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Würm Glaciation of Lake Issyk-Kul Area, Tian Shan Mts.: A Case Study in Glacial History of Central Asia

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ABSTRACT: Recent field research and modeling experiments by the authors suggest that Würm glaciation of Tian Shan Mountains had much larger extent than it was previously believed. Our reconstruction is based upon the following evidence: 1. a till blanket with buried glacier ice occurring on mountain plateaus at altitudes of 3700 to 4000 m asl; 2. trough valleys with U-shaped profiles breaching the border ridges and thus attesting to former outlet glaciers spreading outwards from the plateaus; 3. morphologically young moraines and ice-marginal ramps which mark termini of the outlet glaciers at 1600–1700 m asl (near Lake Issyk-Kul shores) and farther down to 1200 m asl (in Chu River valley); 4. clear evidence of impounding the Chu River by former glaciers and turning Lake Issyk-Kul into an ice-dammed and iceberg-infested basin; 5. radiocarbon dates attesting to the Late Pleistocene age of the whole set of glacial phenomena observed in the area.

Our data on past glaciation provide a solution for the so called "paleogeographical puzzle of Lake Issyk-Kul", in particular they account for the lake-level oscillations (by ice dam formations and destructions), for the origin of Boam Canyon (by impact of lake outbursts), and the deflection of Chu River from Lake Issyk-Kul (by incision of the canyon and build-up of an ice-raft delta near the lake outflow).

The Würm depression of regional snowline was found to be in the range of 1150–1400 m. While today's snowline goes above the plateaus of Tian Shan touching only the higher ridges, the Würmian snowline dropped well below plateau surfaces making their glacierization inevitable. The same change in snowline/bedrock relationship was characteristic of the interglacial-to-glacial climate switches on the Tibetan Plateau resulting in similar changes of glaciation. The whole history of central Asian glaciations seems to be recorded in the Chinese loess sequences.

A finite-element model was used to test two climate scenarios – one with a gradual and another with an abrupt change in snow-line elevation. The model predicted that an equilibrium ice cover would form in 19,000 (first scenario) or 15,000 (second scenario) years of growth. It also yielded ice thicknesses and ice-marginal positions which agreed well with the data of field observations.

Introduction

Tian Shan – one of the largest mountain systems of Eurasia. Together with the Pamirs, Hindu Kush, Karakorum, Kunlun Shan, Himalaya and Tibet it enters the giant, orographically single, Central Asian mountain mass, or super-system. The most elevated core of the mass, confined within the 2000 m contour line, makes up a continuous high terrain having an area of 3.5 million km^2. Mountain ranges of the terrain form a huge asymmetric arch with its sharply convex side turned west and opening to the east to embrace the Tarim Basin with the desert of Takla Makan on its bottom.

Lake Issyk-Kul area belongs to Northern Tian Shan. The lake itself is the second largest mountain lake of the world, its areal extent is 6236 km^2, the catchment basin

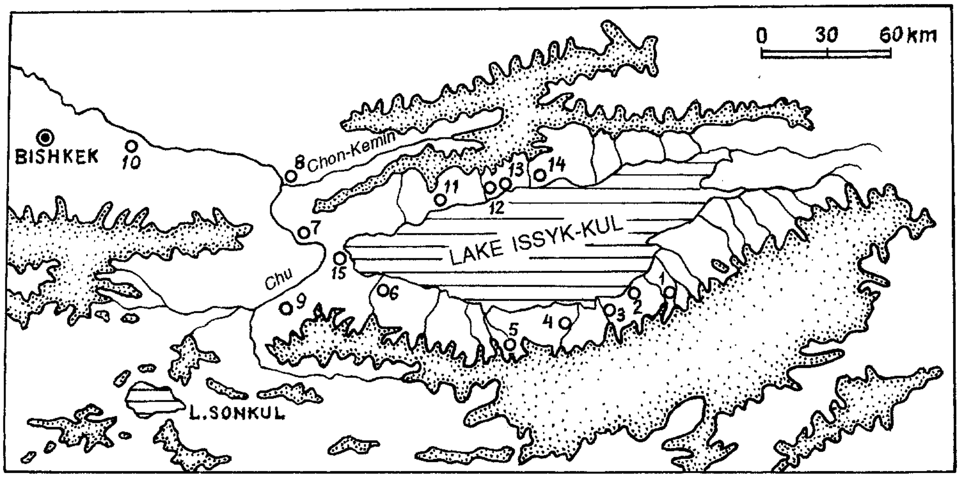


Fig 1
Würm glaciation of Lake Issyk-Kul area, Tian Shan Mts., after Bondarev and Pshenin (Atlas of Snow and Ice Resources [in press]), and the observation sites of the authors:
1 Dzhuku valley (val.)
2 Akterek settlement (stmt.)
3 Barskaun and Tamga vals.
4 Tosor val.
5 Kara-Ortok hill
6 Turasu val and Karashar stmt.
7 Kokpak-Kyrkoo val.
8 Chon-Kemin/Chu River junction
9 Kara-Kungey val.
10 Ivanovka quarry
11 Choktal val.
12 Cholpon-Ata stmt.
13 Sovkhoz "Progress"
14 Prishib hill
15 Bozbarmak hill

amounts to 22,080 km^2, water surface lies at 1607 m asl, the maximum depth reaches 668 m. Presently, the lake has no outflow; Chu River which used to flow into and out of the lake, today misses it by 11 km and enters the Boam Canyon, crossing the Kirgiz Range. Climate of the area is semiarid, the rate of precipitation increases from 115 mm/yr at the west end of the lake to 410 mm/yr at its east end, however on surrounding mountains of Terskey Alatau (up to 5216 m) (Fig 9, 16, 17, 22, 24, 26, 27, 29) and Kungey Alatau (up to 4770 m) (Fig 30, 33, 34, 38, 40) it reaches 800-900 mm/yr. An area of 650.4 km^2 is ice covered in the mountains (Fig 17), with 48 km^3 of water stored in the glaciers (Sevastianov 1991).

The mountains, being a part of the Caledonian orogenic belt of Northern Tian Shan, are built up largely of early Paleozoic rocks. Their structure and relief were rejuvenated during the Alpine orogeny. In the latter's course, a several kilometers of clastic orogenic sediments, the molasse, accumulated on the lake bottom. The beginning of the molasse accumulation, dated back to the Upper Neogene, marked the inception of the lake depression. A number of sedimentary units are recognized in the molasse section, of which the coarsest ones are traditionally attributed to the effects of tectonic activizations. Judging by studies of the southern coast sections, the Oligocene-Neogene beds of the molasses are 4000 m thick (Pomazkov 1972). Vigorous crustal faulting accompanied the tectonic activizations; this faulting is believed to be responsible for the Boam Canyon formation and deflection of Chu River from the lake.

Equilibrium line of present-day glaciers and ice caps of Northern Tian Shan lies within the altitude ranges of 3700–3800 m in the north and 3900–4200 m in the south (Krenke 1982). In Lake Issyk-Kul area the range is 3700 to 4100 m asl; the glacier tongues reach down to 3500–3900 m, while some of north-facing ones descend to 3000–3200 m (Sevastianov 1991). Widespread traces of former glaciations were also reported by many travellers, including such renouned naturalists as Severtsov, Mushketov, Davis, Berg, Prinz, Kalesnik and Gerasimov. Nevertheless, a number of paleoglaciological problems of Tian Shan remained unsolved. Practically unkown were the size and types of former glaciers, the range of snowline lowerings during the Würm and older coolings as well as glacial/interglacial climate changes. Possible role of glaciations in reorganizations of hydrographical systems, landform reshaping and Cenozoic lithogenesis was never considered and discussed. However strange it may seem, and despite the scarcity of factual data, a belief in small-scale glaciation became deeprooted, having been based on mere speculations about the probable consequences of climate aridity in Central Asia. This especially applied to the last glaciation of Tian Shan, which was believed to have been the smallest. Some relatively new data on altitudinal position of end moraines, which appeared to have been formed during the last glacial maximum (LGM) (Alyoshinskaya et al. 1983), along with "old" radiocarbon dates obtained from shores of such high-plateau lakes as Sonkul and Chatyrkul (Sevastianov 1977, 1991), seemed to corroborate this concept. As far as pre-Würm glaciations are concerned, they were envisioned as having larger extent, in fact, the larger the older their age was (Fedorovich 1960; Kachaganov 1979; Prinz 1929; Selivanov 1990).

