further with regard to moraines.

In any case during the past two and a half decades Flohn's declaration did strengthen v. Wissmann's suggestion so much that inconsistent findings of moraines could now be declared to be wrongly diagnosed pseudo moraines, accumulations of material due to a landslip or something similar. This was done with reference to Flohn's aridity, and the resulting impossibility of such findings. One lost sight of the fact that Flohn's attempt at an interpretation had been based on findings which had already been selected from a special point of view. It is evidently a matter of a self-fulfilling circulus vitiosus, which - following a certain trend - anticipates the result, or precipitately moves to the deduction before the data collection has been completed. The longer it takes to collect such data, the more understandable this process becomes: as is the case with the geomorphological observations in hand. If it takes decades, as in the case of geomorphological opening up of the not easily accessible regions of High Asia, a preliminary summary of the findings and their premature interpretation attain paradigmatic quality necessary for future work. Its heuristic value for the process of knowledge is not diminished by errors.

Von Wissmann's arguments pursue two paths in order to pronounce the last Ice Age as being free from dissonant findings of moraines:
a) the indicators of positions of marginal ice concerned, the moraines, are back-dated to older

ice ages like the Mindel or the Riss glaciation. This was done at a time when absolute definitions of age were not available, and even now Tibetan moraines are difficult to date due to the lack of the organic substratum required for radio-carbon dating.

b) amounts of tectonic uplifts are assumed in order to explain the altitudes of Ice Age moraines which are too high, even along the lines adopted by v. Wissman, and a glaciation which thus appears to be rather too small.

In respect of a) v. Wissmann found himself in the company of Dainelli (1922), de Terra and Paterson (1939), who consider some of the moraine deposits to be older than the last ice age. However, this merely shifts to previous ice ages the problem of having to explain the drop in the equilibrium line which is related to these deposits, as a function of the climate, i.e. as a result of colder temperatures and/or increased humidity. Increasing consequential problems argue against this. They arise from point b), the tectonic uplift v. Wissmann takes into consideration in one way only, and his concern that some of the moraines held by him to be from the last Ice Age could be situated at too great a height, was swept away by his argument of the uplift that has taken place since the last Ice Age. This occurred about 20,000 years ago. At a probable rate of uplift of about 6 mm/year (oral communication from A. Gansser, 1982, which is gratefully acknowledged here) for the tectonically active areas of High Asia this would imply a previous position of the moraines 120 m below the present level. It also means that, providing the rate of uplift remains constant, the moraines which were attributed to earlier Ice Ages, must have undergone 5 to 10 times the amount of uplift for from 100,000 to 200,000 years. The same argument which explains the moderately lower position of the moraines resulting from the last ice age which is desired, consequently puts down those dated back to earlier Ice Ages by about 600 to 1,200 m at the time of their formation. This raises the question of how the thus 300 to 600 m larger drop in the equilibrium line can be explained, and in that connection how the shift from a necessarily more humid and earlier Ice Age to a more arid and more recent one is to have occurred remains to be established.

Other glacier regions of the earth, however, are known to have experienced differences in the equilibrium line of about 100 m between the last and the one but last major Ice Age (Riss or Illinoian and Würm or Wisconsin respectively) (cf. inter alia Kuhle 1976), but not approximately of 300-600 m; consequently another question mark needs to be placed here. Finally, it is unlikely in the highly active mountain regions with extreme differences in altitudes over short distances, like the Himalayas, Karakoram and other mountain systems of Tibet, that easily eroded loose rock, like moraines, remains in situ over a long period; i.e. since the penultimate or even earlier ice age. All the agents of erosion like water, ice, the shift of rockslope debris through frequent freeze and thaw, and even spontaneous mass movements such as landslides and rockfalls intensify their effectiveness as the gradient increases. Erosion and transformation of relief features are particularly rapid and short term in the valley bottoms where waters bunch together and follow steep longitudinal profiles. This is illustrated by the post glacial amounts of 100 to 200 m cut down by mountain streams in non-weathered solid rock the author proved to be very likely in the Dhaulagiri-Himalaya (Kuhle 1982a; 1983a). For the Mekong Gorge a down-cutting of 400 m during the past 20,000 years has even been assumed (v. Wissmann 1959).

For all these reasons as well as the methodological need to avoid contradictions and to keep the ensuing problems - that is to say the number of supplementary assumptions - as small as possible, it is not opportune to backdate glacier deposits hoping that this will solve the problem. The question of age is in any case of secondary importance and is not conductive to the explanation of the ice cover which created these very deep moraines. The question remains concerning the climate which made the glaciers - whenever that was - flow down much lower than today. Admittedly this drop in temperature and the worsening of climate should not have occurred too far back, since the uplift that has since taken place increased the climatic discrepancy.

Obstacles to Recognition of the Special Character of Glacial Morphology in High Asia - the Theory of Science Applied to a Concrete Case

Before turning to the investigations in Tibet and in its surrounding mountain ranges over the past ten years, attention needs to be drawn to the obstacles of recognition that face glacial geomorphology in High Asia.

