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Glacial Isostatic Uplift of Tibet as a Consequence of a Former Ice Sheet

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Empirical Data and Circular Arguments

From 1973 onwards there has been no agreement between the reconstructed valley and piedmont glaciations of the semi-arid mountains of Asia (Kuhle 1974, 1977) and the very slight glaciations postulated classically by the treatments and summaries by Bobek (1937) and von Wissmann (1959). This *non agreement with previous ideas of global glaciation* is clearest in relation to the striations and end moraines which extend down to 1000 m above sea level (asl) in the great transverse valleys of the Himalayas. These indicate a *depression of the equilibrium line altitude* (ELA) of between 1200 and 1600 m along the southern edge of the Tibetan plateau between 27° N and 29° N (Kuhle 1980, 1982, 1983, 1987d, 1990d, 1991). Such a depression of the snowline to a level of 3900–4300 m asl lay below the mean level of southern Tibet including the valley floors within it and led to a cover of ice.

With the political opening-up of China from 1981 and of the Soviet Union from 1988 it was possible to extend *geological and geomorphological studies of glaciation* from southern Tibet across central Tibet to the north, west and east as well as into the surrounding mountain systems including the Tien Shan (Fig 1). In all these areas the *reconstructed* glacial ELA lies 1200–1300 m below the *present* snowline (Kuhle 1980–91; cf Weng and Lee 1946; Schroeder-Lanz 1986; Porter 1970) and would therefore be below 83% to 86% of the surface area of Tibet (Fig 3–5). To reconstruct such a prehistoric pattern of the snowline distribution was solely possible by means of detailed geomorphological analysis of the peripheral mountains surrounding the high plateau which themselves form the steep edge of Tibet. The reason therefore is that *only in such locations* could be found striations and moraines (Fig 6) to indicate the *lowest glacial terminal positions* of those glacial height zones which were depressed during the glacial period; on the High Plateau itself, just as in central Scandinavia, only erosional forms are present and indications of the limits of glaciation *are therefore absent.*

Using the evidence that the reconstructed glacial ELA locally lay several hundred metres *below* the high plateau surface of Tibet (v supra) a *working hypothesis* was deduced of an *ice-sheet glaciation* of Tibet (Fig 2). Thence, following the principle of uniformity, an *uparching of the snowline* over the High Plateau was imagined, such as may be reconstructed from the present glaciers of central Tibet (cf von Wissmann 1959; Shi Yafeng & Wang Jingtai 1979). But in this case the *principle failed!* This uparching of the snowline over Tibet was simply the most unfavourable precondition for supporting a glacial period ice-sheet. Any hypothesis of *total glaciation* requires *very careful* support. For this the *present day* uparching provides the *most*

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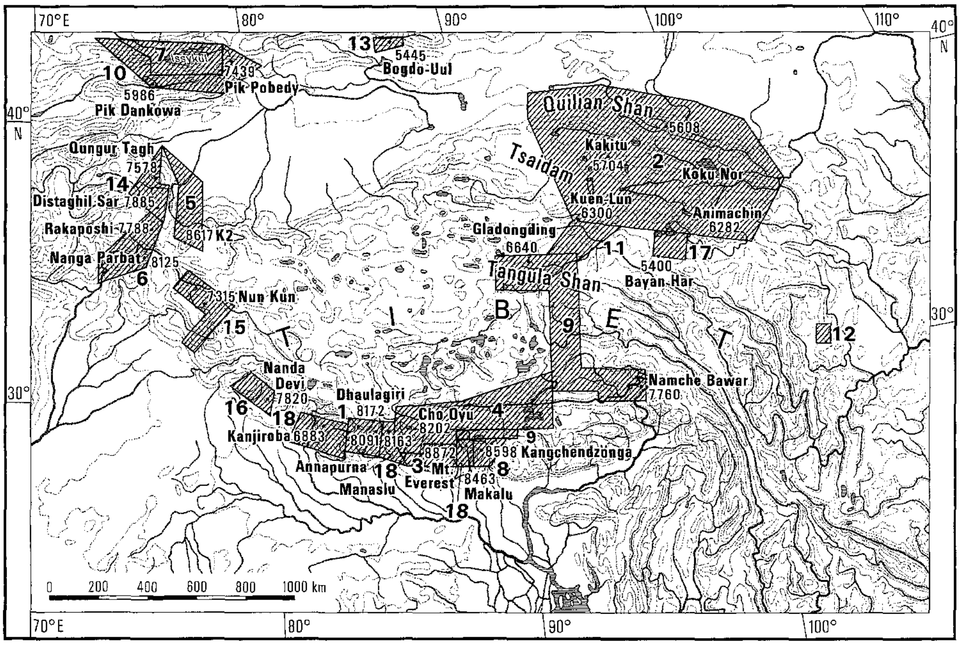

1: *1976 a. 1977* 2: *1981* 3: *1982* 4: *1984* 5: *1986* 6: *1987* 7: *1988* 8: *1988/89*
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17: *1994* 18: *1994/95*

Draft: M. Kuhle (1995)

Fig 1
Research areas in High Asia visited by the author in the course of 20 expeditions

unfavourable evidence for the uparching of the glacial period snowline (equilibrium line Fig 3, 4, 5). But in fact the glacial period ice cover shows the *ineffectiveness* of the present day *thermal surface* conditions of Tibet, in which the dark rock and debris surfaces show such *low albedo* values in their *subtropical* environment and ignores the high reflectivity of snow and firn surfaces. These had such a *cooling effect* (other climatic effects being equal) that *depression* and *concavity* of the ELA rather than uparching must have occurred. Instead of the convexity of the snowlines of Fig 3, 4, 5, 7, 8, 9 and 10 these must have been concave. This means that the climatic conditions in central Tibet must have been even *more favourable* to icesheet formation than those resulting from the previous calculations of the snowline depression. *Positive feedback* favouring snowline depression occurred in central Tibet.

The final step to give evidence of an ice sheet had to be made in the central areas of the Tibetan highland. Investigations on the spot provided characteristic geomorphological indicators and such of Quaternary geology (Fig 1 Nos 2, 4, 9, 11, 17).

The presence of typical *traces of glaciers*, especially of *classical glacigenic erosional forms* and extensive associated ground moraines (Fig 11), witnesses to a fairly *completely covering body* of ice. The author has analysed and described *typical evidence* within this area of fields of *roches moutonnées*, the occurrence of *erratic blocks* on the high surfaces as well as *ground moraine* deposits which *could have been formed in no other way*. Their *positional relationships* witness unequivocally to a *unitary glacial landscape* in all the areal samples with a *high degree of probability*. Up to now *this method is the only way* to solve such problems of a prehistoric ice cover (Kuhle 1990 e, 1991). The same method has been used to elucidate the icesheet covers of N America and N Europe. But the ice of Tibet has its own *climatically determined variety* of glacio-geomorphological characteristics. This is because of the slowly growing cold icesheet characteristic of an annual mean temperature of –10 °C and below at the level of the snowline (Kuhle, Herterich and Calov 1989). In the post-glacial after the retreat of the ice a very intensive freeze-thaw *fully continental climate* continued into the *permafrost* environment that still persists. The cold ice resulted in an ice flow that was *not very intensive*, as well as *local freezing* of the basal ice onto the solid rock whence followed very *strong exaration and detraction* phenomena. The freeze-thaw climate *very rapidly destroyed* the typical striations and polished surfaces. The *easily fractured* sedimentary rocks, which form by far the largest aera of the high plateau of Tibet, very quickly lost their glacial polish by surface disintegration.

Fig 2 gives an idea of the maximum extension of the icesheet over the highland. It will be seen that with regard to its dome-like convexity it was quite *inconsiderable* how far the lowest outlet glacial terminals reached down the marginal steep slopes. In fact the *outline* of the *ice elevation* ie its relation to its length and breadth. Because during the glacial period the ELA was depressed *below the plateau surface* both north and south and west and east as far as the mountain rim the total outline of Tibet formed that of the convex ice surface (Fig 3, 4, 5, 7, 8, 9, 10). It extended almost latitudinally for about 3000 km and reached a maximum meridional extent of some 900 km. The author bases an exact determination of this outline area and that of the

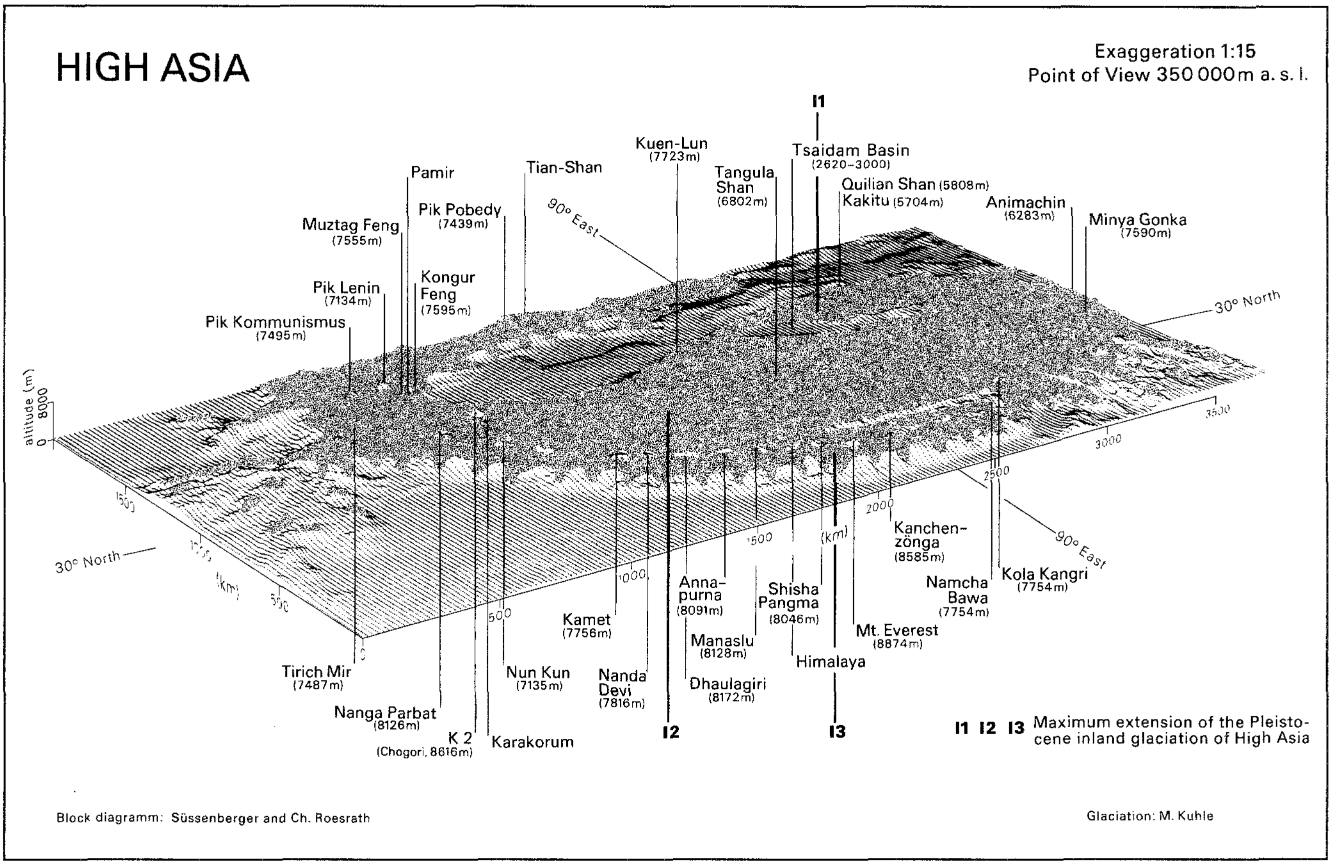
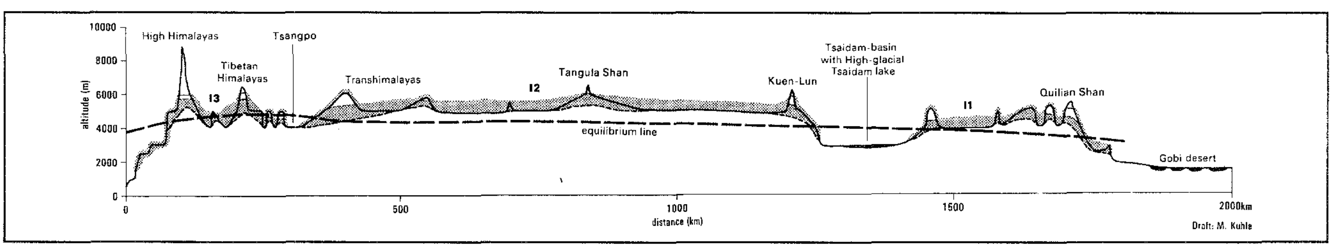