Würmian depression of snow line was estimated as moderate to small, and geographically differentiated. In particular, it was pointed out by Kalesnik and Epstein (1936) and Kalesnik (1936) that on Ak-Shiyrak Range and in upper reaches of Naryn River the depression amounted to 500 m or, according to Prinz (1927) - to 450–500 m. It was further assumed that the range of snowline lowering increased in westerly direction to 600 m, reaching on Terskey Alatau Range and Mount Khan Tengri 700 to 800 m (Prinz 1927). These estimates seemed to have been

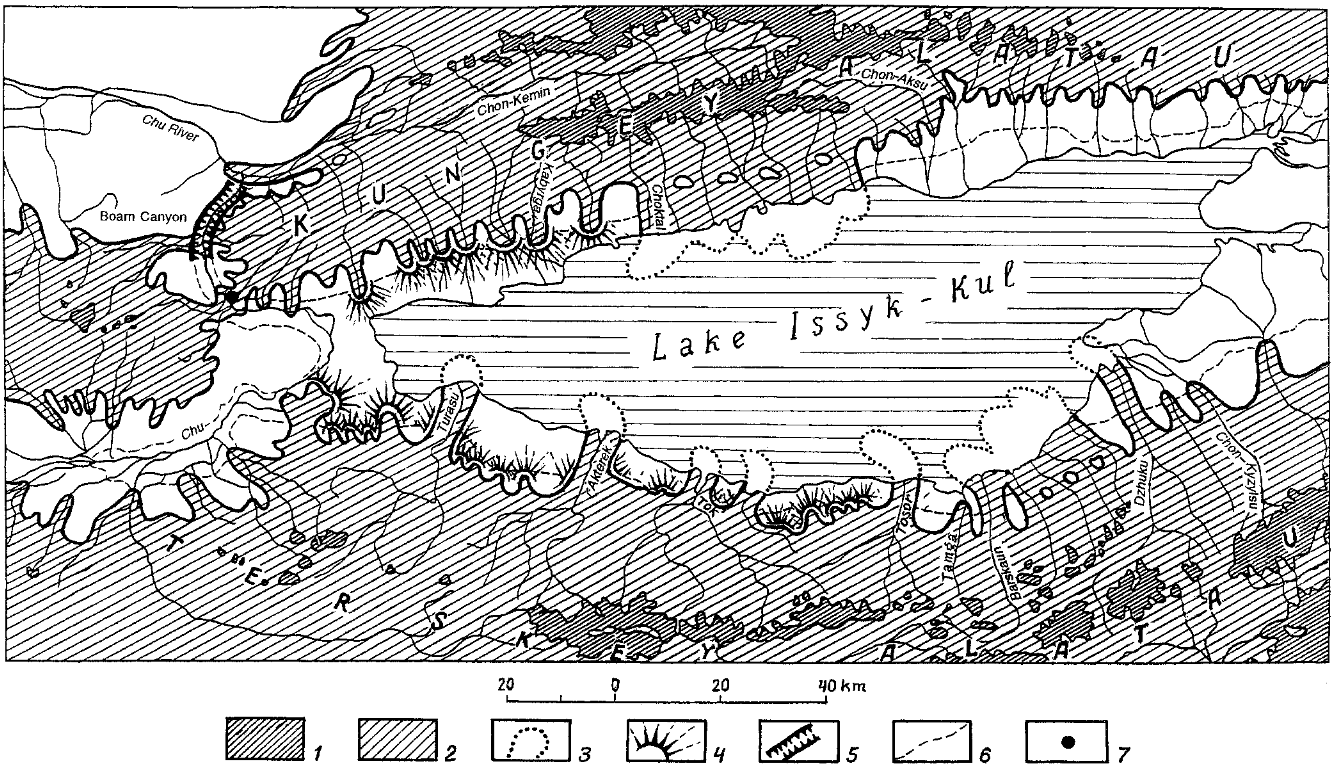


Fig 2 Würm glaciation of Lake Issyk-Kul area. Based on the authors' observations. Also published in: Grosswald et al. (1992). 1 present-day glaciers; 2 Würm ice covers; 3 floating ice lobes (tentative reconstruction); 4 ice marginal ramps; 5 erosional breach - Boam Canyon; 6 tentative limit of Issyk-Kul transgressions; 7 site of sampling for radiocarbon dating - Kokpak-Kyrkoo mouth

confirmed by recent research: the University of Moscow team also inferred that the Würmian snowline depression in Lake Issyk-Kul basin had not exceeded 600 m (Markov 1971). The smallest range of that depression, 200 to 350 m, was inferred from the altitudes of empty cirques on Ak-Shiyrak Range (Bondarev 1965, 1982), and the largest - 1100 to 1200 m - in Kirgiz Alatau Range (Maksimov 1980).

The opposite views had their advocates, also. Over a century ago Severtsov (1877), who spotted "bona fidi" moraines in Chu-River basin at altitudes of about 1500 m asl, inferred that the former glaciations of Tian Shan were quite extensive. This view was shared by Kassin (1915) who, after inspection of boulder till and outwash masses overlying the Issyk-Kul terraces, speculated on "... the former Malaspina-style glaciers that completely inundated all the foothills of the Terskey Alatau and Kungey Alatau Ranges".

Some geologists believe that all, or nearly all, glacial landforms, which are in evidence on Tian Shan, represent only Würm glaciation. According to that concept, all the glaciers formed during different cold epochs of the Pleistocene, were of about the same size, so that the latest of them were to destroy or mask evidence of the earlier glaciations. While the systems of heterochronous moraines known from quite a number of mountain valleys were all considered to have been stadial formations marking ice-terminal oscillations dated from the last deglaciation, not the traces of several independent glaciations. This view was shared by Maksimov (1983, 1985), Serebryannyi and Orlov (1988). It also tallies with the results of our studies.

Lake Issyk-Kul and its "Paleogeographical Puzzle"

Issyk-Kul area of Tian Shan comprises the basin of Lake Issyk-Kul, adjacent Terskey Alatau and Kungey Alatau Ranges and mountain plateaus in upper reaches of Chu and Naryn Rivers, as well as several internal ranges, including Ak-Shiyrak, towering above the plateaus. This area is of the key relevance for solving paleogeographical problems of Tian Shan as a whole. In addition, there are unsolved problems of that particular area itself.

Among the problems are the above mentioned lack of outflow from the lake, clear evidence for its recent connection with Chu River, and the traces of considerable oscillations in lake level, in particular its rises to the altitudes which strongly surpassed the levels of rocky sills

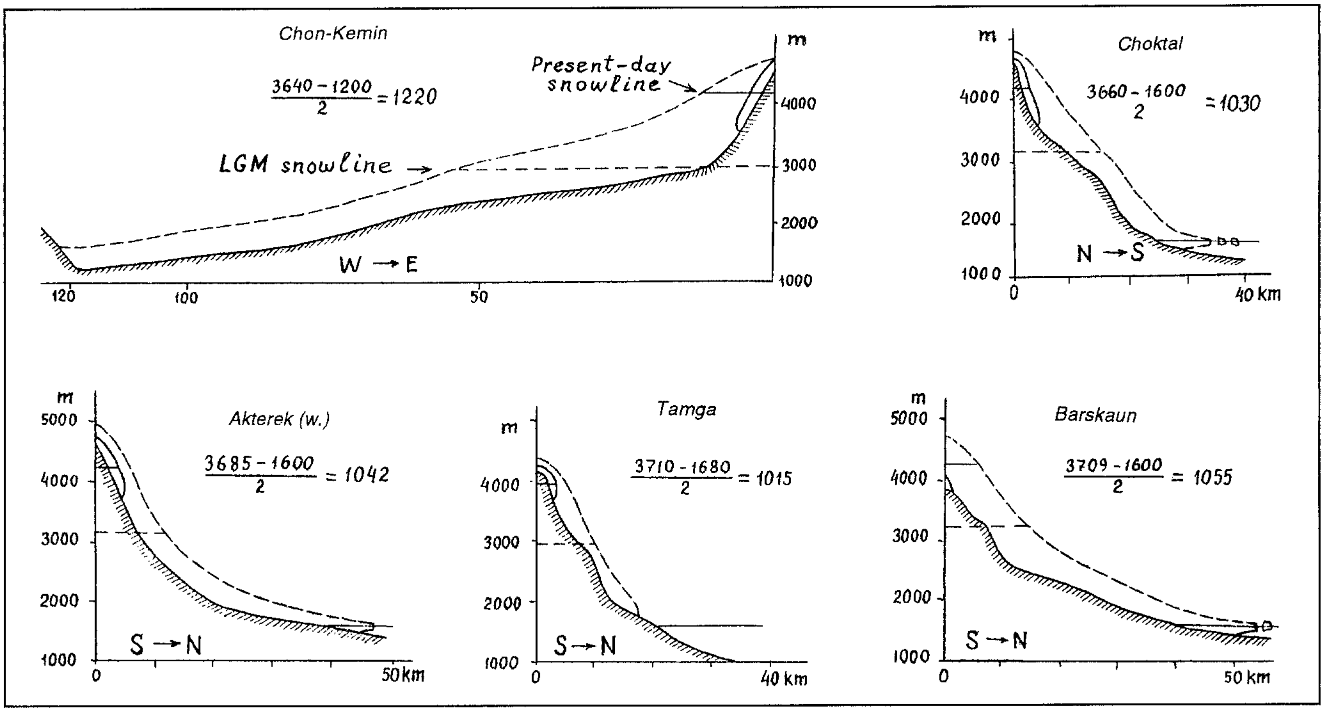


Fig 3 Lowering of snowline during the LGM in the several representative valleys of Lake Issyk-Kul area: Chon-Kemin, Choktal, Akterek (west), Tamga and Barskaun. Determined by the method of Höfer (1879)