1. To search for the lowest ice age moraines in the central or W plateau of Tibet does not hold much promise of success, since the over 5,000 m high plateau is situated only a little below the present equilibrium line. At best the moraines one finds there belong to the late glacial period, when the ice cover had already been greatly reduced. A large number of the moraines v. Wissmann attributed to the high glacial period belong to such deposits and have, in the absence of deeper findings, as the lowest ones locally, been erroneously assigned to a maximum expansion of glaciation. A lowered equilibrium line, approaching the foot of the mountain groups that have been set up on the plateau immediately gave rise to an extensive ice cover which overwhelmed the flat relief and could not deposit complete end moraine arcs on

the highland. Terminal moraines belonging to such total glaciation can only be found on the margin, where Tibet drops to lower regions. This was thus the only place where an ice cover could break up into separate outlets which flowed through the bordering mountain chains down to altitudes of 3,000 or 2,000 m or even less. The conclusion must be this: that if research on glacier termini is confined to high altitudes in Central Tibet, as so far has often been the case, and no overall profile down to the lower valley regions of the highland rim is followed through, the question concerning glacier edges of the high glacial period must be regarded as going unanswered. This fact is not altered by findings of moraines at high altitudes. Since it is a matter of defining a limit, a positive finding without an additional negative finding is bound to remain but feeble evidence here.

2. It seems to be part of the business of research to prefer the deepest definite moraine findings to a yet lower indefinite one as a basis for interpretation. Unfortunately, reliability of diagnosis decreases with the state of preservation of the moraine forms, and this in turn, with their age. This is the reason for the tendency to accept younger recessional moraines at higher altitudes belonging already to the late glacial period rather than the lowest forms of the high glacial period, which have been disfigured by weathering and erosion to a degree that makes them difficult to recognise.

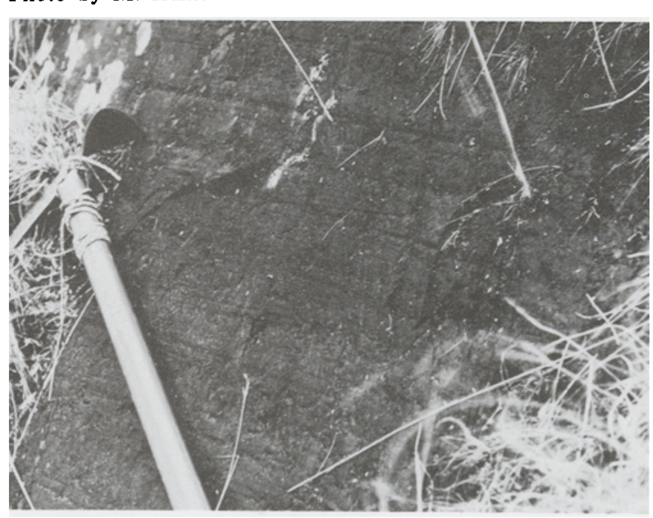
Thus two characteristic attributes regarding the assessment of these altitudinal lines and climatic conditions must be stated here:

a) statistical procedures for finding the largest and lowest former glacial expansions are excluded because the density of random samples is not homogeneous or, to be more precise, becomes greater with the decreasing age of the findings. That is caused in part by the breaking up of a retreating ice sheet into more and more small and separate glaciers, each with its own terminal moraine. Circumstantial evidence is the only proper way of argumentation here, accepting a solitary but conclusive finding as a sufficient proof. The power of assertion of these rare cases or even of one particular case for the palaeoclimate rests on two aspects: on the one hand on the natural law operating in the relations between the lowering of the glacier termini, and that of the equilibrium line; and, on the other hand, by the fact that not all the former glacier tongues have formed terminal moraines, and that some have probably been destroyed and levelled by this time. The poor state of preservation, due to age, of the barely diagnosable rare case indicates as much. Overstating the case somewhat it could therefore be said that a relatively poor state of preservation of a moraine contains a high indicator value for the lowest sites of ice margins which must be attributed to the high glacial period.

b) The certainty of diagnosis which verifies a deposit as a moraine depends to a large extent upon experience. Obviously in the course of decades many testing procedures have been developed and classified according to their value for identification. Flint (1971) and Schwarzbach (1974) have compiled such check-lists for the identification of moraine material. This is to be supplemented by features of the surface forms of moraines. Nonetheless, the level of integration of such deposits is so high and the extent of its composition so large, that it will be difficult to exclude all the possibilities of converging formation purely schematically by means of a few distinctive marks. Often neither the composition of debris particles in respect of mineral content (their rock type), their form and size, or their grain size spectrum, their conditions of stratification (stratified, partly stratified or chaotic) etc., nor the form of the entire deposit - whether in the shape of a wall or of a slightly extended hill - are sufficient evidence for a formation tied to glaciers. One has to know the surrounding terrain, its relief in regard to all of its conditions of gradient, and even the material of the bedrock and adjacent rock waste deposits in order to interpret and evaluate the indices mentioned above in the context of their topographic uniqueness. At the same time all the competing conditions of formations which cause landslides, slumps, mud flows as converging forms must be examined and excluded.

This applies even to young and still fresh moraines. In the case of old moraines, suspected as being from the high glacial period, transformation through post-glacial processes must be taken

Fig 7
Glacier polishing with striae and polish marks on the right flank of the Mayangdi Khola. 1.5 km N of the Baghara settlement in the Dhaulagiri Himalaya (28°35'N/83°25'E, at 2,095 m asl). The striae are 200 m above the valley bottom line (locality - cf. Fig 8⇩). These polish marks are preserved over large areas and prove the survival of the valley cross-section which the Ice Age glacier had created (Fig 8).
Photo by M. Kuhle on 26.1.1977.