Fig 2 The 2.4 million km² inland ice (ice sheet) on the Tibetan highland with its centres I1, I2, I3. Only peaks reaching more than 6000 to 6500 m project above the glacier surface

Tibetan icesheet of 2.4×10^6 km² (Kuhle 1985c) not simply on the distribution of those areas that were investigated by twenty expeditions (Fig 1). High Asia is *too difficult to traverse* and too large for the kind of glacial geomorpholigical investigations based on representative sample areas. It is only possible to form a *total view* of icesheet dimensions by considering the *systematic relationship* between the *altitude* of the high plateau and the *depression of the snowline* ie the interaction between the *climatic height limit* and the *relief of Tibet.*

In this connection it is unimportant whether an early Pleistocene *change of climate* led to a *depression* of the snowline *below the level of the high plateau* or a *primary* plate-tectonically induced *uplift* raised Tibet above a *stable* snowline level and led to an *inland ice sheet cover* which was repeated again during the following Ice Ages until the Würm (Weichsel, Wisconsin, Valdai) glaciation (Fig 3–5, 7–10). The *interference* between *snowline* and *relief* resulted in several *combinations* of *positive feedback.* It has already been indicated that an accumulating, enduring snow, firn and ice cover of Tibet changed the *positive heat balance surface* of today and of the interglacials into a *cooling-surface* due to the reflection of incoming energy. A *second over-riding* feedback occured as a *result* of the primary increase of the snow, firn and glacier cover and the enhanced rate of cooling, which again induced an even faster growth of the glacier area and ice thickness. This led to a secondary enlargement of the glacier catchment areas

Fig 3 The cross section of Tibet (after Kuhle 1985, ie first version) from SW to NE shows the ice sheet with its centres I3, I2, I1 attaining thicknesses of at least 700–1200 m and up to 1600 m in the valleys (exaggeration 30-times). I3 and I1 were of the ice stream system type.



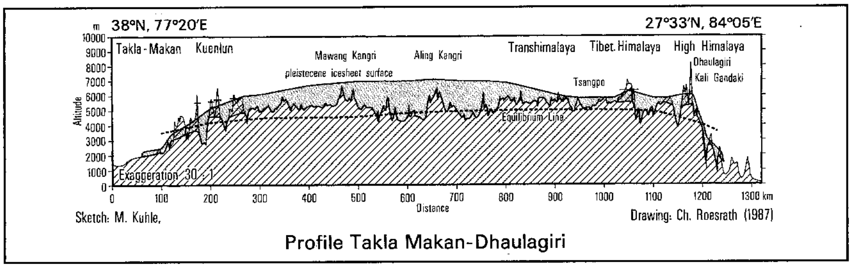


Fig 4
A cross section of the Pleistocene inland glaciation of Tibet (after Kuhle 1988, 1989, ie second version)

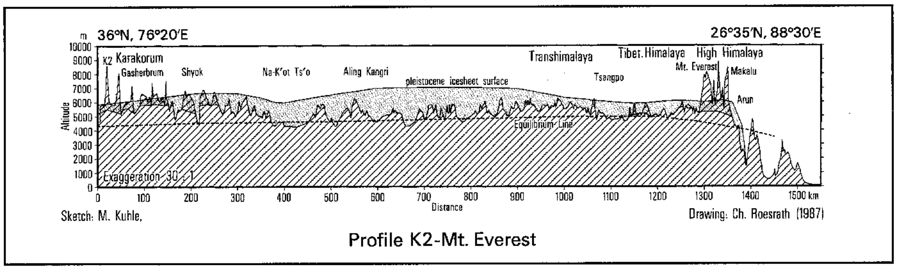


Fig 5
A cross section of the Pleistocene inland glaciation of Tibet (after Kuhle 1988, 1989, ie second version)

especially with regard to the higher and colder regions of the ice surface with increasing accumulation rates. A *third* feedback is a *function* of both of these and a consequence of their results, that of *glacio-isostasy.* An increase of loading by ice produced first a glacio-isostatic *depression.* The snowline parallel to the *meridian* was depressed during the glaciation from 4300 m asl in 29° N to 3200 asl at 40° N (cf Kuhle 1982, 1987b, 1988i, 1991) so that the northern part of Tibet because of its uplift must have reached the *snowline altitude* at an *earlier time* and experienced then an effective *glacial loading.* It thus follows that southern Tibet with its otherwise comparable topographic conditions must have been *uplifted further* by this 1000 m before an impulse of tectonic uplift produced a sloping layer of ice whose *weight* must have been *compensated* for and then *counteracted further uplift.* The *coincidence* of planetary snowline slope towards the north and the similar sense slope towards the north of the height of the Tibetan plateau is in fact an example of a *causal relationship.* This is extraordinarily explained and understandable by means of the mechanism of *glacio-isostasy.* This a matter of a *feedback-systematic relationship* between the plan of the Tibetan plateau, the height of the Tibetan plateau and the magnitude of the icesheet ie of its plan and thickness by means of the altitude of the ELA.

In this connection it is of importance that only large scale climatic changes influenced the former glaciation in High Asia. There are in general *no* great climatic differences between one valley and its neighbour. Because of this it was possible for the author during his expeditions to analyse selected ice-marginal positions all round Tibet from a geomorphological and glacio-geological point of view and to consider them as *representative.* With this kind of presentation, which differs from the *classical* argumentative forms of *linear causality* by incorporating the explanatory value for other phenomena - here the slope of the Tibetan plateau towards the north (and the similarly directed depression of the planetary ELA) - in the form of a *circular argument,* it is clear how difficult or impossible it is to present *purely empirical observations* without at the same time introducing a *systematic significance.*

Icesheet Thickness

It is a similar case with the former *maximum thickness of the icesheet.* There is a contrast between Fig 3 (a profile showing a central maximum thickness of only 1200 m) and Fig 4, 5, 7, 8, 9, 10. Fig 3 shows the *lowest height* based on the highest erratics, maximum height of roches moutonnées, levels of transfluence passes, polished surface boundaries on valley sides, areas of the upper parts of triangular glacial facets on valley sides and also of glacially sharpened mountain forms which extended above the ice sheet as Tinden or Nunataks and thus have the characteristic forms of glacial horns. This kind of ice thickness must have been reached, according to the results of model calculations (Kuhle et al. 1989), within the last 10,000 years. It held if the precipitation feeding the icesheet had been reduced to about *a third* of its present value. This *reduction in precipitation* must be the result of the breakdown of the present monsoon precipitation due to the influence of the ice cover (Kuhle 1989c). This minimum of ice cover attained 1200 m at the centre of the plateau (Fig 3, 12). That it was a *minimum thickness* is supported by the previously mentioned indicators provided by the geomorphology and Quaternary geology. All these indicators *can only support a minimum thickness* since they could equally imply a *greater* icesheet thickness. Even the highest of the *high-lying erratics* (Fig 12) *must* have experienced a *downward movement* as the result of horizontal transport before their deposition. The highest *roches moutonnées* support an even

Fig 6 Exposure of moraine material (lodgement till) in the E of Chung Leh Shan at 610 m asl (30°45'N/103°30'E near Pitong). Polymict boulders "swim" in a loamy ground mass. The till is rather strong weathered with exception of the quartzite blocks (●●). Photo: M. Kuhle, 20. 8. 91

greater height of ice surface than their culminations are, since they must have been *overrun* by ice to produce their rounded forms (Fig 13, 14, 15). The residual highest limit of *glacial scouring merely shows* that the even higher slopes of valleys and mountains must have been above the icesheet surface before the deglaciation. This relates only to the late glacial period. The surface of the glacier at *maximum glaciation* must have been *higher* and the trim-line related to it must have been *destroyed* by undercutting erosion by a level of glaciation that lay below it.

Apart from these facts, the highest level of glaciation must have been occupied for a *very short period*, so that its geomorphological evidence has *not only* been destroyed in the late glacial period but *could hardly have had time* to develop in such a short period. If we bear in mind continual increase of ice thickness from early glacial times to its maximum and its then *immediate* decrease it must be the case that the lower parts of the valley and mountain slopes must have been polished by lateral grinding for a much longer time. It follows that the *higher* and thus *least* polished rock surfaces must have suffered the *quickest* (short duration) *destruction.*

The indicators referred to which provide *minimum ice thicknesses* (Fig 3) also *support* a *greater* icesheet thickness than that of 1200 m in the area of I2; in places they indicate a *much greater* one. The *necessarily convex form* of the icesheet also requires this. This is especially because the outflow of the ice did not destroy the *very moderately convex* icesheet, a convexity of surface curvature which has a *reciprocal* relationship to its area, or more precisely inversely proportional to its *least* diameter which, in the case of the Tibetan icesheet, was about 900 km (Fig 2, diameter of I2). The *dome-shaped* icesheet cross-profiles shown on Fig 4 and 5 occurred in the area of Tibet west of 88°30'E, in which the icesheet areas further east, divided in three centres, were completely combined (Fig 3 I1, I2, I3 from Kuhle 1985c, Fig 2). This similarly related convex surface was interrupted by the *outflow conditions* so that at 400 km in Fig 5, in the area of the Na-K'ot Ts'o and also at 1150 km in the area of the upper Tsangpo valley inset concave depressions subdivided the convex form by slopes in the opposite direction. At the glacial maximum an outflow southward to the Indus valley resulted from the Na-K'ot Ts'o (-lake), Pangong Ts'o area. In a similar way the *glacier flow* was *canalised* towards the east in the Tsangpo valley, thus explaining the *depression* of the surface there. A convex surface form was prevented on both long-profiles (Fig 8 and 9) by drainage maxima (outflow depressions). In Fig 4 and 7 the dome-like form of the icesheet is developed in a more *closed form* and it is only divided by the Tsangpo valley in the boundary area