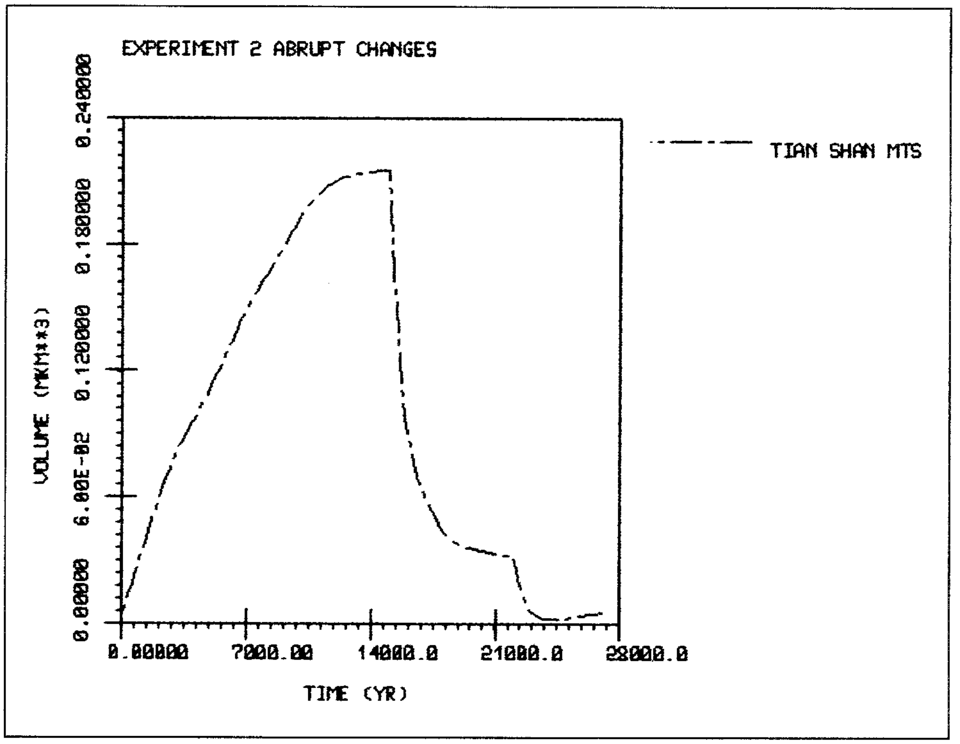
within Chu River valley. A giant Boam Canyon formed where the river breaks through the Kirgiz Range, is an example of another problem, as its origin is under debates for a century. It was this specific bundle of unsolved issues, interconnected with each other into a single complex problem, was ment by Semionov Tian-Shansky and Berg, and later by Gerasimov, Bondarev and Maskimov, when they discussed the "paleogeographical puzzle of Lake Issyk-Kul" (Berg 1904; Bondarev 1958; Gerasimov 1953, Maksimov 1985).

Hence, the unsolved puzzle of Lake Issyk-Kul comprised the following pieces. What caused the past lake-level oscillations resulting in formation of high terraces or, in other words, what kind of natural agency could repeatedly block the lake outflow? Why present-day Chu River does not flow into Lake Issyk-Kul, what forced it to turn away into mountains? And what sort of forces could create the Boam Canyon, what was the specific mechanism of the canyon's formation? Until recently, there was no theory which could account for the whole bundle; at best, only some *ad hoc* explanations were advanced for some of the problems in question.

One of the approaches stemming from the views of Semionov Tian-Shansky and Berg, tended to treat all the above phenomena in terms of gradual geomorphological evolution of the Neogene intermontane basin which predated the present-day Issyk-Kul and its environ. The ancient lake basin was believed to have been much larger than the present-day Lake Issyk-Kul, and the ancient lake level - much higher than the presently existing level. Erosional incision by an overflow stream that, from the outset, discharged water across the lowest saddle in the Kirgiz Range was taken for the chief mechanism both for incision of Boam Canyon and the lake level changes. Consequently, Boam Canyon was considered to be a conventional trough valley produced by erosion of "normal", or relatively uniform, equable stream flow, while all the changes experienced by the lake level were reduced to one-way lowering. Another version of this view, shared by Kvasov and Seliverstov (1960), suggested that Boam Canyon is not a Neogene-age, but a younger, late Quaternary, feature.

Another view originated from Mushketov and Fedorovich. As we already pointed out, it suggested that the leading role in the canyon formation had been played by tectonic, in particular seismotectonic, faulting. Gerasimov, Shnitnikov and Maksimov were among the partisans of this concept. Namely, they all believed that the northern deflection of Chu River and its divorce from Lake Issyk-Kul had resulted from a tectonic rift which subsequently developed into the Boam Canyon. They further maintained that, in addition to tectonism, a natûral dam created by Upper Chu's deltaic accumulation in western part of Lake Issyk-Kul also contributed to the

Fig 4
Volumetric growth and shrinkage of the Northern Tian Shan ice cover with time (modeling experiment 2: abrupt lowering and rise of snowline by 1200 m)



deflection (Gerasimov 1953; Maksimov 1985; Sevastianov Shnitnikov 1980; Sevastianov 1991).

Mushketov-Fedorovich concept is still quite popular and has many supporters (Sevastianov 1991). The same can be said about the older concept of Semionov Tian-Shansky and Berg. Whatever their differences, they both have one major feature in common: neither gives credit for reorganizations of the "Lake Issyk-Kul-Chu River" system to former glaciations. By contrast, our concept suggests that those reorganizations were virtually caused by glaciers. It has been already several years ago that we, basing on geomorphological evidence from Lake Issyk-Kul area, came to realize that "late-Pleistocene snow-line depression in northern Tian Shan Mountains had amounted to 1100–1200 m which forced the glaciers of Terskey Alatau and Kungey Alatau to advance down to Lake Issyk-Kul and to fill and block Boam Canyon thus turning the lake into an ice-dammed basin" (Grosswald 1989, p. 42). A little later, the same idea was put forth by Selivanov (1990) who got involved in discussion of the past Lake Issyk-Kul level oscillations. Selivanov concluded that the oscillations had resulted from past streamflow dammings caused by repeated fillings of Boam Canyon with ice and till. Unfortunately, for some unclear reasons he related those damming events not to the Late, but to Early Quaternary, having for this neither stratigraphic nor geomorphological grounds. It is noteworthy (but not necessary correct) that, according to or Kvasov and Seliverstov (1960) and to Maksimov (1980), no canyon existed in the Kirgiz Range during the Early Quaternary. As well as, possibly, had not existed Lake Issyk-Kul itself (Gerasimov 1953).

How come that the causal links between reorganizations within the Lake Issyk-Kul-Chu River system, on the one hand, and former glaciers, on the other, which seem so obvious, were overlooked for so long? An answer has been provided by Fig 1. It shows a reconstruction of Würm glaciation in Lake Issyk-Kul area, recently produced by Bondarev and Pshenin (not published) for the World Atlas of Snow and Ice Resources. In comparison with previous works, the reconstruction looks maximalistic, and still it reads that not a single Würmian glacier ever approached the lake's shore line nor reached the Boam Canyon. Thus the glaciation was thought unable to directly interfere with evolution of the system. No wonder, the virtual role of glaciation in reorganizations of the system was not assessed, not even acknowledged.

The case is, as now became obvious, that our predecessors, in their majority, simply failed to identify the clear evidence of former ice marginal positions at low altitudes, such as end moraines on Lake Issyk-Kul shores or within Boam Canyon. Hence, they just had to resort to other explanations, such as tectonic or seismotectonic hypotheses.