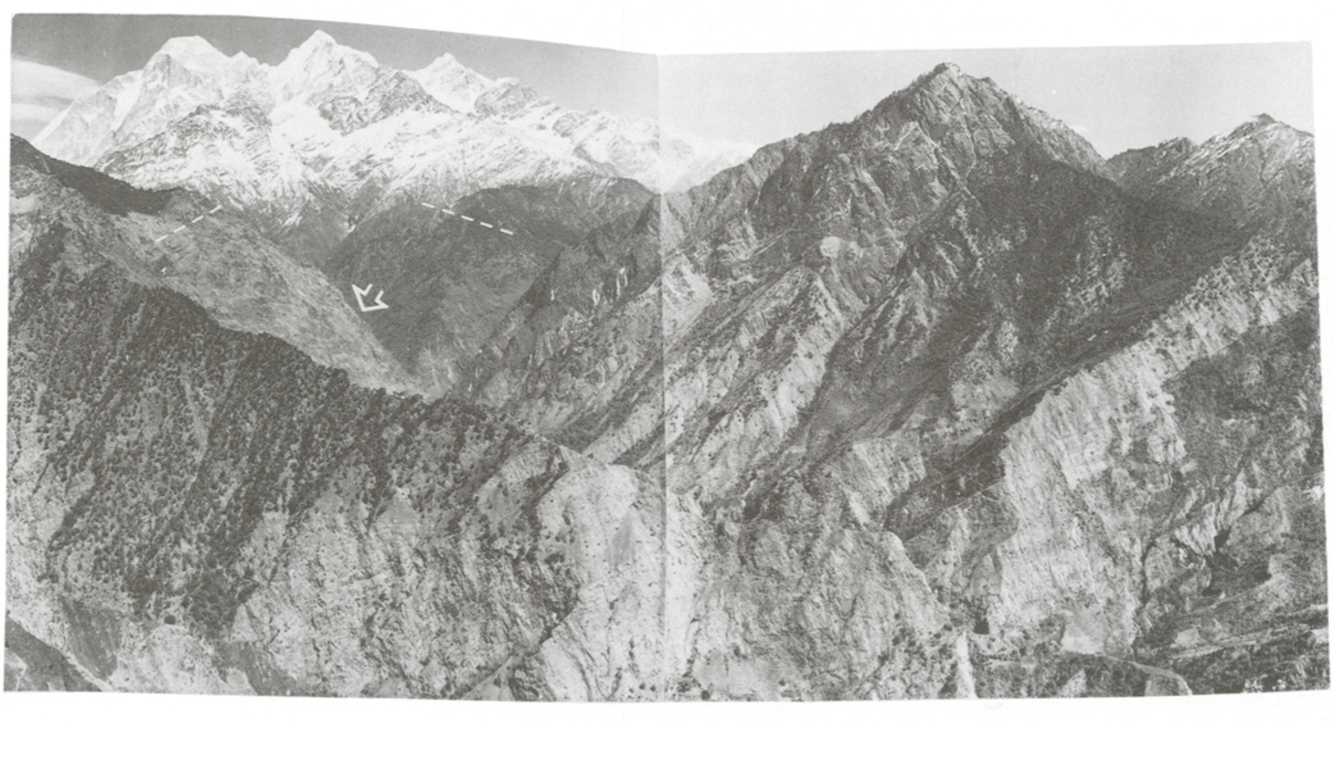


into account such as the reshaping through frost, rain and snow, as well as erosion by river water, that follows the gradient of the valley bottom - all of which need to be reconstructed in the overall context of the terrain for every single case, and retraced. Only then has a conclusive moraine been restored. The complexity and conceptual difficulty of such a process of recognition find a corresponding case in behavioural research, where momentary attitude and gesture must be interpreted in conjunction with their statements, as together they make up the complete course of behaviour. What is recorded with films and thus proved by documentary evidence there, is supported here by panoramic photographs with which the topographic relations are brought back from Tibet and subsequently analyzed at home. Together with the Göttingen Institute for Scientific Film (IWF) we have since 1984 been trying out the film medium as a tool for valuable geomorphological recognition (Kuhle 1985c; 1986d).

3. There is no doubt that techniques of analysis for testing deposits as to their formation by glaciers or other processes have improved since the 'thirties. The probability of the result is increased by a variety of laboratory tests which our samples from the mountains have to undergo in respect of many detailed aspects.

But even field observation and analysis that had - erroneously - been regarded as complete after the era of original discovery, has opened up new possibilities over the past ten years. This must be attributed to the fact that only the most recent technology enabled detailed studies for fundamental research to be carried out in the still very remote and not easily accessible mountain ranges of Asia. Comparative fieldwork on a global scale, which took the author on seven occasions to the Asian Highlands and to Tibet, as well as to the South American Andes, the St. Elias Range and the Alaska Range in North America, and to Spitsbergen (Kuhle 1983b) and Greenland (Kuhle 1983c) in pursuit of questions bearing on the matter, and helped to broaden the horizon in Europe, which had for 200 years been restricted to research in the Alps, permits a methodologically interesting step. Since A. Penck and E. Brückner's fundamental work "Die Alpen im Eiszeitalter" (1901-1909), research on the Alps manifested increasing concentration on questions of detail and their acribic solutions. This is sufficiently contrasted by this kind of expedition research in the field of comparatively speaking rather unknown areas. This change in perspective led to alpine glacier formation no longer being regarded as "the" but as "one" kind of mountain formation