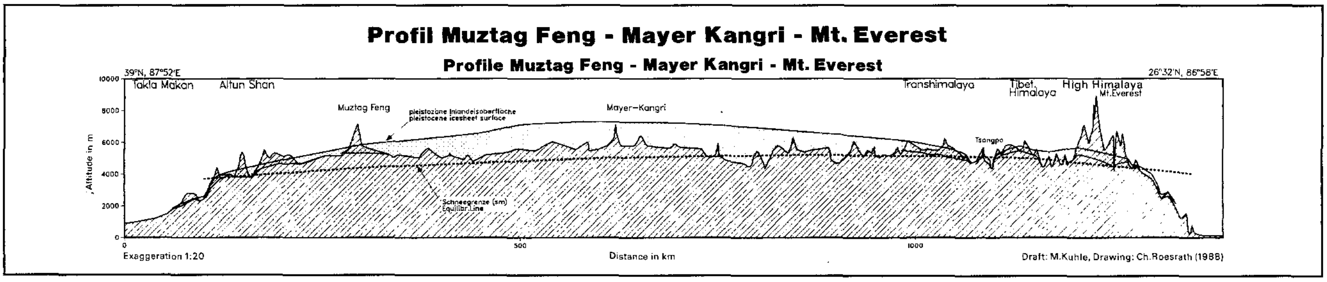


Fig 7 A cross section of the Pleistocene inland glaciation of Tibet (after Kuhle 1989)

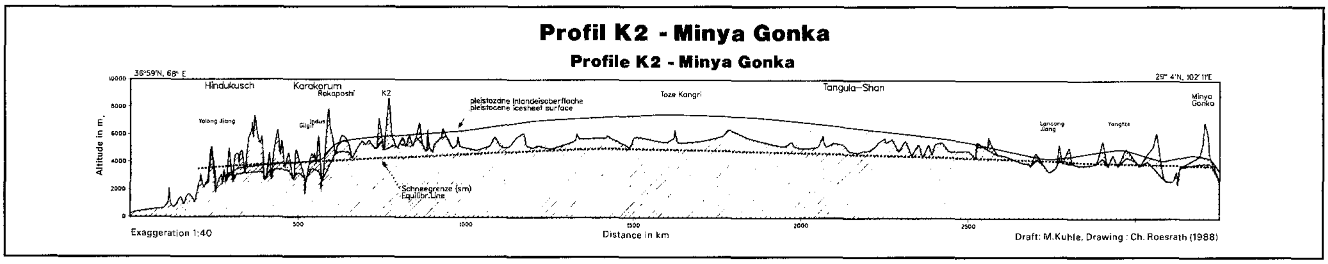


Fig 8 A longitudinal section of the Pleistocene inland glaciation of Tibet (Kuhle 1989)

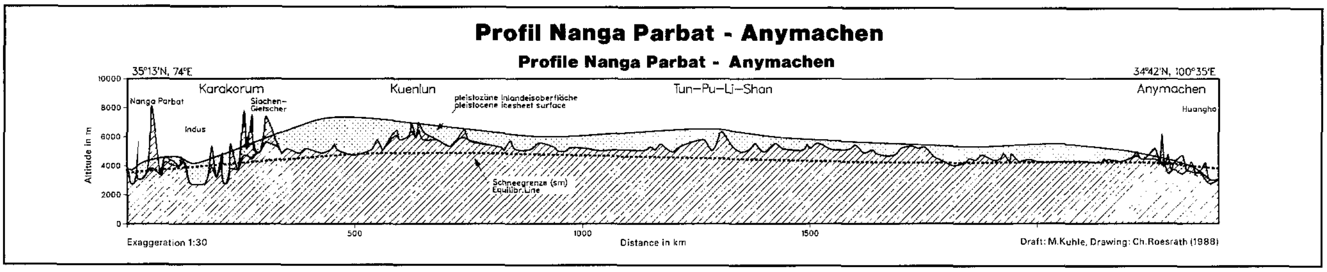


Fig 9 A longitudinal section of the Pleistocene inland glaciation of Tibet (Kuhle 1989)

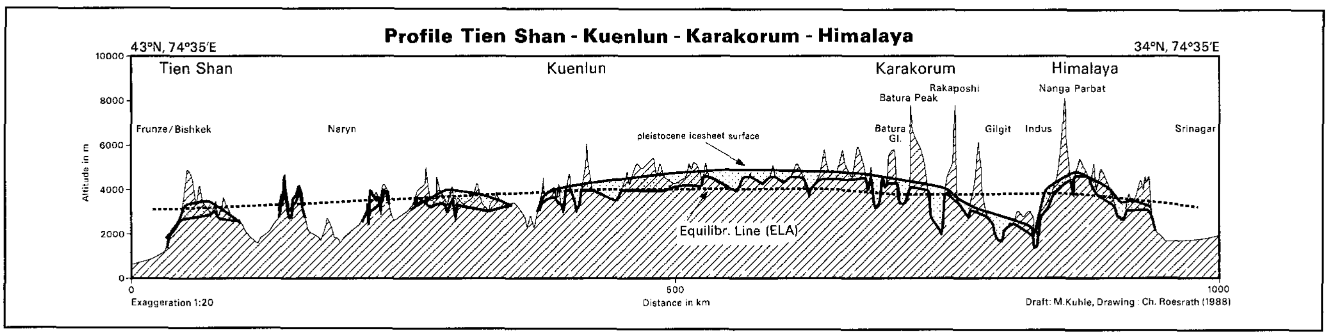


Fig 10 A cross section of the Pleistocene inland glaciation and smaller ice sheets from Tien Shan to the Himalayas (Kuhle 1989)

between I2 and I3 (this division is shown in Fig 2 and Fig 3) ie in the zone of contact between the inland ice complex in the center and the southerly ice flow network of the Tibetan and High Himalayas (Fig 4 at km 950–1000; Fig 7 km 1100).

The reconstructed icesheet shown in Fig 4, 5 and 7–10 must have reached thicknesses of 1500–2300 m. With such *thicknesses* in the plateau area its surface must have been *above* the glacial period ELA. In those places where deeper intra-montane basins and valleys were filled with ice there must have been local thickness up to a *maximum* of nearly 3000 m (Fig 4, km 580–640, Fig 5, km 670). In the *marginal areas* the closed ice surface passed over into *networks of ice currents*. These were transformed at the steep bounding slopes into single downflowing *outlet glaciers* reaching down to 2000 m asl. These formed the lowest ice margins which were subjected to the most intense ablation. Valley glacier thickness locally as thick as 1000–1600 m may be reconstructed in such areas (Kuhle 1982, 1983).

Fig 11
Extensive ground moraine areas at 4190 m asl on the very wide floor of the main valley SE of the Nyainqentanglha massif in the southern part of central Tibet (30°24'N/90°57'E). Large to very large granite blocks "swim" in the loamy fine-grained matrix (●●). In the background glacigenic flank polishings (⏶) on the orographic left-hand flank and glaciated knobs (▼) are visible.
Photo: M. Kuhle, 17.8.1991

The Deduction of Glacio-Isostasy

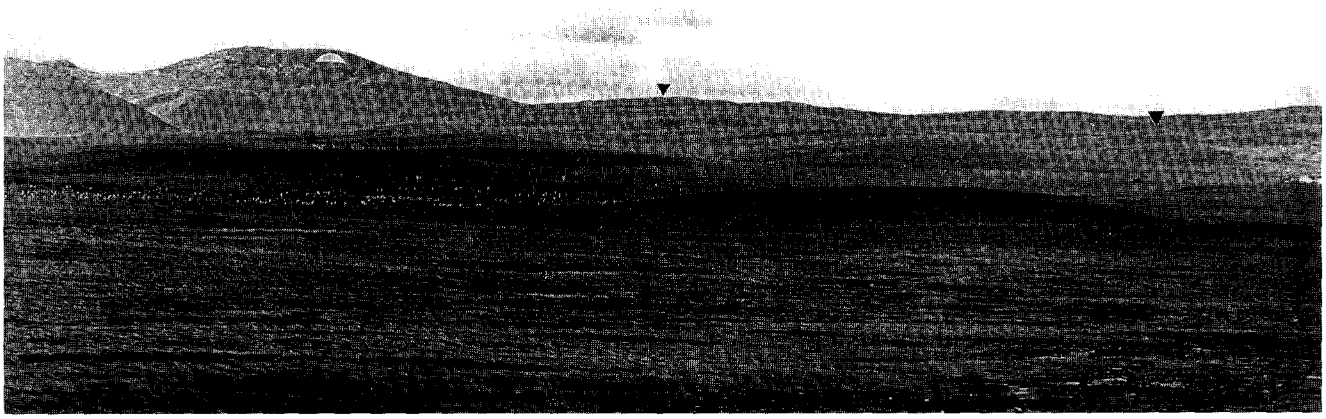
Here in Tibet there is an *absence* of widespread evidence of uplift such as that provided by shore-lines in Scandinavia (Mörner 1969, 1977, 1991, and others). Glacio-isostatic crustal movements *must* be *inferred* by means of glacial geomorphology and glacial geology from reconstructed former icesheet conditions. Using a conception as those developed by Mörner in Fennoscandia, where there was deduced a probable last glacial isostatic depression and post-glacial uplift of 830 m (Mörner 1991), a glacial isostatic depression of c 400–620 m may be deduced for *central Tibet*. It may be that close to the *centre* of the former icesheet, especially in those small areas where its thickness may have reached 3000 m (cf Fig 4 and 5) the amount of depression may have exceeded 700 m (Kuhle 1989c, p. 276). This estimate is based on a density ratio of $\Delta g = 1{:}3.7$ between the ice and the crustal material. This model requires a *transference of material via the asthenosphere* to a marginal uplift (forebulge). This amount of downward and upward movement must have *decreased* towards the edges of the Tibetan plateau. This happened because of the *decrease in ice thickness* towards the edges of the plateau where the ice outflow velocity showed a *sudden* increase. Such an increased outflow led to a marginal *constriction* of the ice cover ie to comparatively *narrow* outlet glaciers (cf Fig 2 13). As an example the *thickness* of such an *outlet glacier* over the (Kuelun pass (Kunlun Shankou 4820 m asl 35°37'N/94°02'E) downward to the north through the transverse Kuenlun valley must have been only 600–700 m, as determined by a moraine cover of erratic granite blocks on the mountain ridges (Fig 12) there reaching 600 m on the valley flanks. These *marginal* reductions in ice thickness are related to the reduced area of the ice surface and its constriction by channels into narrow glacier streams. They go together with the development of these outlet glacier tongues, flowing down up to 3000 m below the ELA. Beyond here the glacier ice, apart from *thin steep hanging glaciers* on the high mountain peaks, is moving only as narrow glacier streams, running in the main direction of the valleys. Thus the *load of ice* in the marginal areas also above or within the snowline level was clearly *less* than in the centre of the plateau, so that the glacio-isostatic movement must have been much *less* here (cf Fig 2, 4, 5, 7, 8, 9, 10).