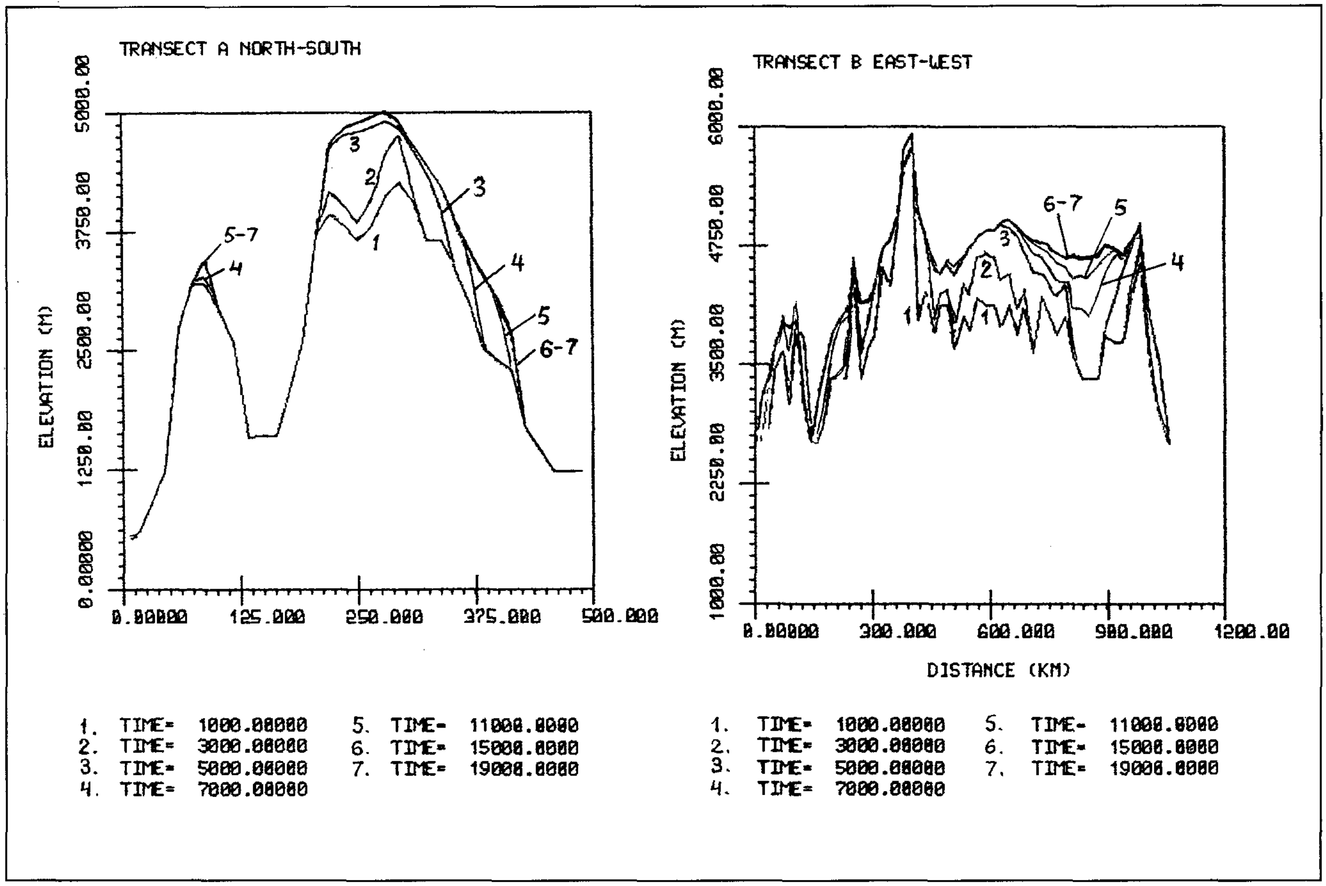


Fig 5 Ice thickness changes on the plateaus of northern Tian Shan with time (modeling experiment 1: gradual lowering of snowline - by 1200 m in 6 ka)

Evidence for Würm Glaciation

Our observations conducted in Lake Issyk-Kul area during 1986–1991 field seasons resulted in establishing the broad occurrence of morphologically fresh glacial landforms - end moraines, glaci-fluvial fans and terraces as well as a variety of ice scour features, lying at surprisingly low altitudes - near the lake's shore line at about 1600 m asl and within Chu-River valley down to 1200 m asl. It was also found that a specific kind of end moraines, namely ice marginal ramps (IMRs), or *Bortensander*, (Fig 9, 24, 27, 29, 33, 34, 36) which are peculiar to the glaciated semi-arid mountains (Kuhle 1989, 1990) broadly occur throughout foothills of Terskey Alatau and Kungey Alatau Ranges facing Lake Issyk-Kul.

Fig 1 shows the most important sites of our field observations. All the sites lie beyond the area which was formerly shown as glaciated. Nevertheless, fresh looking glacial landforms, in most instances end moraines, were identified at each one of them (Fig 9, 10, 18–41). The largest field of till deposits and glacial landforms occurs south of the lake, on high plateaus (Fig 17), or so called "syrty", and mountain ranges (Fig 13–16). Both the plateaus and adjacent mountain slopes are mantled by lodgment till containing giant erratic blocks (Fig 11) and rafts. Tabular bodies of ground ice were found within the till in several excavations. Plateau geomorphology is dominated by a number of recessional moraines and dead-ice ("kettle-hole") landform complexes.

The plateau surface has the altitudes of 3700 to 4000 m asl (Fig 17), the mountain ranges rise to 5000 m and more (Fig 17, 25, 27, 29), while mean present-day snow line in the area is at about 4100 m asl. This implies that extensive Pleistocene glaciation was there inevitable: even in case that the snow line lowering was as small as 500–600 m (which was assumed by Prinz and Kalesnik), the whole area of plateaus and ranges south of Lake Issyk-Kul had to turn into a continuous field of net snow accumulation. Which, in turn, led to formation of a big ice cover (Fig 17) with its margins descending to the mountain foothills (Fig 9, 10, 22, 24, 25-27, 29) where its net ablation was possible. As suggested by specific topography of the area, the former ice

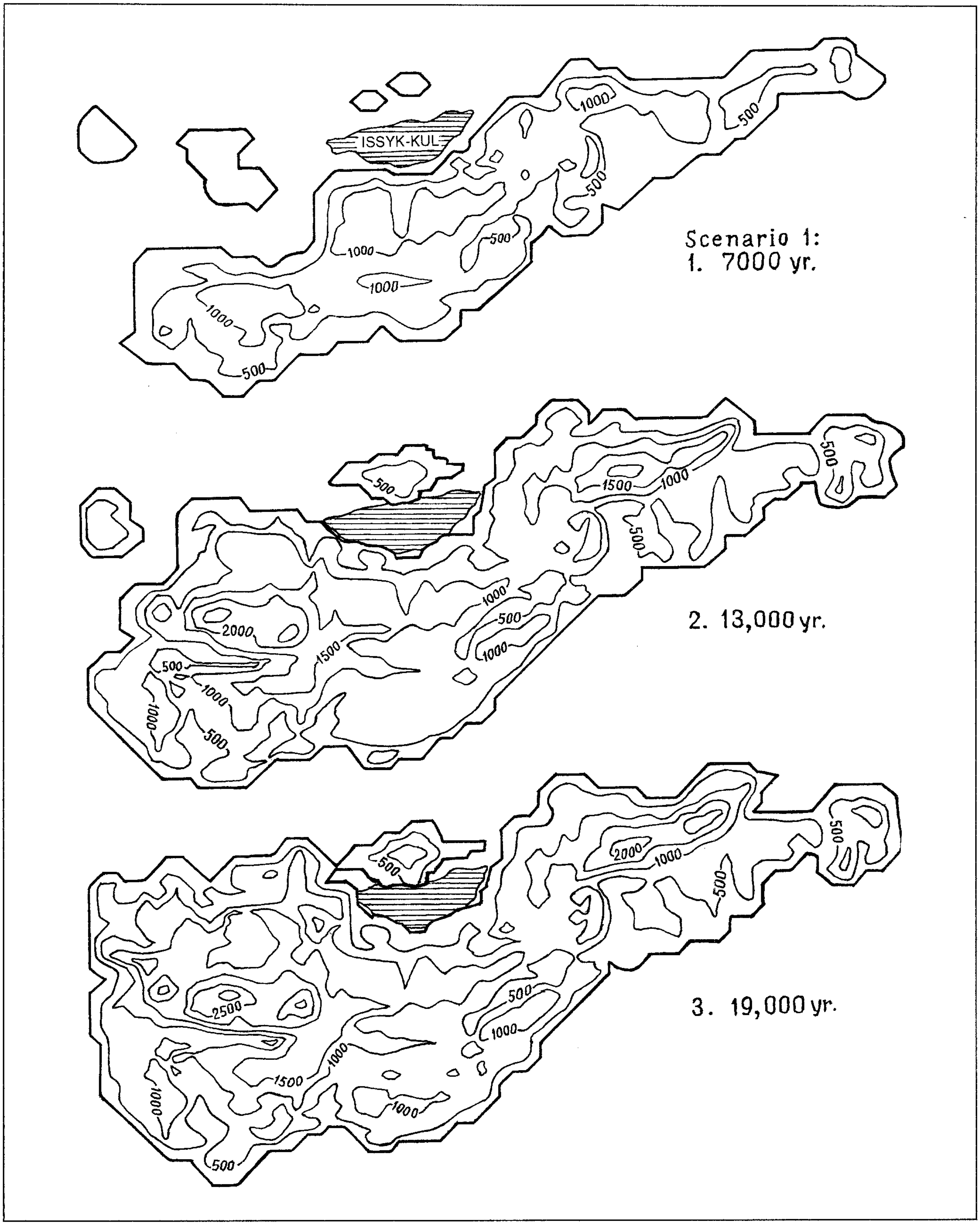


Fig 6 Changes in ground-plan configuration and thickness of the Northern Tian Shan ice cover with time (modeling experiment 1: gradual lowering of snowline - 1200 m in 6 ka). Note the rapid ice-cover formation at 7 ka (only 1 ka after full lowering of the snowline) and relatively small difference between ice configurations at 13 and 19 ka. Issyk-Kul is not filled in with ice due to the assignment of high (–5 m/yr) ablation rate within the lake's boundary.