Fig 8
The Mayangdi Khola falls southwards from Dhaulagiri, the 8,172 m peak on the extreme left, and drops to below 1,500 m in the right hand foreground. The valley has a V-profile, although a fully 50 km-long valley glacier with a maximum thickness of 1,600 m (- - - -) flowed through it down to a height of 1,100 m asl. The glacier polishings preserved on the valley flanks are proof of the glacial genesis of the V-profile (⇙ locality of polishing in Fig 7). An additional cause of the V-profile is to be seen in the sub-glacial erosion of meltwaters as the glacier flowed beneath the equilibrium line over a horizontal distance of more than 30 km, extending to almost 3,000 m far below the equilibrium line and into the warm, forested region at the foot of the mountains. Due to the steepness of the valley, the tractive powers inherent in the glacier prevailed over those of pressure. This, too, favoured the V-profile of the valley as opposed to the trough-like one.
Photo: M. Kuhle, 30.1.1977 at 2,300 m asl, from W of the settlement of Muri, facing NE.



resulting from ice. A simple comparison of base areas of different mountain systems, or even with High Asia, reduces the particular case of the "Alps" to an example of secondary importance, the global relevance of which becomes more than doubtful with regard to parameters like climatic diversity and altitudinal differences which are twice as manifold in the Himalayas.

Scientific tradition is bound to distort in this way, for the foundation of quaternary geology in mountains, of high mountain geomorphology, and at the same time of mountain glacier research, had been laid down in the Alps. Hand in hand with it went next the directive step of generalization - necessary, yet at the same time in need of overhauling. The alpine induction thus became the premiss of a global deduction as, for example, that only a trough valley such as is found predominantly in the Alps, is a valley formed by glaciation; only those hillocks of rock, which unquestionably show glacial striae, or at least glacial polishing, are so-called roches moutonnées, and as such indicators of former glaciation; only arcuate walls of chaotic material without water-sorted strata are unambiguously terminal moraines.

Other work by the author shows how little this applies to many high mountain ranges, how many of the pure formations and the associations of the glacial forms are special features of the Alps, and how inadequate they are as the sole concepts for conducting world-wide palaeo-climatology and research into the ice ages. Though glaciated during the Ice Age most of the Himalayan valleys were not trough valleys but glacier-made incisions (Kuhle 1982a; 1983a) with a V-profile (Fig 7 and 8)[3]. That is the result of the much steeper gradient curves of the valleys as compared to those occurring in the Alps, and of drainage that took place below the glacier. There are numerous roches moutonnées in formerly heavily glaciated parts of Tibet which show next to no polishing and certainly no striae at all, both the effect of effective splintering-off by high continental frost-weathering (Kuhle 1982b; d; 1983d; e), which does not allow these miniature forms in rocks to persist in the way they do in the Alps, where they are subject to much snow and smaller temperature fluctuations (Fig 9). Extending over hundreds of kilometres in Tibet - as also in the Zagros Mountains, in the Andes and in Alaska, i.e. always in semi-arid mountain forelands - the large-scale former sites of ice margins are in some respects more reminiscent of large alluvial fans than of Alpine terminal moraines. That is why, for decades, they have consequently been taken for former alluvial fans, if they were noticed at all. Under the term "Bortensander = ice marginal ramps", these peculiar ramp forms were first described by the author for Persia in 1973, and as unambiguous glacial indicators compared with the alpine terminal wall moraines (Kuhle 1974; 1976) (Fig 10). The author regarded this form as a small-scale speciality until he found it in the sub-tropically arid Andes in 1980 (1984a; 1984b) (Fig 11), and again in 1981 in the N hemisphere in the Kuen-Lun Mountains (Kuhle 1984c), Datsaidan Shan (Fig 12) and in the Quilian Shan which forms the border between N Tibet and the Gobi Desert (Kuhle 1982b; d; 1983d; e) (Fig 13). The glaciological significance of ice marginal ramps, which do not occur in the Alps, was established, when in 1983 they were also found at the foot of the mountains of the Alaska Range; these were once arid as well and, in 1984, it was possible to identify them again in large dimensions on the Shisha Pangma in Tibet (Fig 14) (Kuhle 1984a; 1985a; b). They owe their formation from a moraine core of unstratified boulder clay which was overlaid by a cover of deposits which the melt-waters had stratified (Fig 15). The significant quantities of rock fragments required for this type of deposit were produced by the continental frequency of freeze-thaw cycles. The lower temperature of the ice that accompanied the arid climate, had the effect of drainage occurring mainly by way of the glacier surface. It dressed the terminal moraine with sorted and stratified deposits, which are characteristic for running water (Kuhle 1984a).

The recognition of this indicator of ice margin sites was made more difficult by the peculiarity of the theory of science, that the principle of uniformitarianism, though common in geomorphology and quaternary geology, does not apply to ice marginal ramps. This is illustrated by the relation of the two altitudinal lines: equilibrium line and limit of the permanently frozen soil. In the continental arid climate the two are in a fixed temperature relationship. Today, however, suitably extensive glaciers of the high continental kind are absent from the earth, the equili-

Fig 9
Glacigenic forms of denudation on the S Tibetan Plateau at 5,100 m asl. The glacier polishing at these roches moutonnées is still evident. However, on the top strata glacier striae and rock polishings have splintered-off. The extreme frost weathering of the continental highland does not permit a better state of preservation. In the foreground a ground moraine can be discerned.
Photo: from N of the Menlungste Group facing W, at 28°32'N/86°09'E, 31.8.1984. M. Kuhle.