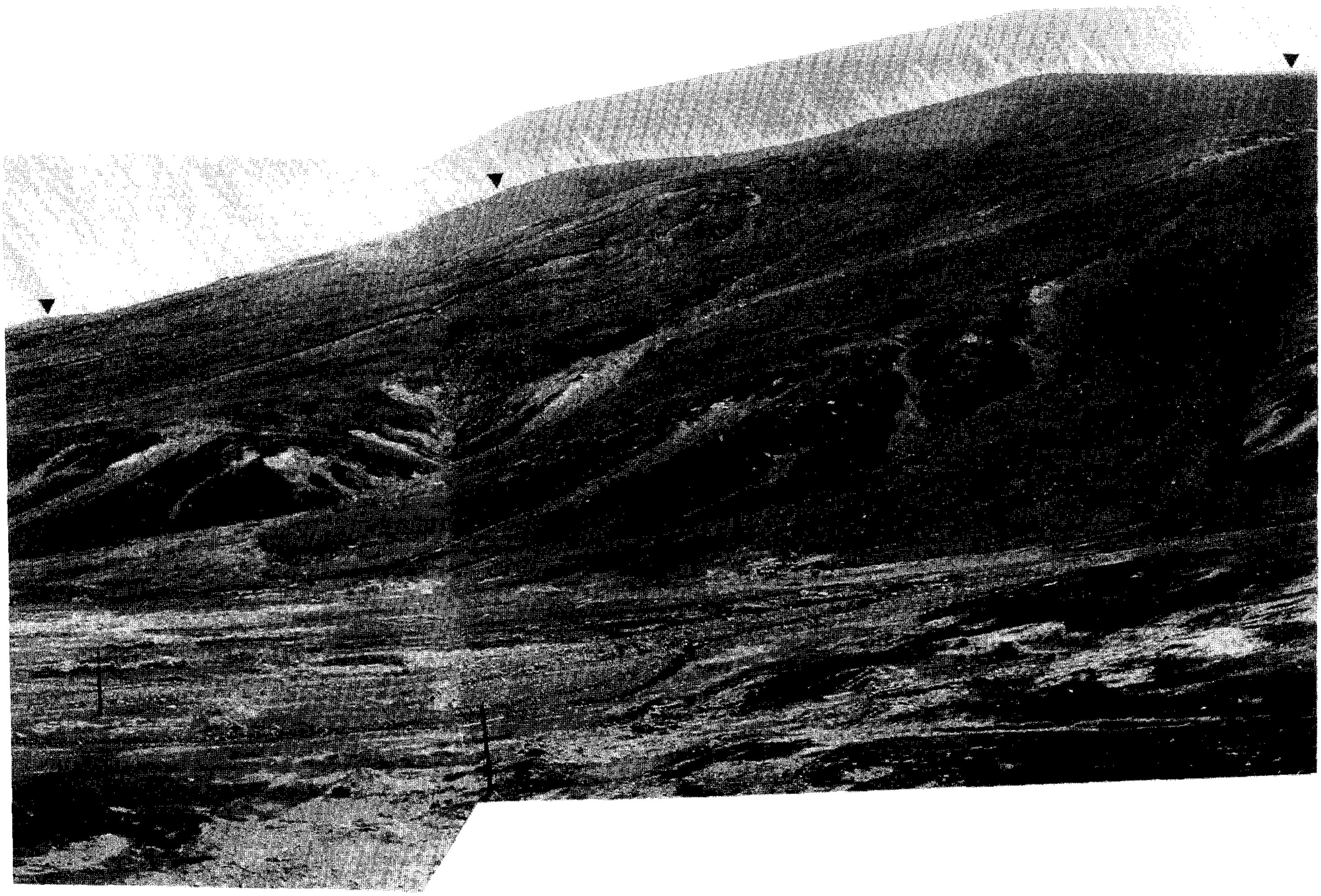
Glacio-Geomorphological, Glaciological and Palaeoclimatic Indicators of the Most Recent Glacio-Isostatic Uplift Movement in Tibet

On the north slope of the Shisha Pangma Massif (8046 m high in the Central Himalayas 28°38'N/85°39'E) there lie 10 to 15 Ka old *end moraines* and *Bortensander (IMR)* extending down to 5015 m asl (Fig 16). They belong to the area in front of the recent Yepokangara glacier which *ends today* at 5545 m asl, some 530 m *higher*. This proves a depression of the ELA of *only* about 265 m (Kuhle 1988i pp. 483-5). This however is a *much too small* snowline depression for the late glacial. In the Himalayas it is at best typical of the neoglacial, some 2000–4500 BP ago (cf Kuhle 1986e; Shiraiwa et al. 1991). From the age of the moraines and Bortensander, which relate geomorphologically to the *late glacial* Ghasa stadium (I), an ELA depression of over 1000 m would be appropriate (in the Dhaulagiri and Annapurna Himalaya to the west 1200–1250 m according to Kuhle 1982, 1983). This difference of 700–800 m could be explained by a post high glacial *glacio-isostatic-uplift* of

Fig 12 Morainic material (till and lodgement till) and erratic large granite blocks, coming from the Tanggula Shan in the south, are deposited on the ridges and summits of these Kuenlun Mountains up to an altitude of 5300 m asl (▼▼). The decametre-thick morainic layer covers the solid schist-rock. The altitude of the valley floor is 4600 m asl. The morainic deposits prove a thickness of the former inland ice sheet here on its northern margin of more than 600–700 m. We are looking from the Kunlun Shankou (35°39'N/94°05'E) to the north.
Photo: M. Kuhle, 15.8.1991

Fig 13 The peaks, some of them in excess of 5400 m asl (⏶), were polished round even more perfectly than most of the Scandinavian "fjell"-landscapes (31°33'N/91°55'E; 4600 m asl, in the foreground). Also typical for central Tibet is banded outcrop polishing (▼▼). The glacial polishing has etched out the outcrops from the sedimentary rocks. Photo: M. Kuhle, 17.8.1991





some 600 m during the last 15,000 years. Then these end moraines, when they were pushed up by the Yepokangara glacier, must have been at 4400 m instead of 5000 m asl. Thus a depression at the end of the glacier of almost 1200 m (1130 m) would explain a late glacial depression of the ELA of at least 600 m (1200/2 = 600 from ELA depression = (tp-ti)/2 (m); tp = present altitude of end of glacier tongue, ti = its previous value). A greater glacio-isostatic uplift is not to be expected on the southern edge of the Tibetan plateau on *topographical grounds* because ice thicknesses significantly over 1500 m are improbable as the result of drainage via the steep S slope of the Himalaya. We must thus consider an even *younger* late glacial arrangement of ice terminal positions (at about 10,000 BP). This is provided by the Sirkung Stadium (IV) with an ELA depression of 700 m (Kuhle 1982 pp 158-9). The absolute age of this stadium is *only a little* younger than that of the oldest late glacial stadium (Ghasa Stadium I) referred to above.

The argument for a *very considerable* uplift, which can only be understood as *glacio-isostatic*, is based on the extraordinarily slight climatic snowline depression (200-300 m) shown by the *late glacial* end moraines, whilst in neighbouring *similar* climatic areas associated with the S slope of the Himalayas the end moraines of the *same age* witness to a snowline depression of 700 m. The *apparently only slight snowline depression (ie the extraordinarily high* moraine position) *coincides* with the 4600-5600 m high southern edge of the Tibetan plateau where, because of the damming effect of the Himalayan mountain wall, an *ice sheet over 1000 m thick* must have existed. In the flat, plateau-like relief relationships, where the roche moutonnée landscape witnesses to the *ice cover*, the reasons for the formulated causality are to be seen. There was *no difference* in climate; (the nearby valleys to the south were *too close* and the advective balance of temperature in the free atmosphere was *too massive*) but it is *only here* that the formerly *glaciated high plateau* supports a resultant *glacio-isostatic* movement since the late glacial. The maximum of uplift described by Mörner (1991 Fig 4) for Scandinavia between 13 and 4.5 Ka BP *supports* the *real possibility* of the above approach.

There are, apart from the above, indices derived by *other methods* which lead to *very significant* uplift. *Today* the Yepokangara glacier tongue end, as well as those of its parallel neighbours, lie 8-12 km from the above mentioned *late glacial* end moraine walls of the Ghasa and Sirkung