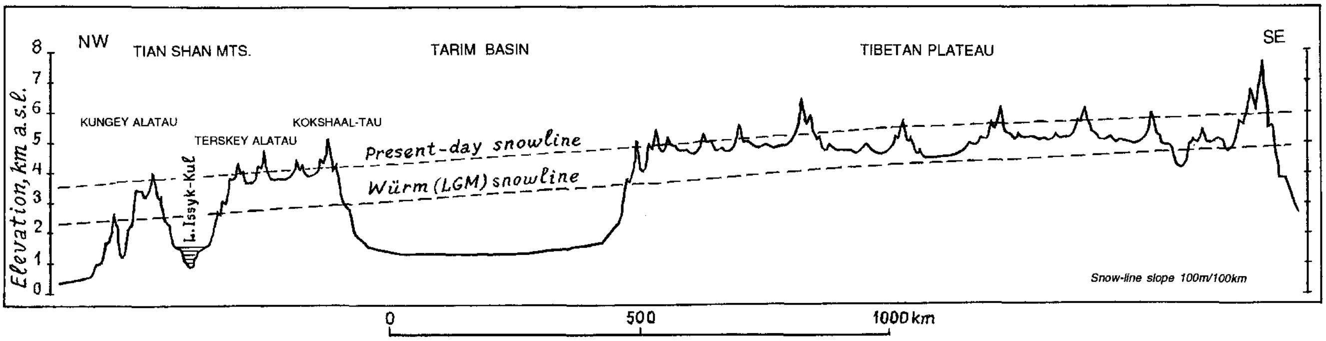


Fig 7 Generalized NW-SE profile across northern Tian Shan, Tarim Basin, Tibetan Plateau and Himalayas showing relationships between present-day and Würmian snowline, on the one hand, and the earth-surface topography, on the other.

flow directed there mainly due southwest and west into broad valleys of the Naryn River system, while minor outlets of the ice cover moved in eastern and northern directions penetrating mountain passes (Fig 17) and trough valleys (Fig 13–16).

Specifically, several north-flowing outlets, which discharged the plateau ice into Lake Issyk-Kul, breached the Terskey Alatau Range forming the trough valleys of Dzhuku and Barskaun (Fig 22). The upper and middle reaches of the valleys have a morphology of typical glacial troughs. Their long profiles look like successions of basins and reagels and the cross sections are U-shaped (Fig 13–16, 22). The surface of the plateau grades into the valley floors through broad ice-scour funnels (Fig 17), the valley mouths open up to the lake (Fig 9, 22, 24, 25); there are no terminal moraines there, only lateral moraines occur on both sides, each represented by a set of a few short, echelon-spaced ridges with the relief of about 200 m. Judging by observations in several exposures, the ridges are made up of tightly packed boulders of various granites and sandstones cemented by buff-coloured silty sands, many boulders are really big, measuring tens cubic meters; they are often faceted and grooved (Fig 26, 30, 31, 33, 34, 36, 38,41). At the trough mouths the moraines diverge and flatten out while thick accumulations of late-glacial and post-glacial gravels bury the moraine bases (Fig 9, 22, 24, 25). This geomorphology suggests that during the last glacial maximum the ice streams of the Dzhuku and Barskaun valleys advanced well into Lake Issyk-Kul, getting there afloat and producing icebergs.

Pronounced glacial geomorphology is characteristic for the rest of the Terskey Alatau valleys as well. In particular, this is true for troughs of the Tamga, Tosor, Kara-Ortok and Turasu rivers which we studied (Fig 24–27, 29). These troughs also open up to Lake Issyk-Kul and, judging by morphology of their moraines, conveyed glacier ice into the basin. In fact, only a few glaciers did not reach the lake, among them – the Tamga and Chon-Kyzylsu glaciers (Fig 9). Not only lateral (like in all the valleys) but also end moraines occur in the said troughs. In Tamga valley the moraines are in evidence down to 1900 m asl; they look like steep-slope ridges made up of big blocks and boulders cemented by sandy matrix, with a 5 to 10 m-thick sheet of milk-coloured loess-like sand overlying their crests. In ground plan, the moraines form a system of a few subparallel arches of which the proximal one is only a few miles from Lake Issyk-Kul. Longitudinal gradients of Tamga lateral moraines are much gentler than those of the valley floor, so that in some 3 km the moraines rise to the crests of inter-valley divides and merge with moraines of neighbouring valleys. The same style of moraine/bedrock relationship holds for all other valleys of the area: everywhere the lateral moraines quickly ascend to watersheds. Thus they strongly suggest that the northern slope of Terskey Alatau Range was glaciated by a continuous ice cover, not by a number of separate alpine glaciers. Only the very lake-side margin of the ice cover was divided into lobes, and higher up, in the zone of the plateau break, a chain of nunataks probably protruded through the ice cover (Fig 11, 13, 17).

Some evidence for glaciers/lake basin interaction was uncovered on the coast between settlements of Akterek and Zhenish. There, in an a partly submerged zone, extending for 15 km along the present shore line and having apparent width of 150 to 200 m, a multitude of loose giant boulders of granite and sandstone rocks occur. The boulders are glacially shaped-faceted, polished and scarred by crescentic gouges. Basing upon geomorphological setting and petrographic composition of the boulder field, we concluded that the boulder field is a residual of a large end moraine, resulting from a long lasting wash-out process. The moraine appears to have been deposited by a piedmont glacier which moved far into the basin and, at least partly, went afloat.

We counted another five valleys west of Barskaun, that used to contain Terskey's outlet glaciers that were calving into the lake. Among the valleys – the troughs of Tosor (Fig 24), Tok (Fig 25) and Turasu. No end moraines could be