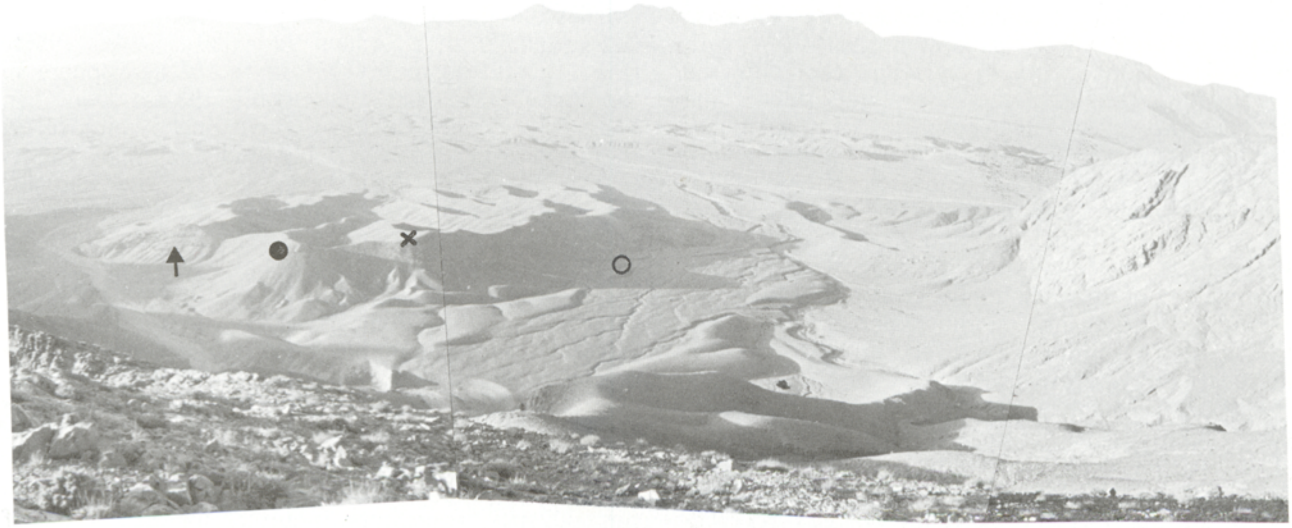


Fig 10
Ice-marginal ramps as characteristic indicators of ice termini of semi-arid piedmont glaciation (• x). The photograph shows ice-marginal ramps in the N foreland of the 4,135 m-high Kuh-i-Jupar Mountains (cf. Fig 5 and 6) between 2,300 and 2,000 m asl. They mark the extent of glaciers during the last period of glaciation (cf. Fig 5). Glaciofluvial ramps with increasingly sorted substrate follow beyond the wall form (x) (cf. Fig 15). Their backs have gradients of 10-15° and, just as the small valleys intersecting them, they run at right angles to the two parallel tongue basins; (0) marks the right hand tongue basin, ↗ denotes a ridge of bedrock conglomerate which is enveloped by the moraines.
Photograph taken by M. Kuhle at 2,645 m asl, facing NE; 9.7.1973.

brium line of which would be so high above the permafrost limit as then, whilst their terminus reaches further down than the line of permanently frozen soil. To elucidate further it ought to be added that, if the drop in the equilibrium line is the same as that of the permafrost limit, the glacier edge which descends twice as far as what the lowering of the equilibrium line amounted to, changes its altitudinal distance to the line of permanently frozen soil. Thus all the present-day glaciers of High Tibet end well above the lower line of permanently frozen soil, whereas they flowed further down than that during the Ice Age. Assuming otherwise equal conditions in respect of temperature, weathering, rate of rock fragments and incidence of melt-water the essential factor for the formation of a moraine finds expression in the position of the two altitudinal limits mentioned above in relation to the situation of the lower glacier edge (Hövermann and Kuhle 1985). To summarize this section: it is to be placed on record that the alpine inventory of forms has no global validity; this was revealed only by large-scale comparisons. The very observations which

Fig 11
High glacial ice-marginal ramps of the S hemisphere in the semi-arid Andes (Aconcagua Massif) at 32°34'S/69°30'W (Fig 4, 'piedmont outwash apron'). This glacigenic accumulation is situated between 2,210 and 2,620 m asl, W of the Uspallata settlement and made up of polymict blocks. On the left, in the direction of the tongue basin, close to the foot of the mountain, the inner slope of the front moraine falls away (▲). Separated by small valleys the ice-marginal ramps of glaciofluvial gravel material on the right (—) descend further into the foreland in the direction of the outwash plains, the slope angle being 10-12°. The glacier tongue sat close to the inner slope of the moraine, and the meltwaters built up the steep pile of outwash deposits beyond the moraine ridge (cf. Fig 15).
Photograph at 2,630 m asl, facing E to ESE. M. Kuhle, 20.4.1980.