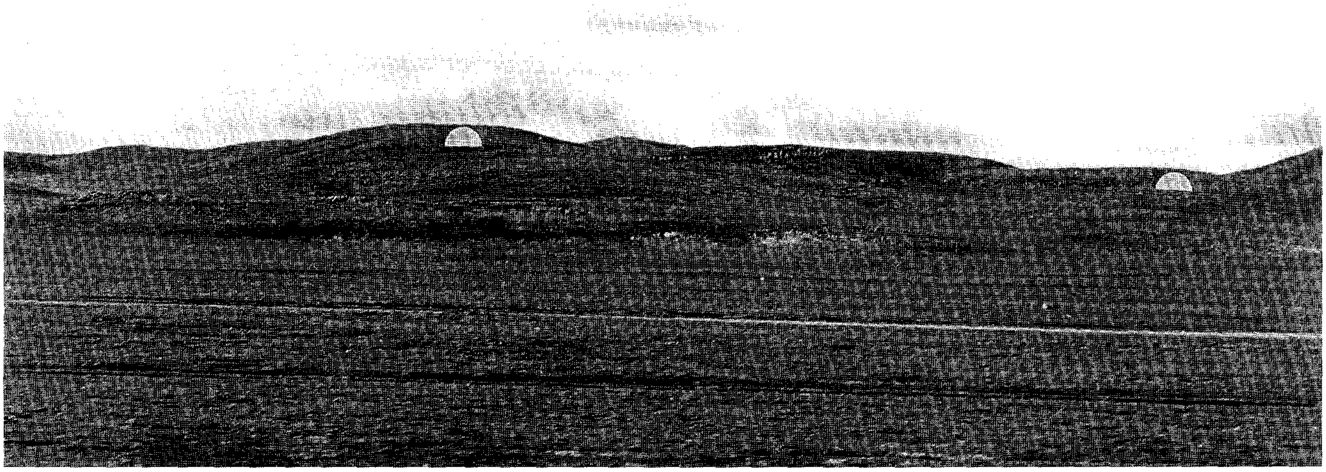


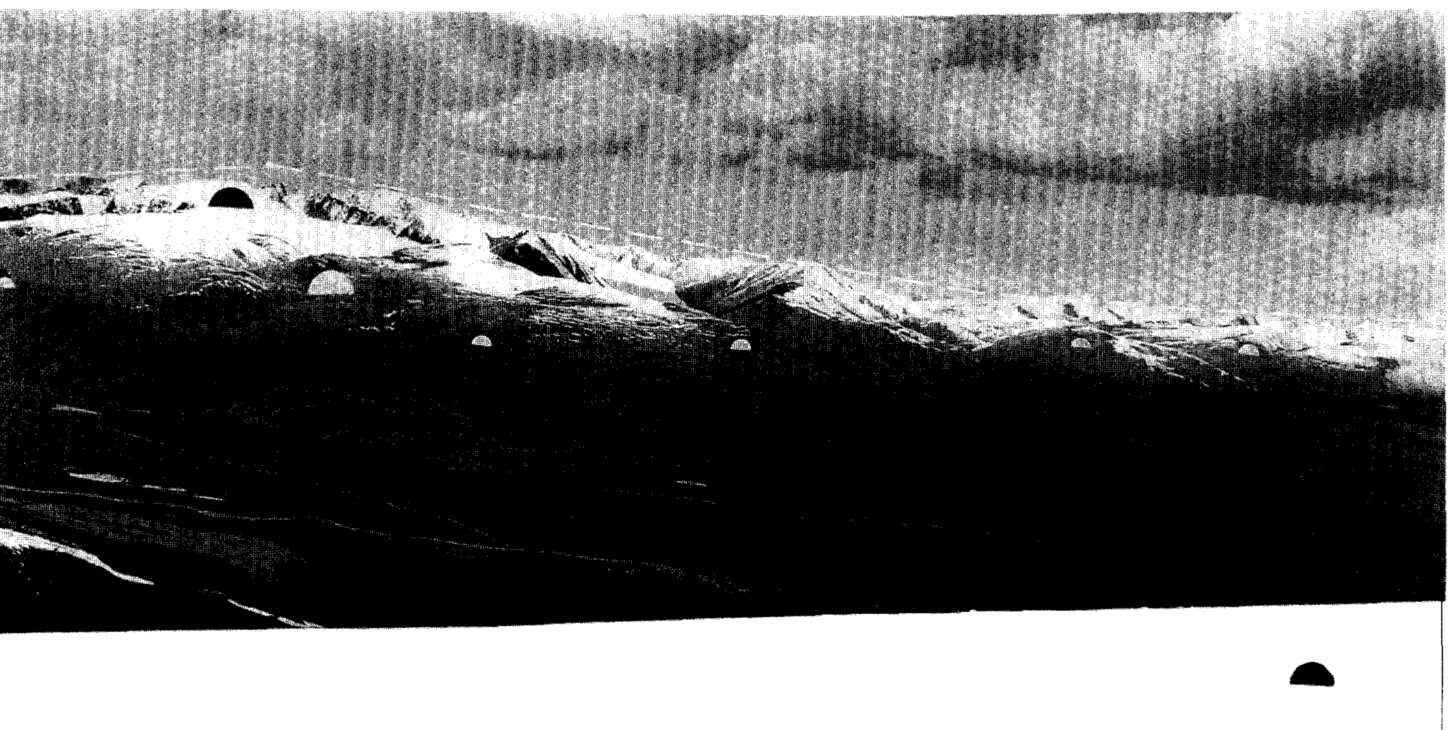
Fig 14 Landscape featuring polished undulations and depressions in central Tibet (31°35'N/91°49'E; 4580–4800 m asl). These thresholds sometimes present classic forms of roches moutonnées (▲▲). Photo: M. Kuhle, 17.8.1991

Stadia (I–IV). In these later periods these *end moraines* and the *Bortensander* (IMR = ice marginal ramps) which were deposited between the individual glacier tongues reaching down from the Tibetan plateau must have been *well below* the related snowline.

But *today* there lie *remarkably* upon these Bortensander and end moraine deposits some small *ice caps* and *plateau ice* ("flat-top" glaciers) (Fig 16). However it is a striking fact, that at the same time the Yepokangara glacier and its parallel neighbouring glaciers have not reached the *former ice-marginal position* again. The depression of the ELA as a possibility for the *local glaciation* of these *end moraines* and *Bortensanders* by their own, must also have extended to the Shisha Pangma Massif, ie the even today glaciated

Fig 15 In its central part the Tien Shan Plateau was also covered by an ice sheet. The whole mountain landscape (here taken from the Akschirak massif (Ak-Shyyrak) to the WNW from 4250 m asl; 42°10'N/78°30'E) was polished round (▲) up to 4400–4600 m asl (ice level: - - -). This proves an ice thickness of more than 800 m. The valley floors are filled with lodgement till (▽). Photo: M. Kuhle, 26.6.1991

alimentary area of the High Himalaya and *not just* the few kilometres into the mountain foreland of the Tibetan plateau to the north. This *cannot* be the case, for *otherwise* the *present* glacier tongues which previously laid down the ice marginal deposits referred to *must have reached them afresh* or even *overrun* them. This conclusion is based on the fact that when formerly these end moraines and Bortensander were deposited they *could not* have carried local ice caps. This is so because of *two* considerations (1) a climatic one, for this kind of sediment, glacifluvially effected, are deposited *far below* the ELA; they are the glacier's *lowest* deposit; (2) the typical forms "end moraine" and "Bortensander" are deposited subaerial ie *not* subglacial but without simultaneous ice cover. Because of these reasons it follows that it is necessary to look for some cause why it is possible for there to be a *new local* formation of glaciers *on* the end moraines and Bortensander *without* any simultaneous increase of the alimentary area of the glaciers flowing from the north slope of the Himalayas. The only remaining possibility is a *differential strong uplift* between the Tibetan plateau and the high Himalaya, the former being the mountain foreland of the latter. A *differential uplift* is supported by geological and geomorphological evidence. As an example are the *antecedent transverse valleys* across the Himalaya, such as the Thak Khola (Kali Kandaki), the Bote Chu (Sun Kosi), the Arun and the Tamur valley, which run from the plateau and are *older* than the Himalaya and have syngenetically incised themselves *during* the uplift of the main range of the Himalayas. Although the high Himalayas are *younger* than the edge of the south Tibetan plateau they are 3000 m *higher*, indicating a more *rapid tectonic uplift* of the Himalayas. In our case this means a more *rapid increase* in the alimentary areas of the glaciers on the north of the Himalayas. So their glacier tongues in the meantime must have *not only reached* the end moraines and Bortensander referred to but even *overridden* them *without* their having carried an ice cover *developed in situ*. The relationships here are thus *inverted*: the local glaciation of the end moraines and Bortensander *without* the glaciers flowing from the Himalayas reaching them at the same time indicates that the *plateau* was *uplifted faster* than the Himalayas. This represents a notable *special case* based on the geologico-tectonic premisses set out above which requires an explanation. The *well accepted*, if not only explanation for the fact that the Himalayas have been uplifted faster since some million years (4 mm per year according to Gansser 1991) but *occasionally more slowly* than the Tibetan plateau (as in the last 15,000 years) is the following: The *deglaciation* of the southern plateau edge has *glacio-isostatically* unloaded it and thus raised the end moraines and Bortensander above the ELA, resulting in their *local glaciation*. This uplift is associated with a *reversed* uplift velocity along the marginal fault of the northern Himalayas. Such an event must have been *frequent* during the course of the Pleistocene, probably with each *interglacial*, and accompanied *each new* deglaciation. The *constitutive* causality is the very different *relief specific* ice loading of plateau versus high mountain ridge. *Even though* they have *always* been glaciated, it has only been at the height of glaciation that the High Himalayas, because of their precipices and *steep slopes*, have carried an ice load *only slightly* exceeding that of today, whilst the *flat* plateau was *extremely* loaded by the



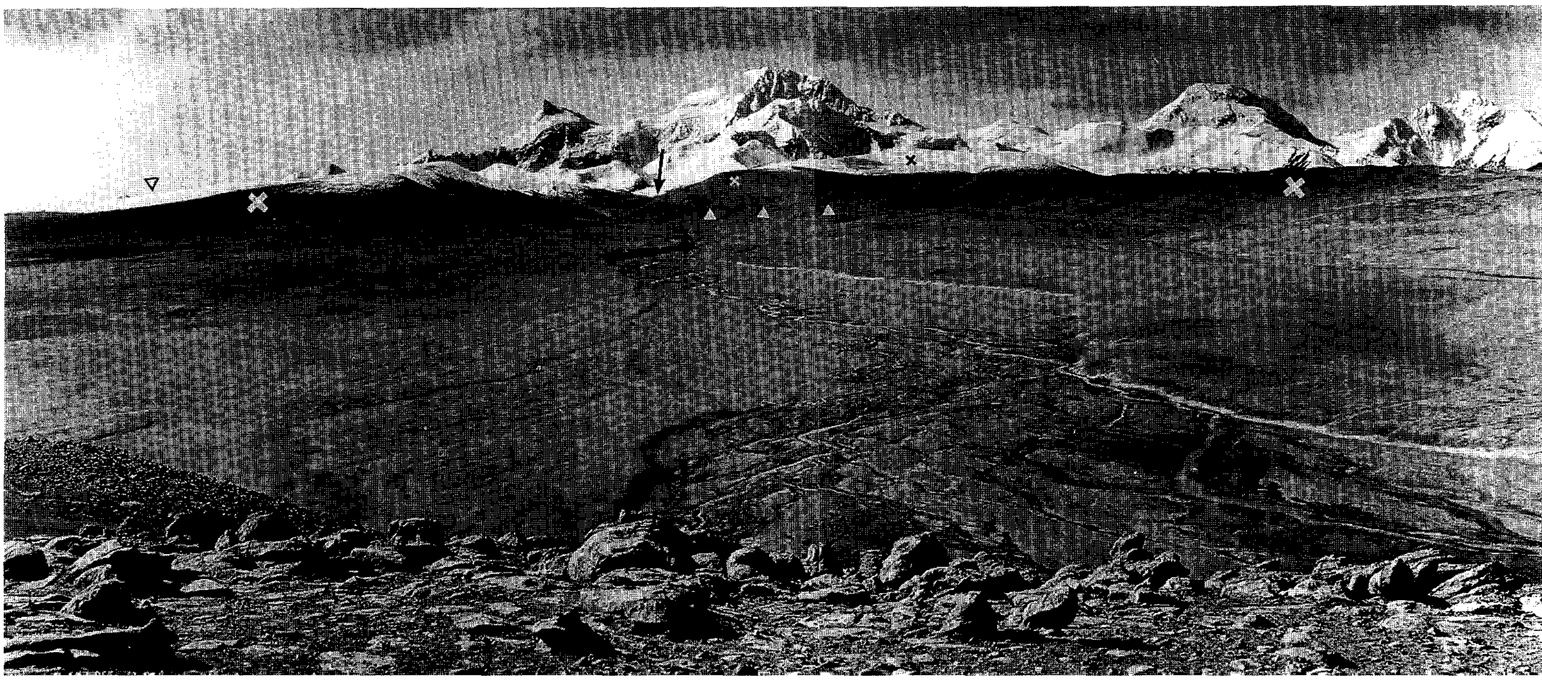


Fig 16 N slope of Shisha Pangma seen from 5250 m asl (28°23'N/85°47'E) on the S Tibetan plateau. The high plateau in the foreground adjoins directly to the High Himalayas. (▲▲) show three Late Glacial stadial positions of the Yepokangara glacier which flowed down from Shisha Pangma. Today its tongue ends at the foot of the 8046 m high mountain (↓). The former endmoraines (▲▲) deposited between the Late Glacial piedmont glacier tongues are Bortensander (ice marginal ramps = IMR, X X). The IMR were raised above the equilibrium line (ELA) during the Post Glacial so that today they have individual ice patches (small flat top glaciers; ▽). This new glaciation shows that Tibet has been uplifted more rapidly than the Himalayas because the recent tongue of the Yepokangara glacier (↓) no longer reaches these lowest end moraines. Photo: M. Kuhle, 15.9.1994