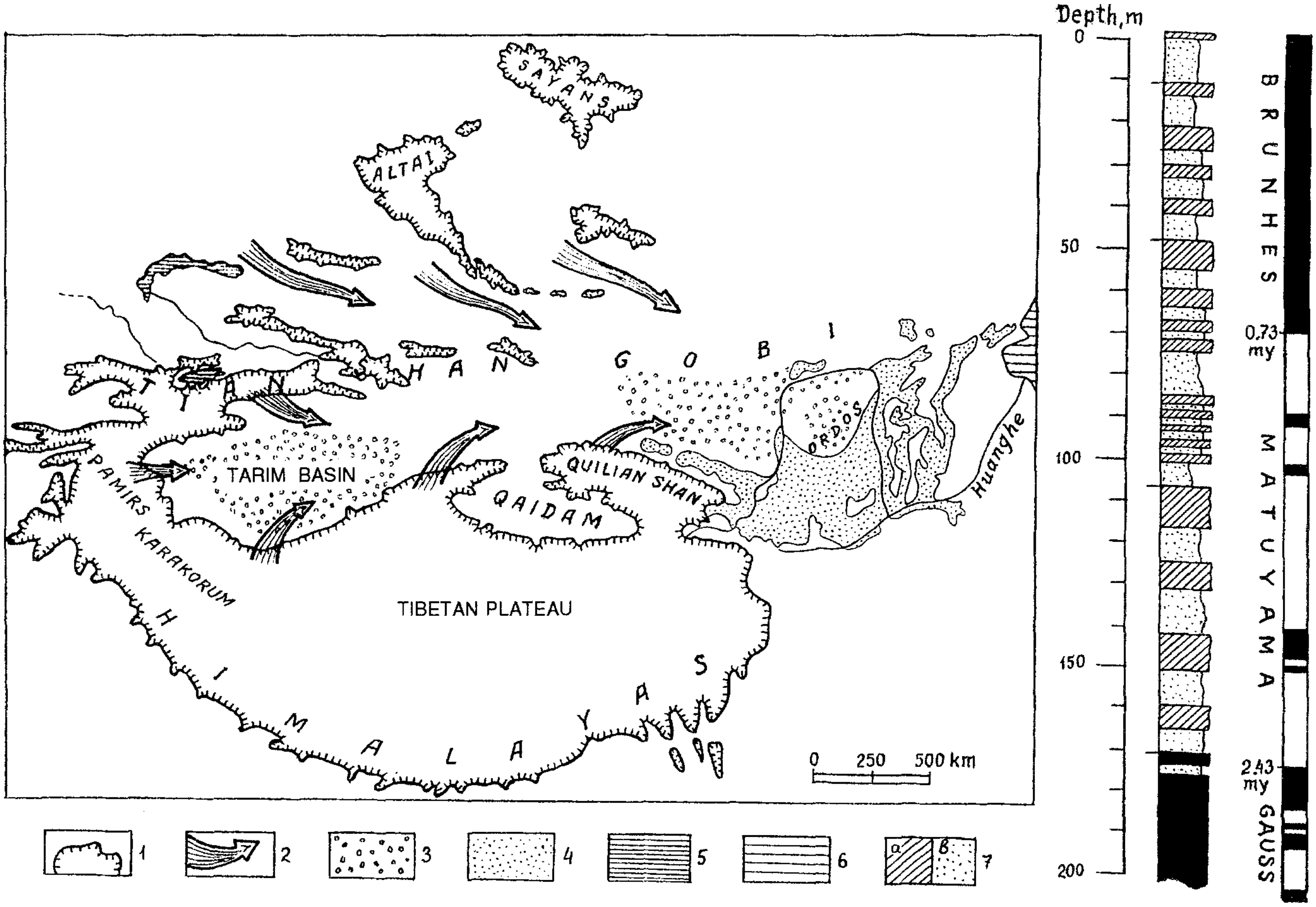


Fig 8 Ice covers, deserts and loess accumulation in Central and Eastern Asia during the last and older glaciations: the map shows directions of winds and their relationship with loess sources and major loess accumulation grounds. On the right: the Chinese loess stratigraphy after Kukla (1988).
1 ice covers; 2 directions of katabatic and general circulation winds; 3 largest deserts; 4 main field of the Chinese loesses; 5 lakes; 6 the sea; 7 major elements of the loess stratigraphy: a - paleosol beds, b - loess beds, as compared to the paleomagnetic epochs and events (extreme right)

spotted in the valleys (except Turasu), while the lateral moraines are virtually truncated on the boundary with the former - high-level - Lake Issyk-Kul. Only in the lower Turasu valley, some 100 m south of the settlement of Karashar and the circum-Issyk-Kul highway, a chain of asymmetric hills identified as remnants of ice marginal ramps were found at 1650–1680 m asl. This "Karashar Moraine" is erosionally dissected into a few asymmetric hills, aligned along an arch turned by its convex side to the north; the tops of the hills reach the altitudes of 1720-1740 m, which is about 130 m above the present-day level of Lake Issyk-Kul. The hills are made up of glacially shaped boulders and pebbles of granites, quartzites and other rocks, cemented by buff-coloured clayey sands, their southern (stoss) slopes are steep, around 30°, the northern (lee) slopes - much gentler, only 10° and less. Huge accumulations of grooved and faceted boulders mantle the western part of Terskey Alatau down to Chu River valley. The boulder masses, normally concealed by surface sediments, were open to inspection in Kara-Kungey valley due to fresh incision produced by a recent mudflow.

Wealth of evidence attests to past ice incursions into the lake from the opposite side of its basin, too. Morphologically fresh end moraines and ice marginal ramps are widespread in the southern foothills of the Kungey Alatau Range (Fig 30–38). In particular, such a moraine with apparent till thickness of 80 m occurs in lower reaches of the Choktal valley (Fig 30, 31), at the head of a piedmont outwash fan. Much larger moraines were found on eastern outskirts of the settlement of Cholpon Ata, at Sovkhoz "Progress" and Mount Prishib. Ample accumulations of large glacially faceted and striated boulders and blocks form there an impressive ridge at 1650 m asl (Fig 33–36), at the very shore line of the lake (see Fig 32 in: Kuhle 1990).

Of utmost importance for explaining the environment reorganizations in question are moraines of Chu River valley. One of a key sites was found to be a few kilometers

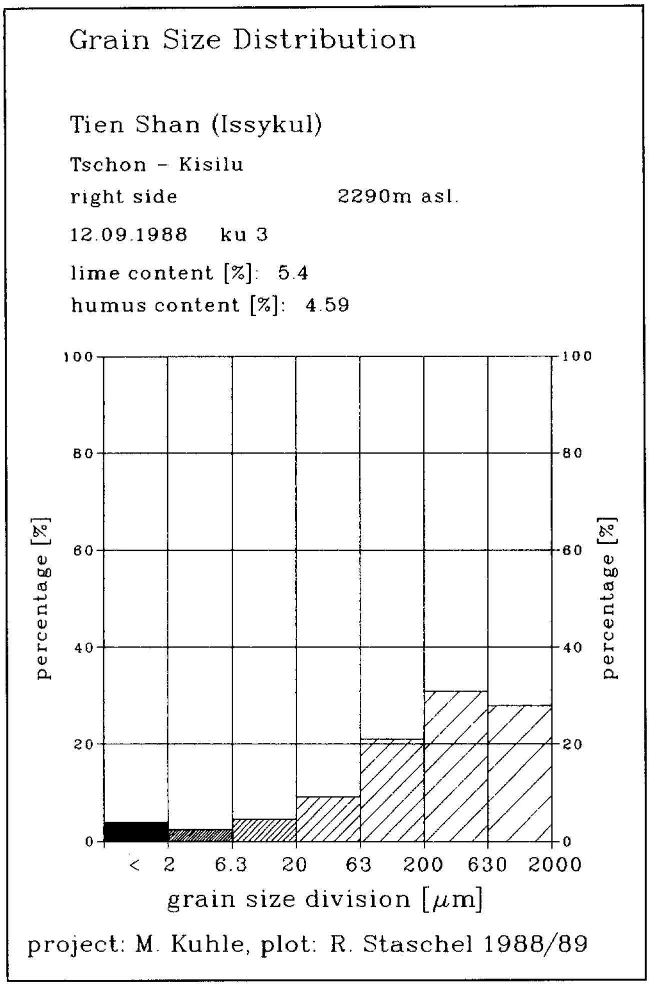


Fig 12 Analysis of the finely grained moraine substratum between the erratic granite blocks (Fig 11) on the orographic right-hand flank of the Chon Kyzylsu (Tschon Kisilsu). It occurs on bedrock phyllites as a fine matrix between these large moraine blocks. Taken from a depth of 0.20 m. The composition of grain sizes shows the characteristic proportion of grain sizes, and can be identified as moraine material on the basis of the two peaks, ie of a coarse-grained and a fine-grained peak. Bi-modal grain-size graphs of this kind are typical for ground moraines. Location of the sample taken: 42°17'N/ 78°08'28"E; Fig 1 right-hand of No. 2

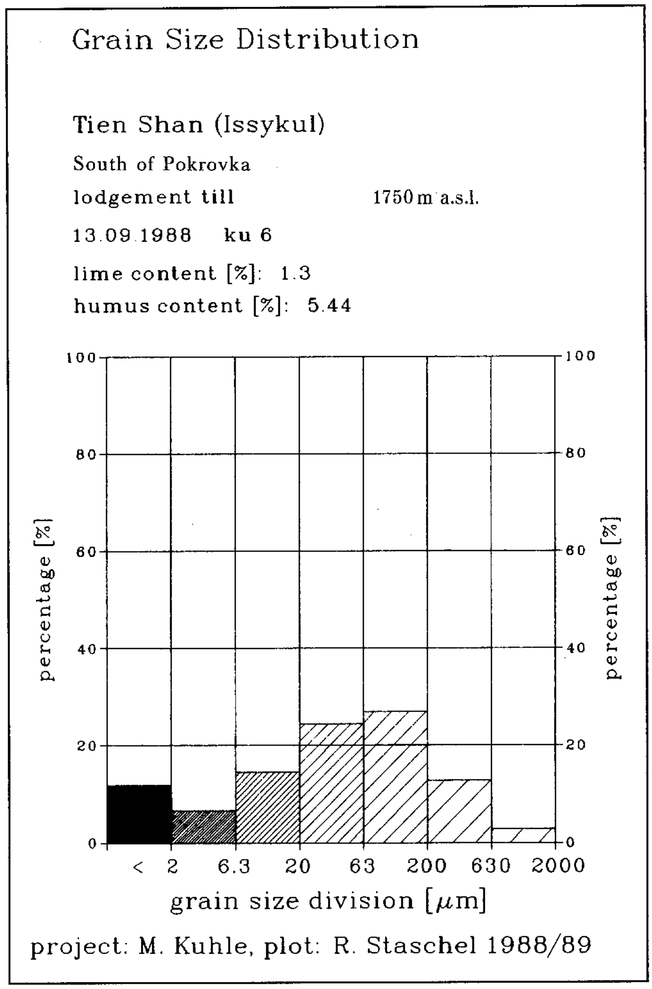


Fig 19 Locality of sample, cf. Fig 18 X. The bi-modal course of the grain-size graph, ie renewed rise to a peak of fine grain sizes, shows that this is typical ground moraine material (basal till).

upstream of Boam Canyon, at the junction of Chu River with its right-hand tributary Kokpak-Kyrkoo. The Kokpak-Kyrkoo valley was glaciated by an outlet glacier of the last ice cover of the Kungey Alatau Range, the outlet's signature being two tiers of lateral moraines on both sides of the valley. The moraines grade into lacustrine terraces, resting on the bottom of Chu River valley, the lower (60 m), and the upper (120 m) ones. In fact, the masses of till are replaced there, in a way of interfingering, by lacustrine sediments - loess-like yellow-white silts containing frequent dropstones; this all was clearly seen in bluff sections of the Chu terraces.