Fig 12
High glacial ice-marginal ramps on the Datsaidan Shan S slope in N Tibet (37°53'N/95°24'E). View from the outwash plain (foreground) in the foreland towards the mountains, at 3,430 m asl (cf. Fig 15). In the background the 5,050 m-high catchment area with rounded mountain forms, indicating glacial polishing. During the Ice Age it was entirely covered by glaciers (●). Ice marginal ramps with an 11-14° slope are attached to the foot of the mountains (—) and frame the string of glacier tongue basins. The huge blocks indicate the morainic character of the deposit (▾▾▾▾▾).
Photograph by M. Kuhle, 24.7.1981, facing NE.

had been found to be characteristic for the glacier formation in the Alps have led to wrong assessments and misinterpretations in the High Asia region.

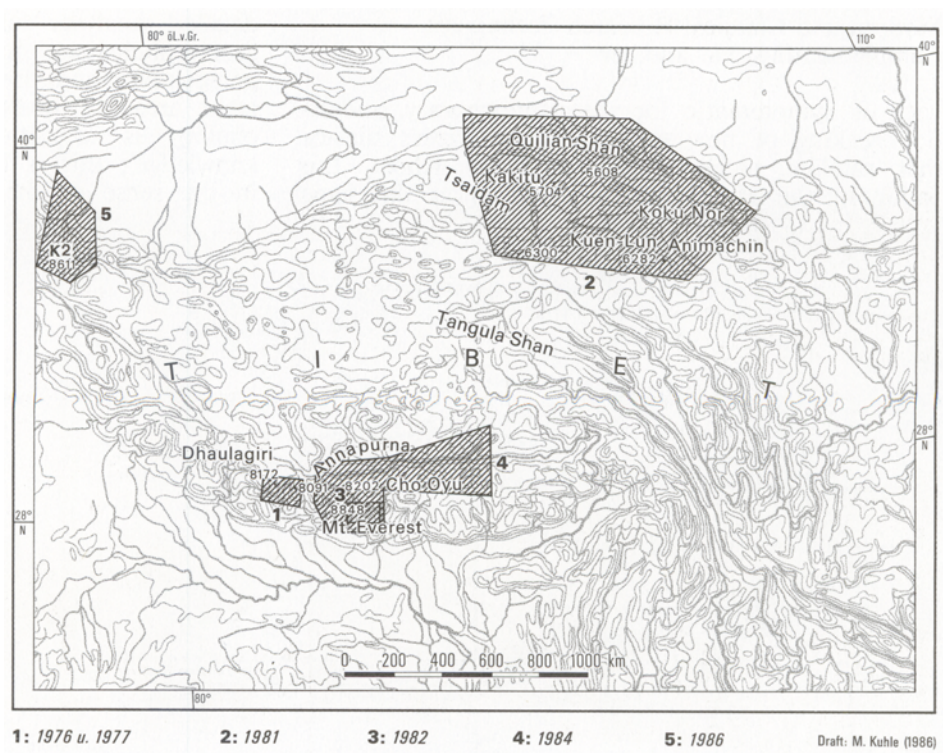
Concluding the problem of the equilibrium line controversy and the previous state of glacier and ice age research, it remains to be stated that long before these renowned explorers like v. Klebelsberg (1922) and v. Ficker (1925; 1933) had identified depressions of 1000 to 1500 m in the equilibrium line of the last Ice Age by fieldwork in the Transaltai Mountains (W High Asia, N of the Central Pamirs) in places where v. Wissmann's interpretation of Russian literature admits to 800 m at the most.

The Himalaya and Tibet Expeditions of the Geographical Institute of Göttingen University and their Results

Dhaulagiri- and Annapurna-Himalaya 1976, 1977

When the investigations carried out in the SE mountains of Iran in 1973 and 1974 had yielded unexpectedly significant drops in the equilibrium line during the Ice Age, and comparative studies in Spitsbergen in the summer of 1976 had been completed in addition, it was possible in the autumn of that year and in 1977 to extend ice age research to the High- and Tibetan-Himalayas, as well as to part of S Tibet N of the Dhaulagiri (Fig 13,

Fig 13
Research areas in High Asia visited by the author in the course of six expeditions.