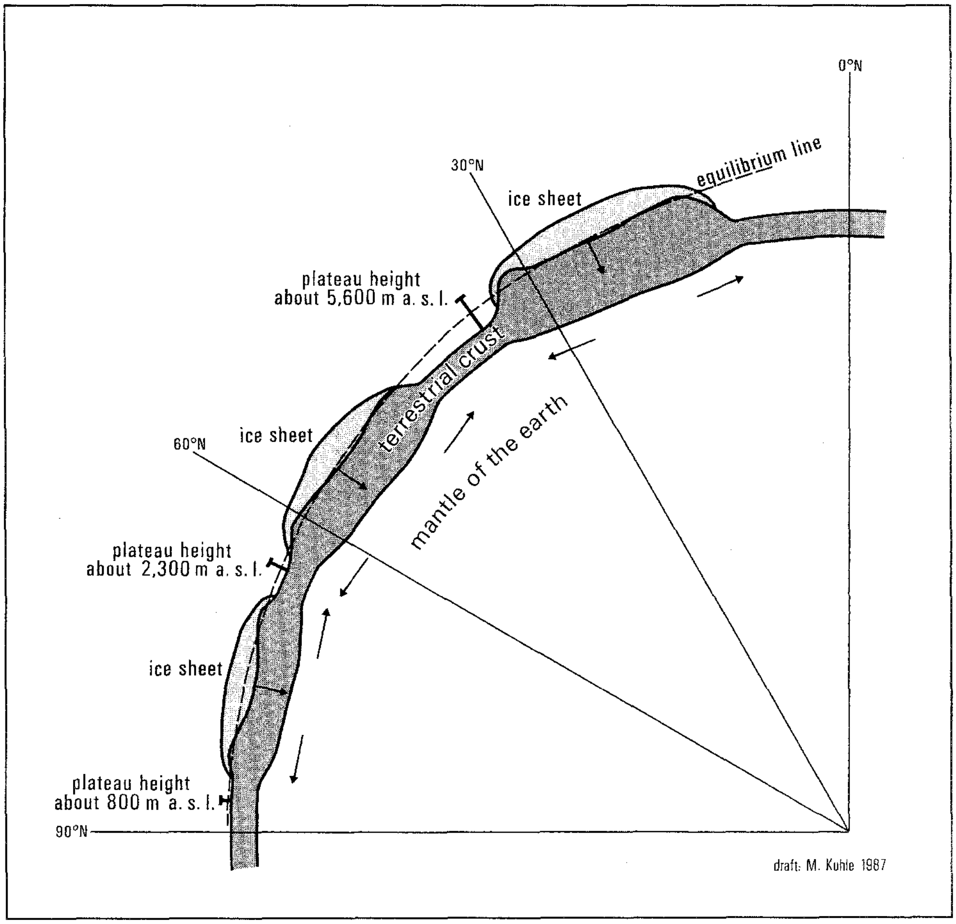
former ice. The *stress* produced by the glacio-isostatic depression must thus have produced a correspondingly *rapid* unloading *uplift*. Thus it is proposed that an *glacial-interglacial-maximum reversal* from faster *Himalayan* uplift to faster *Tibetan* plateau uplift occurred along the *N Himalayan ie S Tibetan marginal fault*. In this way the movement of the Himalayas is *throughout uniformly directed upward* whereas the south Tibetan slab *sinks* under the load of maximum glaciation and *rises very rapidly* with deglaciation.

The *Himalayan uplift velocity* of a few millimetres per year is about a tenth power less than that which can be calculated from the *local glaciation* of the end moraines and Bortensander of the *southern Tibetan plateau* (a glaciation which covers only the highest parts of these end moraines (cf Fig 16). Thus about 15,000 to 10,000 years were required to raise the end moraines and Bortensander from their *original* position of formation 600 m *below* their present height to their current level of more than 5000 m close to the ELA. This signifies an uplift of 40-60 mm/year. Such a *magnitude* of movement has, to the knowledge of the author, *no* equivalent on Earth as a *purely* tectonic uplift. But a *glacio-tectonic* mechanism would allow such a value (cf Mörner 1980, 1990, 1991 etc.). These *very* different uplift *rates* provide further *qualitative* evidence for the effectiveness of *glacio-tectonics* in this test area of S Tibet: In *spite* of the repeated *very* rapid *glacio-tectonic* uplifts of the plateau, during the *whole period* of the *Quaternary* the Himalayas compared to Tibet have been uplifted more and more.

Further Consequences of the Glacio-Isostatic Depression of Tibet by a Maximum Glacial Ice Sheet

A maximum plateau depression of some 500–700 m (400–730 m) further means that this must reflect the ice load of a *climax stadium*. That is, there was a *mature* dome-shaped ice body which fed an *outflow of ice* across the overflowed montane ridges and transfluence pass summits of the surrounding mountain systems (Fig 12), as well as through the antecedent transverse mountain valleys down to an altitude of 2000 m or lower in front of them. These kinds of glacial and outflow relationships resemble those found *today* in east Greenland. In this way there arises an equivalence between the *central Tibetan* ice sheet regime under *very cold* and probably *semi-arid* conditions and an *evaporative and melting ablation* regime of draining outlet-glaciers such as is met with in the *very low* glacier terminal positions known in *subtropical* environments. This *mature* stadium of marginal ice flow is estimated to have occurred from the *rate of growth* of the icesheet under an annual precipitation of at least 100 mm above the ELA (cf Kuhle, Herterich and Calov 1989 Fig 6 and 7, p. 205). Within some 10,000 years the *thickness* of the ice was able to increase by about 1000 m (1100 m according to Kuhle 1989c, p. 281). The

Fig 17
Decrease of the potential plateau height as a function of the inclination of the ELA from lower to upper latitudes. The glaciation, which in consequence of the uplift of the plateau sets in, leads to a glacio-isostatic compensation of the vertical tectonic movement. That means: the endogene tectonic uplift is limited by the exogene climatic factor.



maximum ice thickness referred to above could have been attained in some 15,000 years even in the *model conditions of alimentation and* growth reduced by *aridity* (Fig 4, 5 and 7-10). The *build up* of ice which according to the oldest last glacial dates of moraines in High Asia happened about 70,000 to 50,000 years BP (Schroder & Saqid Khan 1988; Xu Daoming 1991) must have been that *much quicker* because this *initial condition* was related to *no marginal outflow* of ice from the Tibetan plateau. At the same time the *glacio-isostatic depression* producing a subsidence trough in central Tibet must have been *increasingly* active. This depression must have eventually attained such a depth of 500-700 m (v supra) as to have led to a *further* 500 m of ice sheet thickness under *equivalent* ice sheet dome conditions. Such a depression is *omitted* on Fig 3 to 5 and 7 to 10 because it is already the *consequence* of the icesheet depicted there, as was able to be reconstructed from *geomorphological* and *Quaternary-geological* evidence. There is to imagine a *slightly depressed basin form* from which the ice sheet flowed *across* the surrounding mountains. It is not clear if it was in the first place an outflow *close to* the *surface* or if, in spite of glacio-isostatic *overdeepening*, the load of the ice dome produced an outflow at the *base* of the "depression basin" and over a *reversed slope* at the margins of Tibet. The *central* depression produced by the *greater ice load* in the centre must have been associated - according to the forebulge model (Daly 1934) - with a *marginal uplift* of Tibet ie of its surrounding mountains such as Kuenlun, Karakorum and Himalayas. This is shown on Fig 2 to 5 and 7 to 10 as a much *smaller* load of ice which is *reduced* in thickness by the flow of the *steep* outflow glaciers (v supra). Active in the same way on the plateau margin is the *narrowing* by the ice confluences in the upper origination areas of the valleys between the mountains. It may also be explained as a result of the *abrupt intensification* of the outflow at the edge of the high plateau. A *rapidly accelerating* high glacial *glacial-tectonic* uplift must therefore have been experienced by the mountain margins of Tibet which must have been *superimposed* in an accelerating manner upon the primary orogenetic uplift. After the pattern of the several hundred kilometres wide "forebulge" uplift in N Europe (cf Mörner 1991, p. 76, Fig 1) there must have been a corresponding *very extensive* area of uplift into the Himalayan foreland to the south and in the areas of the Tarim basin, the Tsaidam basin and the Gobi desert to the north. It is of course questionable whether an analogy between Tibet and Fennoscandia is permissible. In contrast the *present day* (and correspondingly *interglacial*) *depression* of the "forebulge" must be associated with the *unloading* of the previous central *subsidence trough* and its *uplift* by deglaciation. It may be that this could explain a *depression* of, for example, the main range of the Himalayas by as much as 100 m during the last 10,000 to 15,000 years. This must have indeed been a *relative depression* because it must have been considerably *compensated* for by the *primary tectonic* ie *orogenetic uplift* of the Himalayas.

The *accepted* 100 m of *upward* and then *downward* movement of the *"forebulge"* between glacial maximum and interglacial is the result of a *vague* analogy from the data of Mörner (1991, pp. 76–7, Fig 1, 2, 3). He calculated the maximum depression of Scandinavia to have been 830 m. This produced a *maximum uplift* of the "forebulge" of 170 m. In the case of Tibet it is *deduced* that the central depression was some 500–700 m, so that from this a "forebulge" uplift of a clear 100 m is a *coarse approximation.* Such a *gross approximation* must not remain unmentioned since the overall depressional relationships must be understood in relation to the difference between the *crustal properties* of Fennoscandia and Tibet, and also that the different *basal diameters* of the subsidence trough must have led to differences of volume, so that the outlined development of the "forebulge" must be understood as *careful hypothetical first approximation.*

The Classical View of the Uplift History of Tibet and its Inconsistency with the Glacio-Geomorphological Evidence

Up till now the uplift history of Tibet was understood as being based on *primary tectonic* phenomena ie *orogenetic* uplift (X. Chen 1991; Fang Qian 1991 etc). This has been the result of the recent literature of *plate tectonics* (cf L. Lu 1991; Gansser 1991 etc.). Such an explanatory model is appropriate and satisfactory. But such a mechanism could have been effective *only* until to the uplift above the ELA. Afterwards the *growth* of an *icesheet load* effected the *compensation* of the forces of uplift and this eventually resulted in a *glacio-isostatic depression* (cf for this Fig 17). The *temporal* arrangement of the *first* uplift of the Tibetan plateau *above the snowline* must be questioned as well as the first ice loading and the ceasing of the further uplift ie of its first *interruption* by a glacio-isostatic *depression.*

According to Fang Qian (1991) and also Wu Xihao, Wang Fubao, An Zhisheng, Qian Fang, Lu Yanchou & Zhang Xuanyang (1991) before 4.9 to 6.5 Ma BP the surface of the Tibetan plateau lay at 1000–2200 m asl. This is based on the discovery of Hipparion guiznongensis and its *warm living conditions* in the lowlands. Thence the authors, supported by less significant lake sediments, *extrapolate* to a *continuous* but in its speed *oscillating* uplift of Tibet until now.

Opposite to this, having accepted the *lowland position* at 4.9 to 6.5 Ma BP indicated by the marker fossils of Hipparion as a *time marker*, an *acceleration* of the uplift of *only one quarter* would place the Tibetan plateau already at its present altitude in the *early Pleistocene* about 2–1 Ma BP ie rather higher and thus above the ELA of *that period.* In that case the *last glaciation* was *not* the *first* ice sheet to leave geomorphological and glacio-geological indicators as they are *still* observable. Since the *early* Pleistocene ie the beginning of the Quaternary there could have indeed been alternations between *glacial maximum* ice sheets and *interglacial* deglaciations ie ice-free periods. This clearly means that phases of glacio-isostatic *depression* and *uplift* must have alternated since 1–2 Ma BP. Why should it not also have been the case for *plate-tectonic phenomena* produced by the impact of the Indian subcontinental and Eurasian plates persisted more or less *unaltered* over 40 Ma (cf X. Chen 1991 etc.) so that the uplift situation, accepted until now as *primarily tectonic* without question, could have culminated 1–2 Ma *earlier* ie been *attained* before 1–2 Ma BP.