Another morainic lobe enters the valley on its opposite side, from the Bailamtal valley, the eastern Kirgiz Range. That lobe is dissected by a number of fanning ravines and turned into a system of short radial ridges, which also grade into the lacustrine terraces of Chu River. The moraines of both sides of the river merge into each other on the valley floor to form a single continuous field of glacial deposits extending along that floor for about 10 km - just till the upper entrance into the Boam Canyon. Obviously, the masses of ice flowing from the Kungey Alatau and Kirgiz Ranges and joining on the valley bottom had to form a dam which was high enough to cause the Lake Issyk-Kul level rise by hundreds of meters (Fig 39). And thus to account, with big margin, for all the lake-level oscillations recorded by Alyoshinskaya and Bondarev (1970), Gerasimov (1953) and others.

Several additional ice dams were formed within the Boam Canyon itself. This is suggested by river-cut masses of till entering the canyon from its hanging tributaries. Of particular importance is the moraine which was detected on the left-hand slope of the Chu valley at its junction with Chon-Kemin river, some 200–220 m above the valley bottom. The moraine was deposited by a former glacier of the Chon-Kemin valley (Fig 40, 41); this fact suggests that the glacier was by 100 km longer than today, and its snout lowered to the altitude of 1200 m asl (Grosswald et al. 1992). All the evidence for ice marginal positions during the LGM (Last Glacial Maximum) are presented in Fig 2.

To determine the age of the discussed ice-damming event, two samples of organic detritus were collected from the base of 60 m glaciolacustrine terrace in Chu River valley at the mouth of Kokpak-Kyrkoo (Site 7 in Fig 1). Their radiocarbon dating yielded the following results:

26,100± 600 yr BP (IGAN-616) and
32,390±1780 yr BP (IGAN-971),

which warrant the conclusion - basing on these dates along with unambiguous position of the sampling site relative to the till and lacustrine beds - that the ice-damming event started *later* than 26,000 yr BP, and probably climaxed during the LGM.

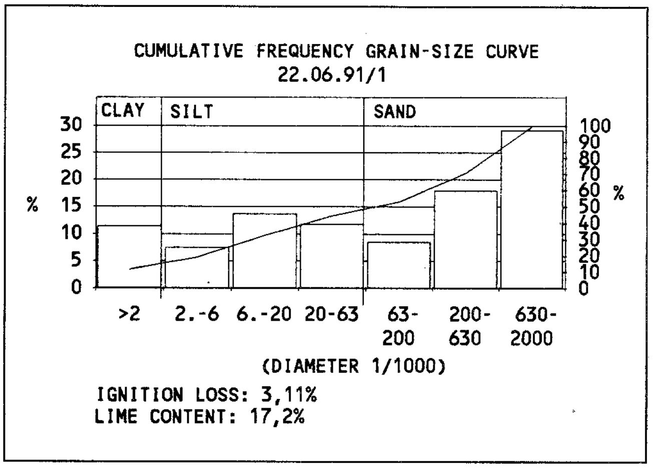
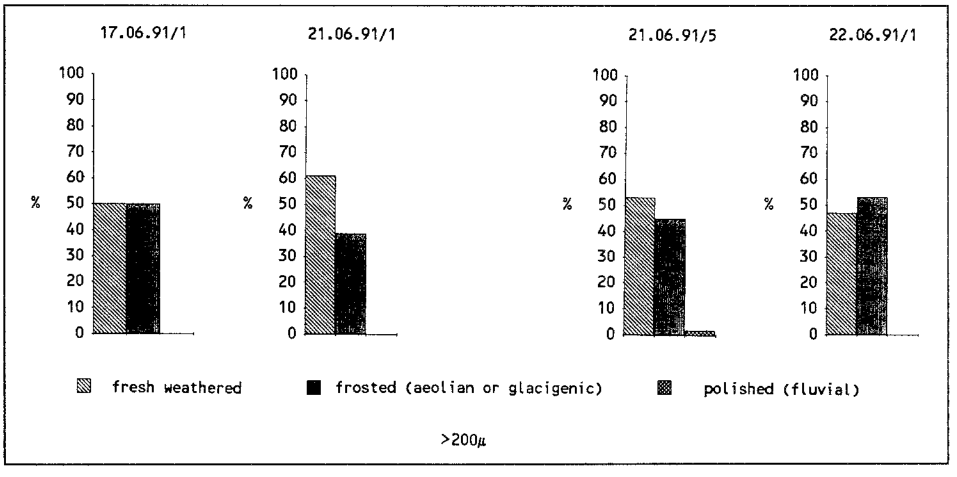


Fig 20 1650 m asl, grain size distribution in the boulder clay of a ground moraine, which reaches the south bank of Lake Issyk Kul between the ice-marginal ramps (IMRs) before disappearing below the lake level. This is matrix material from between large erratic blocks of granite which originated in the Terskey Alatau chain (Fig 1, 2, 3). As shown in Fig 2, the northern outlet glaciers of the Tian Shan inland ice cap between Dzhuku in the E and Barskaun in the W reached Lake Issyk Kul here, and calved into the lake (cf. Fig 21). Localitiy of samples taken: 42°12'N/77°43'E.

Discussion

Snowline depression and the extent of glaciation. Our map (Fig 2) provides information on the extent of last glaciation in Lake Issyk-Kul area (Grosswald et al. 1992). It implies that the glaciation of the area was twice as extensive as was previously believed (compare with Fig 1). The glaciers extended not only over the high-mountain zone, but on the mid-altitude zone, also. Obviously, this gave the glaciation a new dimension since ice discended to such low levels that it just couldn't help but invaded the Lake Issyk-Kul and Chu River valley. Which, in turn, had to cause the formation of ice-dammed lake and choking it with icebergs. This implies that the interaction between glaciation and the said elements of paleoenvironment turned out much more immediate and vigorous, than it was previously deemed possible. This further implies that not only melt water, but also glacier ice, till and outwash materials were brought into direct contact with the lake and river, producing floating ice tongues and icebergs, dumping the diamictons, impeding the surface runoff.

Fig 21
Morphometry of some fine moraine grains in the northern foreland of the Terskey Alatau chain between Bishkek in the W and Chon Dzhuku in the E; among them also the sample 22. 6. 91/1 shown in Fig 20. It is a characteristic feature of the ground moraine that glacigenically weathered material predominates over recently weathered material. The reverse obtains in end moraines (21. 6. 91/1/5). If the sample contains polished material, as in sample 21. 6. 91/5, it is a case of ice-marginal ramps (IMRs) and implies meltwater involvement in their construction as a matter of course. Sample locality 22. 6. 91/1, Fig 20.