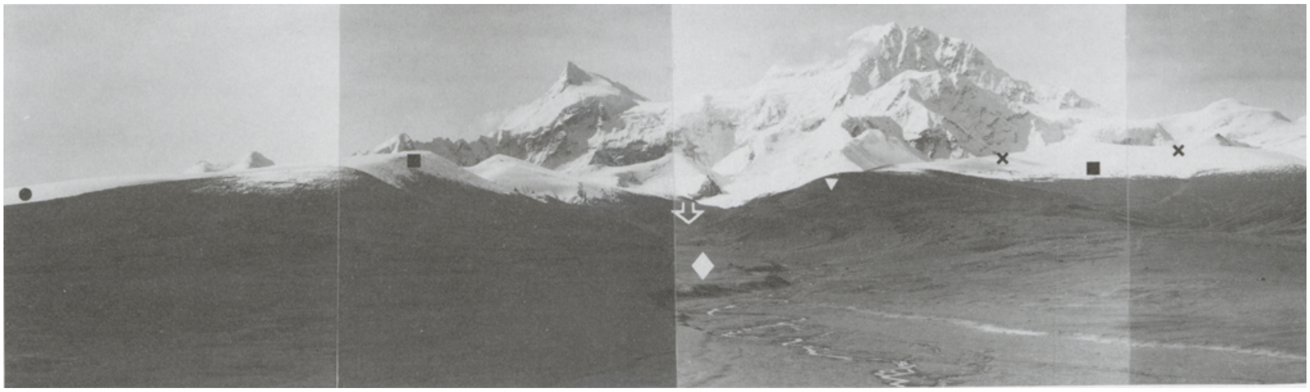


Fig 14
Late glacial ice-marginal ramps on the Shisha Pangma N slope of the Central Himalayas in S Tibet, at 28°25'N/85°48'E. The Tibetan High Plateau immediately adjoins to the main Himalayan ridge (central peaks) which rise to a height of 8,046 m at this place. The up to 600 m thick deposits of ice-marginal ramps (■■), were built up by glacier tongues, which reached the foreland at altitudes between 5,150 and c. 6,000 m asl. The present glacier tongues here - as for instance the one of the Yepokangara Glacier (⇩) at 5,500 m - end in valleys set deep in the ice-marginal ramps near their roof (cf. Fig 15). The location of the former glacier edges at the marginal deposits can be reconstructed along the slope fringes (▼). The material of the outwash plains was poured out from these valleys (◆). On some ice-marginal ramps local plateau glaciers have formed (●); they are not to be mistaken for the cover of freshly fallen snow (xx). They prove a lowering of the equilibrium line, which is caused by a greater humidity than that prevailing in the late glacial period.
Photograph at 5,250 m asl, facing S; M. Kuhle, 16.9.1984.

No. 1). Accompanied by Georg Miehe, the plant geographer, the author led two four-month expeditions to unexplored areas of the Central Himalayas (Kuhle 1979/80; Kuhle 1982a; 1983a). In the course of these expeditions sections like the upper Thulo Khola below the S wall of the Dhaulagiri were investigated which had not even been gone over[4].

Modern and Classical Research Techniques Complementing one another

It is symptomatic for the contemporary scientific breaking of new ground on the earth's surface that satellite pictures of the Thulo Khola, this valley in the Himalayas, were taken at the same time, and that the "third discovery of the earth from space" as Bodechtel and Gierloff-Emden (1974) have called it, took place sooner than the first one by a group of people on foot. Even now, another years on, when the Spacelab takes 23 x 23 cm format photographs from a height of 250 km, which are capable of separating distances of 20 m, traversing the ground and expedition research are indispensable. Only work on the ground provides detailed analyses and samples, which verify the geomorphological interpretation of the vertical perspective and permit an integral transfer to other areas of investigation. Decisive for geomorphology is "cognition as a source of scientific knowledge"; this is by all means to be understood in the sense of the behavioural researcher Lorenz

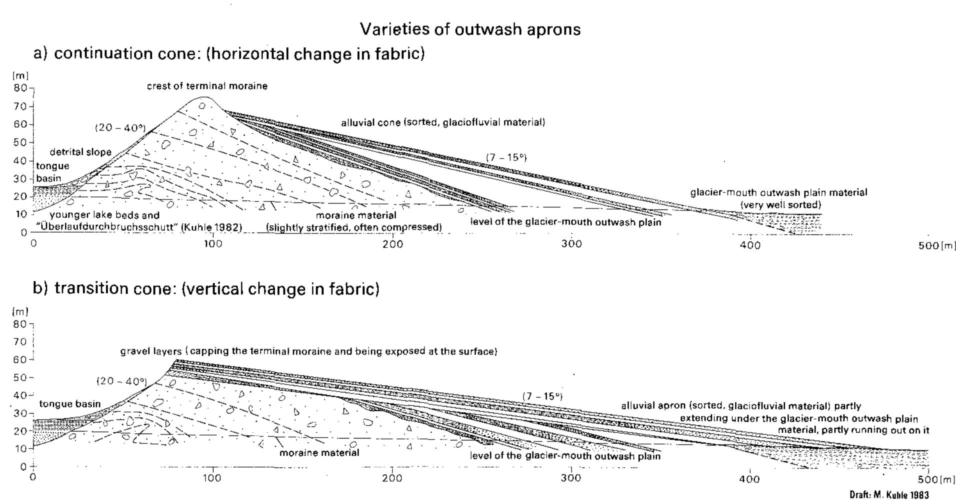


Fig 15
Ice-marginal ramp forms

(1959) and in that of the gestalt psychologist Köhler (1971) - which thus gains for itself the new perspective mentioned above[5]. This has also proved particularly fruitful for the ice marginal ramps, the landmarks characteristic of glacier termini (Fig 10). Once the author had been able to examine them in detail in various mountain ranges, though he initially misinterpreted their elements as aggregates of giant alluvial fans, they were gradually recognised as parts of another system of formation, of another whole, namely of an ice marginal ramp. Already well appreciated in its entirity from the ground, unexpected support was forthcoming from satellite pictures for the perception of these macro-forms making it possible to recognize them at a glance and to realize that the alluvial fan-like ground plan shows a system of channels and small valleys which converge at its centre. So there is a depression in the form of the ice marginal ramp where the genuine alluvial fan - despite its similar ground-plan - shows some up-doming and rather a diverging network of channels (Fig 10, 16). Ice marginal ramps are to be regarded as a moraine gusset between glacier tongues. They were washed down from the glacier surface vertically to the edge of the ice, and dissected by little valleys. In this way, intelligible as a geomorphological system, the form of the ice marginal ramps can be unambiguously diagnosed in satellite images of many foreland regions of Tibet and mapped on a large scale (Kuhle 1984a).