This *new view* of the *uplift history* of Tibet, contrasting a Quaternary *glacio-isostatic up and down movement* of Tibet with one of unidirectional tectonic uplift, is based on the hypothesis that the *icesheet* glaciation of Tibet could have *caused the Quaternary ice periods* (Kuhle 1985c, 1987d). This is based on the idea that an icesheet of 2.4 x 10^6 km^2 with its 70% *greater albedo* than that of the present *ice-free* Tibetan plateau must have *reflected* back into space *four times* more incoming *radiation* than did the northern ice sheets because of its highland and latitudinal ie subtropical position. Thus the uplift of the Tibetan plateau above the ELA must have, according to this model, *triggered* a *global cooling* that brought with it a build up of *montane* and *foreland glaciers* and *ice sheets* and thus the glaciations (cf in relation to this Kuhle 1987d, 1988b, 1989c). Thus the *potential for world-wide ice periods* was produced by the uplift of this great plateau above the snowline. The complete glaciation of Tibet was a *precursor* of the Quaternary glaciations. The author's idea of a *terrestrial cause* of Pleistocene glaciation dependent on plate tectonic phenomena comes from that of Tibet having already *reached* an approximation to its *present height* near to the climatic ELA by the *beginning* of the period of glaciations. Such a *terrestrial* triggering is an *unavoidable necessity* because the Milankovitch radiation anomalies which continued to act after Permocarboniferous times had been *unable* to perform such a triggering. According to this model the Milankovitch cycles were only responsible for the *interruption* of the Quaternary ice age by *interglacials ie its cyclic* interruption by *deglacials.* With the plate-tectonic induced total glaciation of Tibet being accepted as a *once acting cause*, the *cyclic* regularly repeated *extra-terrestrial* effect produces *another kind* of action (ie another quality) in this *new* combination: *changed* earth-orbital parameters could activate the period of glaciations a *little earlier* by a small depression of the ELA and tune into an *interglacial* rhythm (cf Kuhle 1988b, 1989c).

This kind of explanation may be spoken of as *circular* ie reasoning from *cause to effect* and as *too* hypothetical if further *empirical* indices were not found of *early-Pleistocene* uplift of Tibet up to or above the snowline. In many ice-marginal localities around the Tibetan highland with its surrounding mountains besides the moraines of the last glaciation there are also found *older* and *lower sited end moraines*. The author observed such lower moraines in eleven localities (Kuhle 1987d, b, cf Fig 1) on the W, N, E and S edges of Tibet. In NE and NW Tibet, for example, such end moraines lie 150–300 m *lower* than the end moraines of the Würm period (cf Kuhle 1989c, p. 283).

On the eastern edge of Tibet (30°45'N/103°20'-40'E) west of the town of Chengdu at little above 600 m asl there are *ground moraine* deposits several (2-15) metres thick over a considerable area of some 40 x 50 km (Fig 6). Their origin as older than the last ice period is confirmed by their *intensive degree* of *tropical weathering*. Colleagues, such as Professor Tianchi of the Geographical Institute in Chengdu, confirm their glacial origin. They *confirm* these ground moraines as *even older* than the Riss glacial period and as belonging to the *early or middle Pleistocene* (c 500 Ka by friendly verbal information in August 1991 in Chengdu) without however a definite absolute date being available. In a mountainous area close to that older ground moraines and a few kilometres from the plateau edge of Tibet rising to the west there is the Chung Leh-shan at some 4500 m. Here there is an indication of *early to middle* Pleistocene *piedmont glaciation* which, *because* it extends down into present *warm subtropical* climatic conditions, *must* have flowed from an *already highly uplifted* Tibetan plateau in order to have been able to reach down so far and cover such an extended area. The lowest of the *last glacial* glacier terminals in this area of the edge of the Tibetan plateau *reached down only* as far as 1300–1500 m (see v. Locy 1893; Li Tianchi 1988 etc.). This means that at the time of *that older* piedmont glaciation the ELA must have been 300–400 m lower than during the last glaciation with the *same alimentation area* ie the *same height of the Tibetan plateau*. Judging from the knowledge of a *world-wide* comparison of *ELA differences* between the Würm and older glacial periods, the snowline of these earlier glacials was *only* some 100 m *lower* than during the Würm. This means that the height of the area of ice supply (the *height of the plateau*) must have been some 600 m *greater* than during the *last* glacial period (during which the ELA was running some 100 m higher) and that the *lowest ice margin* related to the last glacial period must have been even 800 m *higher* than at the time of the older piedmont glaciation.

In the case of the other chosen example of 150–200 m *lower and older* end moraines and ice *terminal positions* on the NW edge of Tibet at the S edge of the Tarim basin (ca 50 km S of the Yeh Cheng oasis in 36°N/77°E) these must have come in the same way during the *penultimate (Riss) glaciation* from a Tibetan plateau with *at least an equal height*, if not higher. These *older moraines* could *not* otherwise have been preserved if the Tibetan plateau had been *further* uplifted *from the Riss* to *the Würm* glacial periods. They were *overridden* by the edges of the Würm period glacier ends. At an *average rate* of uplift of 4 mm/a (cf Gansser 1991, p. 56) the Tibetan plateau must have experienced during the Riß-Würm-interglacial (100–140 Ka) an uplift of some 400–560 m. Thus a glacier source area 400–560 m *higher* during the *Würm* than the *Riss* glaciation *must* have led to an *ice terminal position* during the Würm 200–360 m *lower* than the Riss end moraines. The Riss moraines would have been *overridden* and thus would have been *destroyed*. That the *latter* however *are still there* and lie 150–300 m *below* those of the last glaciation shows that a *continual uplift* during the Pleistocene, or at least from the penultimate to the Würm glaciation, *could not have occurred!* These facts *do not* support a block uplift of Tibet *with or without* the low foreland to its east and northwest, for from this point of view the *difference in height* of the end moraines between the last glacial and older periods would *not matter*. The conclusions, speaking for a *not* continued increase of height during the course of the Quarternary, would *not* be contradicted.

The solution to this problem may be also approached from *climatic* results. If for a total glaciation of Tibet and the formation of the lowest *last glacial* end moraines a *sinking* of the climatic ELA to 1200 m below the present height was necessary, the *snowline depression* during the *penultimate glaciation* must have been 400–560 m lower to have produced a corresponding *total* glaciation of a Tibetan plateau which then lay 400–560 m *lower* than during the Last Ice Age (with a depression of 100 m greater, which follows for the 150–300 m lower moraines of the Riss period). This requires a *snowline depression* of 1700–1860 m. From a *global comparison* this is *much too large* and would thus require a special, *unexplainably* strong local alteration of climate. Because of this the author comes to the conclusion that Tibet had already reached its *maximum height* at the *beginning* of the glacial periods. This leads to a first *total glaciation* with *glacio-isostatic depression*. During the course of the Quaternary this condition was repeated from ice period to ice period, in alternation with interglacial *unloading uplifts* as the result of deglaciation. *At present* there is a state of interglacial unloading uplift, which, should it reach again a height of 5400–5600 m, must lead to a *renewed* ice sheet formation since the snowline level will then have been *reached once more*.

Is there a Basic Absence of Agreement between the Indicators for the History of Uplift of Tibet Contained in the Literature and the here Proposed Model of a Superimposed Glacio-Isostatic Uplift?

The wave-field characteristics and velocity-structure derived from the DSS data (X. Chen 1991) indicate a three part crustal structure which was divided by the inserted uppermost mantle (ie low-velocity crust-mantle zone, litosphere) and an upper mantle layer (ie two low-velocity layers, astenosphere). This crustal structure with its marginal heterogeneities and intrusions of mantle material, as well as the longitudinal stretching and latitudinal compression of Tibet as the result of plate tectonics which has thickened the lower crust by layered thrusting in the last 40 million years, provides *no reason* for *not* accepting Pleistocene *glacio-isostasy*. It is, with the *negative gravitational* anomalies, a further *precondition* for the *very* significant uplift of the Plateau to a level *above* the snowline which is here, in the *subtropics*, at its *highest*. Chen and others find in many places *disturbances* and *faults* with intrusions of upper mantle material which could *explain* the *strong claims* of recent glacio-isostatic *alternating movements* of several hundreds of metres. Neither does it contradict the time table of the *final beginning* of a *forced* uplift 2.5 million years ago. *It fits well in the time scale* of a total glaciation of Tibet some 1.5 million years later.

The evidence of tectono-genesis provided by L. Lu (1991) which describes the plate tectonic development originating in the Mesozoic is amplified by the detailed description of the docking of single plate elements eg the Lhasa block provided by Chen. There is also a description of corresponding subduction phenomena along the Moho or the upper mantle. The authors follow an *isostatic uplift model* proving at the same time a basis for a negative gravity anomaly. The results of Lu support our view that the gravity anomaly of Tibet *is still very important today*. This would also be the fact for a still persistent *glacio-tectonic uplift* of the plateau, which was *far above normal* tectonic uplift. The relationship seen by Lu between the present day strong uplift and the many, *widespread thermal phenomena*, which according to him derive from the area of fusion of the lower crust and upper mantle, *could* correspondingly be *activated* by *glacio-isostatic depression*.

As already mentioned, Fang Qian (1991) has accepted that, on the evidence of the living conditions of *Hipparion guiznongensis* at 1000 m asl, the Tibetan plateau must have experienced a mean uplift of 3500 m during the past 4.9 million years and thus an average rate of only 0.714 mm/year. There is no reason why *such a movement* should not have taken *only 3 million years* so that Tibet had reached its *present level* and thus the ELA by the *early* Pleistocene ie the *beginning* of the Quaternary ice ages. It is also the opinion of Fang Qian (1991), Ling Xiaohui et al. (1991) and Jiang Fuchu et al. (1991) that a *period of intensive younger* uplift ("Yuanmou movement") resulted *between* ca 1.5 Ma BP (1.35 ± 0.15 million years; or 1.3 ± 0.1 million years or 1.2) *and today*. These authors are quite surely *correct* that *great* tectonic activity occurred in this *most recent* period of time. This must have resulted simply in a uniformly directed uplift *because* they were *unable* to consider the participation of *glacio-isostatic* movements. The author considers it probable that the *ice sheet glaciation* (and its periodic melting) he reconstructed for Tibet resulted in up and down glacio-isostatic movements of about 500–700 m during the course of the "Yuanmou movements". It remains to be proved in the future whether the more than 300 m thick fluvio-lacustrine sediments of the "Zongga formation" and the "Woma formation" (Fang Qian 1991), formed from sands and gravels deposited in the *early Pleistocene*, could have been *interglacially* formed between the *ice covers*.