Like those in the Zagros and Andes, the results (Kuhle 1979/80) achieved in the Dhaulagiri- and Annapurna-Himalaya were out of place as far as

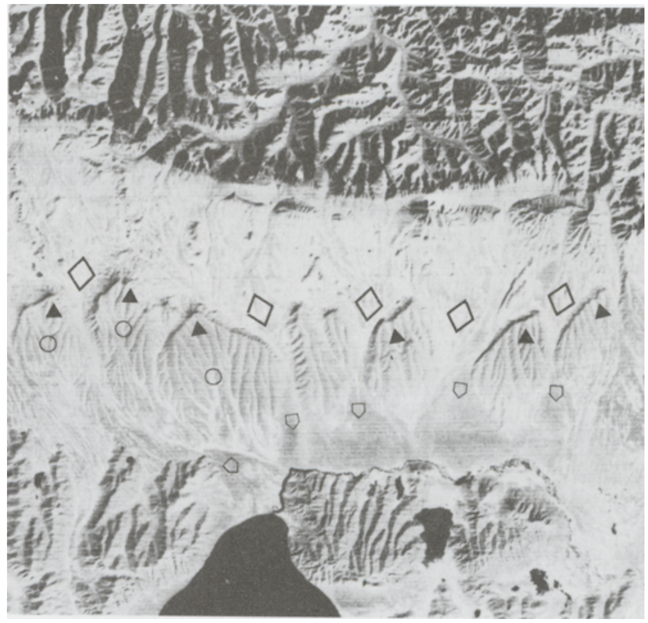


Fig 16
The ice-marginal ramps on the S slope of the Kuen Lun Mountainsin NE Tibet (35°13'N/97°50'E) at about 4,550 m asl follow the border line of the late glacial piedmont glacier at a distance of 10-12 km from the foot of the mountain (▲▲). They taper off towards the mountains and divide the mountain foreland into separate tongue basins (♦♦). The small ice-marginal ramp valleys start off at right angles to the former ice margin at the frontal moraines and converge towards a central depression (oo). Penetrating the ice-marginal ramp, the outwash plains were heaped up in the manner of alluvial fans (⇩⇩). In satellite pictures ice-marginal ramps appear as clearly diagnosable major forms.
Nasa ERTS E-2691-031 12-701, 13.12.1976.

Fig 17
Typical terminal moraine (I) in a mountain valley, like those found in the Alps as well; typologically a more linear indicator of locations on the edge of the ice by contrast with the ice-marginal ramps with their two-dimensional ground-plan. This frontal moraine marks the lowest late glacial glacier level in the Himalayas. It proves a drop in the equilibrium line of 1,190 m. Taking this classical moraine at the Ghasa settlement (in the gravel field terrace in the middleground) the author introduced this stage as "Ghasa Stadium I" (Kuhle 1979/1980; 1982a; 1983a). The moraine is adjacent to the orographical right-hand flank of the Thak Khola (Dhaulagiri Himalaya at 28°36'N/83°37'E). Its base is at 1,870 m. The former tongue basin is filled with the outwash plain terraces (1,2,3) of the late glacial stages immediately following. The glacigenic V-valley profile of the Thak Khola is visible in the background.
Photograph at 2,070 m asl, facing WSW. M. Kuhle, 11.11.1976.

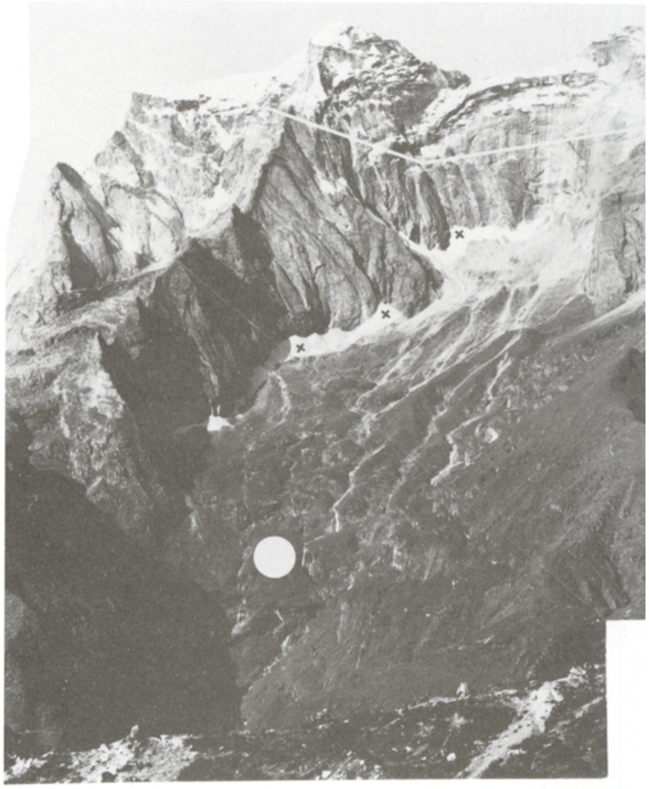


Fig 18
Large high glacial cirque on the S slope of the Mount Everest area (Khumbu Himal at 27°48'N/86°37'E). Nupla, a 5,885 m-high peak of the Kongde Shar crest is now able to supply only a small amount of avalanche snow to the NE-facing corrie (xx), so that the concave form is almost completely free 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