The accumulation of such lake deposits is *not only* explicable in terms of the contemporaneous uplift of the Himalayas ie as primary tectonic. They could possibly be the *result of lakes* being *dammed by glacier tongues* such as those to be observed today in the Himalayas and Karakorum (cf Kuhle 1982 and 1983). The "Daqingliangzi movement" found in Tibet by Jiang Fuchu et al. (1991) as a subdivision of the "Yuanmou movement" followed at ca. 0.4 Ma BP could have also likewise have been *glacio-isostatic* leading to a series of *Graben-Horst-Graben sediments* and *rift processes*. The uplift phases 4 and 5 of Jiang Fuchu and Fang Qian (1991) deduced from the "Xigeda formation" with its fluvial gravel along the Shilong-Gaoshanbao fault are dated 12,000 years and thus middle Holocene. This *uplift* persisting until today is *most simply explained* as a *post-glacial glacio-isostatic* uplift according to the model of Mörner (1991, p. 78 ie 13,000 to 4500 BP). In relation to this the author finds the results of Wu Xihao et al. (1991) interesting because they deal with *episodic* ie *discontinuous* uplift during the Quaternary. The kind of *unequal rhythmic* uplift presented there comes very close in *principle* to the proposed *alternating glacio-isostatic depression and uplift*. They *also* find *old moraines* of 1.4–1.2 Ma BP explicable by an *early Pleistocene* uplift *above* the snowline. But these moraines *cannot* have been deposited at 2000–3000 m asl as the authors propose because a *depression* of the snowline of 3000 m would be required; the ELA, which lies today at 5100 to 5900 m, would have had to be depressed to about 2500 m asl. This would mean a *very significant* reduction in the summer temperature of about 18 °C which is *extremely improbable*. It is much more likely that the *maximum* snowline depression was 1200–1500 m, as can be shown for the last glacial period in High Asia (cf Kuhle 1974a–1991; Porter 1970; Schroeder-Lanz 1986 etc.). This *requires* Tibet to have been about 1500–2000 m *higher*, that means at 4000–4500 m asl. But these findings clearly show that 1.4–1.2 million years ago in the early Quaternary Tibet lay at a similar *height as today*. Wu Xihao et al. (1991) also show that the *rate of uplift* since 8000 BP *increased* from 5.4 mm/year to 18.8 mm/year; such values *strengthen* the idea of a *glacio-isostatic cause* (see Mörner 1991, pp. 77 and 79, Fig 2, 3 and 4).

A further view, already referred to, *close* to that of *discontinuous* uplift is that of a *cyclic series* of *neo-tectonic episodes* since the *early* Pleistocene (Wu Xihao et al. 1991). A *major period* of uplift is proposed for the last million years. The *author (Kuhle) understands* this to be the whole period of the Quaternary glaciations which thus includes all the *big* movements *because* they were *glacio-isostatic*. The *sub-cycles* proposed by Wu Xihao et al. have a period of 0.4 million years, two or three times too long for the *glacial-interglacial tectonic cycle* proposed by the author. But it is *very favourable* for a *glacio-isostatic* interpretation to find that Wu Xihao et al. (1991) describe an *accelerated* uplift at the very *beginning* of each cycle which is followed by a *slower uniform* uplift lasting until its *end*. This is the picture of uplift which Mörner (1991) describes for Fennoscandia. This is similarly *divisible* into a large *exponential* uplift between 13,000 and 4500 BP and a lesser *linear* one. The *comparative* consideration of such an uplift mechanism requires future detailed understanding. Quite apart from this obvious *similarity* with the picture with the phenomenon of glacio-isostatic movements in Fennoscandia after the last ice age, *methodology* requires an evaluation of *climatic* ie *exogenous* causes. It is much more difficult to pursue the other or *endogenous* route which could easily be suggested were it *not entirely hypothetical*, to explain the *coincidence* of a *cyclic* uplift with the *Quaternary ice ages*. The effectiveness of the *plate-tectonic* collision from the south of the Indian subcontinent with Eurasia has continued undiminished since the middle Tertiary as a proof of the late-Tertiary uplift of High Asia. It is *not* all that clear why this phenomenon should have acquired a *cyclic* character in the Quaternary. It is equally *theoretically undetermined* on the other hand what kind of phenomena in the lower crust near to its transition to the more or less fluid region of the mantle (atmosphere) either above or below the Moho could have *led* to a *rhythmical* uplift. On the other hand there is an *exogenic* type of explanation in the *comparable rhythmic* phenomenon of the *Quaternary glaciations* (and its association with overall glacial covers) linked to the *glacio-isostatic* crustal movements which must have had an induced *rhythmicity*.

It has already been mentioned that the *uplift rate* of 5.4 to even 18.8 mm/year must be considered *much too* large to have *continued* from the beginning of the Quaternary until today. With an uplift of about 10 mm/year the Tibetan plateau would have attained 10,000 m in the Quaternary alone. This *degree of uplift* shows that, bearing in mind the *present height* of Tibet of only 5000 m and a *similarly* significant initial value attained already in the *pre-Quaternary*, an *episodic* and *rhythmic sinking* in the course of the Quaternary might be *needed* to help its explanation. Put another way: such a rapid uplift *would not fit* the height of the plateau *without* at the same time a compensating depression. Such a *contemporaneous* depression is *most* simply, though not *exclusively*, understood as *glacio-isostatic*. The *maximum rate* of uplift of 4.5 mm/year is based on the results of Zeitler (1985) for the Nanga Parbat Massif (W Himalaya) and is referred to by Gansser (1991) in a comprehensive up-to-date compilation of the history of the uplift of Tibet. This is *only a quarter* of that which the above-named authors maintain for Tibet. It is thus clear that the most important rates of the uplift of Tibet and its surrounding mountains do not coincide with its highest peaks, such as would be required on a *purely primary tectonic* interpretation. On the contrary, *greater* uplift in the about 3000 m lower plateau areas of Tibet *supports* the *glacio-isostatic* interpretation. For this (for the ice load), *areas covered with ice* must have been present on the high plateau. The view of Gansser (1991) on Gubler et al. (1981) is useful here; it points out that the greatest present day uplift of the Alps is where the marginal areas of the mountains show the *greatest incision* and *uncovering* of the underground structure and *not* where the highest peaks culminate (the case in the central Alpine area). This Alpine data could explain the uplift of the south slopes of the Himalayas and the pre-Himalayan ranges as very intensive, *but not* that of Tibet. The High Plateau of Tibet is in fact completely *isolated* from *deep* incision or deep-reaching uncovering of the topographical basement areas of the mountains or high plateaux. *Topographical requirements* only make these possible in the surrounding ring of high mountains, as for example in the Himalaya, Karakorum or Kuenlun. *Only* there and on the *outer slopes* of the mountains can there be such deep erosive exposure ie where the erosion base level itself is *low down*. With a *complete absence* of deep reaching uncovering of the basement the *uplift* of the High Plateau is today completely *untypical* from a *tectonic point of view* and at least *four times* as significant as that of the deeply incised young marginal mountains. This must be seen as *further evidence* for a *glacio-isostatic* uplift of Tibet.

As a conclusion to these examinations of the state of knowledge in the *literature* of the proposal of the author that a large part of the uplift of Tibet *must be understood* as glacio-isostatic, two *sedimentological* indicators provided by Gansser (1991) need to be mentioned. The *step-like* arrangement of the terraces (ie their being *step-wise inset*) in almost all the steep Himalayan valleys gives evidence of *uplift impulses* of different intensities ie peaceful phases *alternating* with active ones. This view equally supports the *rhythmic-cyclic* uplift already discussed. As an example in the Thak Khola and Miristi Khola in the Dhaulagiri and Annapurna Himalaya the *step-wise inset* of the gravel terraces composed of coarse block fanglomeratic aggregates (as with those of Gansser [1991] already described) leads back to prehistorical *ice terminal* positions (Kuhle 1982, 1983). This glacial character is to recognise by the fact, that the gravel terraces on the valley flanks set in *suddenly* and *unexpectedly* and the terrace surfaces reach out into space in an up valley direction. Such a step-like arrangement also *negates* a tectonic explanation. Gansser (1991) also sees in the *significant alluvial deposits* along the Yarlung Tsangpo and in the *exceptionally large suspension load* and *gravel transport* of the Ganges, as well as in the formation of the world's *largest submarine deltas*, those of the Indus and Bengal, a result of the *extremely rapid* recent *uplift* of Tibet. This conclusion is *reinforced* by the discharge of sediment and resulting submarine deltas having resulted from the uplift of Tibet *above the forest* limit into the periglacial, frost debris and permafrost regions, which facilitated intensive *interglacial frost shattering*, as well as the *repeated maximum glacial erosion* of the inland ice sheet and its glacio-fluvial melt-water transport. Such a complex of sedimentological indicators adduced by Gansser is *associated* with this *extreme uplift* to great elevations and with the effectiveness of the *icesheet* made *possible* by this. This *method of treatment* is *supported* by the 400 m to over 500 m thick Quaternary sedimentation in the southern marginal regions of the ice age ice sheet in the North German Plain. Such significant terrestrial sediment thicknesses have not only developed in the *short Quaternary period* but also in a *long distance* to the montane and high plateau types of recently uplifted areas of supply. Consequently the intensity of sedimentation resulted *not* just from the uplift, but was *dominated* by the climatic-geomorphological factor in the form of *glacial erosion* and transport mechanisms.

Summary

The reconstruction in Tibet of an *ice sheet cover* of up to 2000 m *thick* covering an *area* of 2.4 million km^2 was made possible from the Quaternary-geological and glacio-geomorphological indicators found since 1976 during twenty expeditions and research journeys lasting up to 4 months each. Both formerly and now the *snowline level decreased* (caused by the planetary factor) from south to north in Tibet by 1000 m. This is *followed* by a *surface slope* of the Tibetan plateau from south to north. This *load of ice* produced a *glacial-isostatic* vertical movement of ca. 500 to 700 m. In addition *direct empirical evidence* of various kinds indicates a most recent ie post-late-glacial *glacio-isostatic uplift* of from one to several centimetres per year. Such an amount is supported by several authors for other areas of High Tibet. This *degree of uplift* is *more significant* than that of the high Himalayas, which are *higher* and *younger* than the Tibetan plateau, and *must* be related to *glacio-isostasy.* It was the result of a *primary tectonic* uplift of Tibet into the *level of the snowline* in the *early* Quaternary. During the course of the Pleistocene the High Plateau was glaciated *several times* so that at each time there *alternated* a *maximum glacial isostatic depression* and an *interglacial uplift*, such as that resulting again today. This is proved by the ground and end moraines of the *older* glaciations lying in the marginal areas of Tibet. Continuous glacio-isostatic uplift *resulted* in the Tibetan plateau nearly *reaching and exceeding the ELA* in a few thousand years. A then *renewed ice sheet will overcompensate* this uplift. For this the plateau *must reach* 5600 m asl, the *present day* level of the snowline. Possibly the *slight* ELA depression induced by the Milankovitch radiation anomalies acted in conjunction with a lower plateau level, ie the extraterrestrial caused snowline depression leads earlier to a total glaciation of the plateau. Since the resulting *subtropical icesheet* and the reversal of the *radiation balance* induced by it is seen as the *terrestrial cause* of the glacial periods, the Quaternary glacial period *ended*, according to this hypothesis, with the *long term erosion* of Tibet *to below* the snowline level, which otherwise the uplift would have brought it up to once again. The thesis provided here shows that the plate tectonic ie primarily endogenous uplift through a *climatic height limit* (ELA), whose crossing *led* to the *glaciation*, has *ceased* and partially reversed *glacio-tectonically.*

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