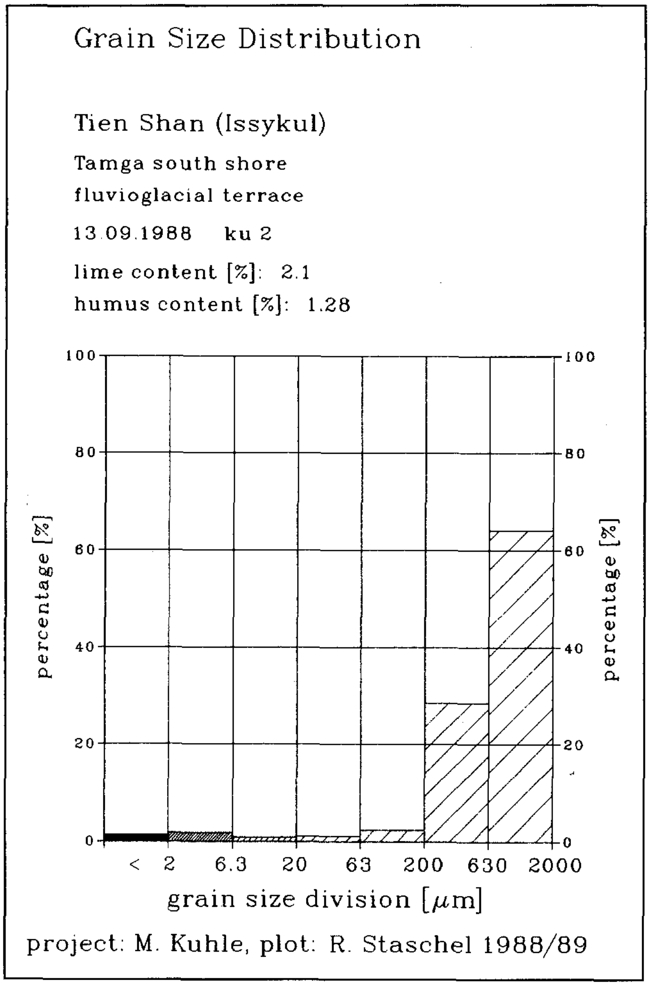


Fig 23 The grain size analysis shows the typical picture of Ice Age mountain foreland outwash plains (glacifluvial sediments) with their characteristic lack of fine material and the rapid increase in the proportion of sand to coarser material (630–2000 μm). Location of extraction: area of the mouth of the Tamga river (-valley) in the mountain foreland near the line of the south bank of Lake Issyk Kul; 1660 m asl (Fig 1, No. 3; see Fig 2); 42°09'20"N/77°33'E.

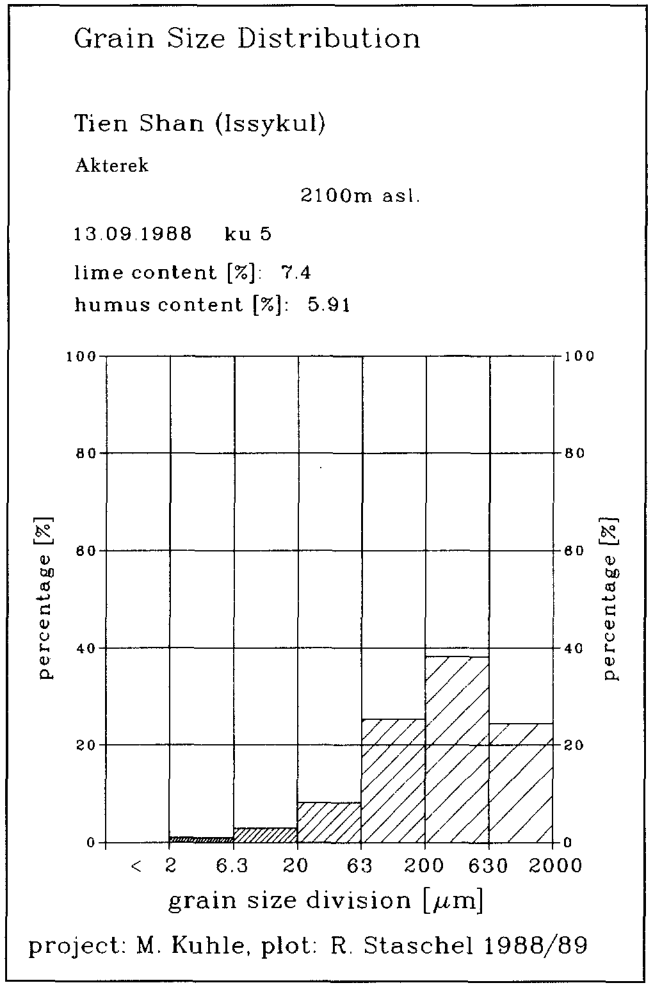


Fig 28 The composition of grain sizes is typical of the kind of outwash moraines occurring on the surface of ice marginal ramps behind the end moraine: the fine grain peak of the moraine is missing – having obviously been the first to be washed out fast. For locality of samples taken on the ice marginal ramp see locality of the photograph in Fig 27 (42°07'20"N/76°45'E) and Fig 29 with the IMR outer slope concerned.

Our data on the altitudes of past glacier snouts made it possible to determine the range of Würmian snowline depression by means of Höfer's techniques (Höfer 1879). To this end, several large glaciated valleys were selected, having "live" glaciers in their headwaters and *prima facie* end moraines of LGM in low reaches. Then, we had to determine the snout altitudes for the present-day and former glaciers of the valleys; to calculate the altitude differences; and to divide the differences by two. Specifically, this was done for the valleys of Chon-Kemin, Choktal, Akterek (west), Tamga, and Barskaun rivers. The results are presented in Fig 3, which implies that at Chon-Kemin the snowline lowering amounted to 1220 m, whereas at the rest of the valleys it was some smaller, though exceeded 1000 m, anyway. Moreover, three (of those four) glacier tongues were cut short by calving, which definitely prevented them from reaching even lower altitudes. Considerable depression of past snowline characterized the westernmost Kungey Alatau Range, too. This comes from the fact that ice-free cirques lie in the range at 2700–2800 m asl, while the equilibrium line of existing glaciers - at 3800–3900 m asl, suggests that the past, probably Würm, snowline depression measured there 1000 to 1200 m.

On the average, the Würmian lowering of snowline in the Lake Issyk-Kul area of Tian Shan was about 1150 m (Grosswald et al. 1992). It turned out to have been at least twice as large as it was accepted by our predecessors. On

Fig 9 ▲
View from the south bank of Lake Issyk Kul at 1650 m asl facing SE towards the eastern Terskey-Alatau chain and up into the Chon-Kyzylsu valley (cf. Fig 1 on the right-hand side of No. 1). Numbers 1, 2 and 3 mark 5216 m-, 4845 m- and 4590 m-high massifs, which continue to be under glaciation. ∇ indicates persisting hanging glacier tongues. Several 100 m- high ice-marginal ramps (IMR) are evidence (■) of the main Last Ice Age piedmont glacier lobe which flowed out of this valley towards the NW and to within at least 13 km of the present edge of Lake Issyk-Kul (cf. Fig 2). Initially, at the height of the Würm Ice Age (0), the Chon-Kyzylsu outlet glacier bordered on (↙) the highest end moraine, or IMR level (■0), and found its surface undergoing a step-by-step melt-down during the Late Ice Age. This allows another four lower IMR levels (■■) to be identified, which descend in steps. The more recent, Late Glacial glacier positions within the Main Glacial location of the ice margin (■0) can be seen from the mountains down in the tongue basin (I, II, III) as shown in Fig 10 (■). —— shows the glacifluvially formed and relatively steeply inclined (7–9°) IMR surface, which falls away from the glacier and further into the mountain foreland. ● indicates the sweep of the oldest tongue basin, which is covered with more recent glacifluvial drift. ▼▼ mark post -Ice Age glacier rill washings and formation of small valleys. - - - - indicate the Ice Age glacier level reconstructed on the basis of flank polishings (◖◗), and thus the considerable glacier thickness. ↗ marks the position from which Fig 10 was taken, and indicates the locality of the erratica findings of Fig 11. Locality: 42°24'N/78°04'E; Photo M. Kuhle 10. 9. 88.

Fig 10 ▶
View from the orographic right-hand rock spur (consisting of phyllites) at the exit of the Chon-Kyzylsu valley at 2400 m asl, facing NW across the Late to Main Glacial piedmont moraines (■) towards Lake Issyk-Kul (O). (Fig 1 right-hand of No. 1). The orographic right-hand valley flank, which is in view here, was polished by the Chon-Kysylsu outlet glacier (◢◗), during the last Main Ice Age (Würm or Waldai) when the terminal moraines marked ■ 0 were laid down by the piedmont glacier (cf. Fig 9). This glacial flank polishing is 350–400 m above the valley talweg (above the river on the right edge of the section) at 2160 m asl. The Main Ice Age piedmont glaciation of this valley spread like a hammerhead spit, so that it formed a foreland ice together with similarly extended foreland ice masses of the adjacent parallel valleys (cf. Fig 2). However, this applied only to the Main Ice Age. During the Late Glacial stages I (Ghasa stage), II (Taglung stage) and III (Dhampu stage) the tongues of the outlet glaciers not only became shorter (ie failed to extend so far out into the foreland), but also steadily narrowed (see sequence ■I, ■II, III). Lateral moraines contained them on their sides (■). Glacifluvial kames (X) have been piled up against the lateral moraines of Stage I. ↓ mark Holocene runnel washings in the moraine material; ▼ shows the position of erratic moraine material (cf. Fig 12, sample 12. 9. 88/3 and Fig 11). Evidence of large erratic blocks of granite occurs in the moraines ■I up to levels of 2300–2400 m asl, and indeed up to the moraine ridge. These moraines are deposited upon crystalline slates. The Main Ice Age moraines (■ 0) rest on more or less disordered neogenic and older sedimentary rock. Locality: 42°17'N/78°08'30"E; Photo: M. Kuhle 12. 9. 88.

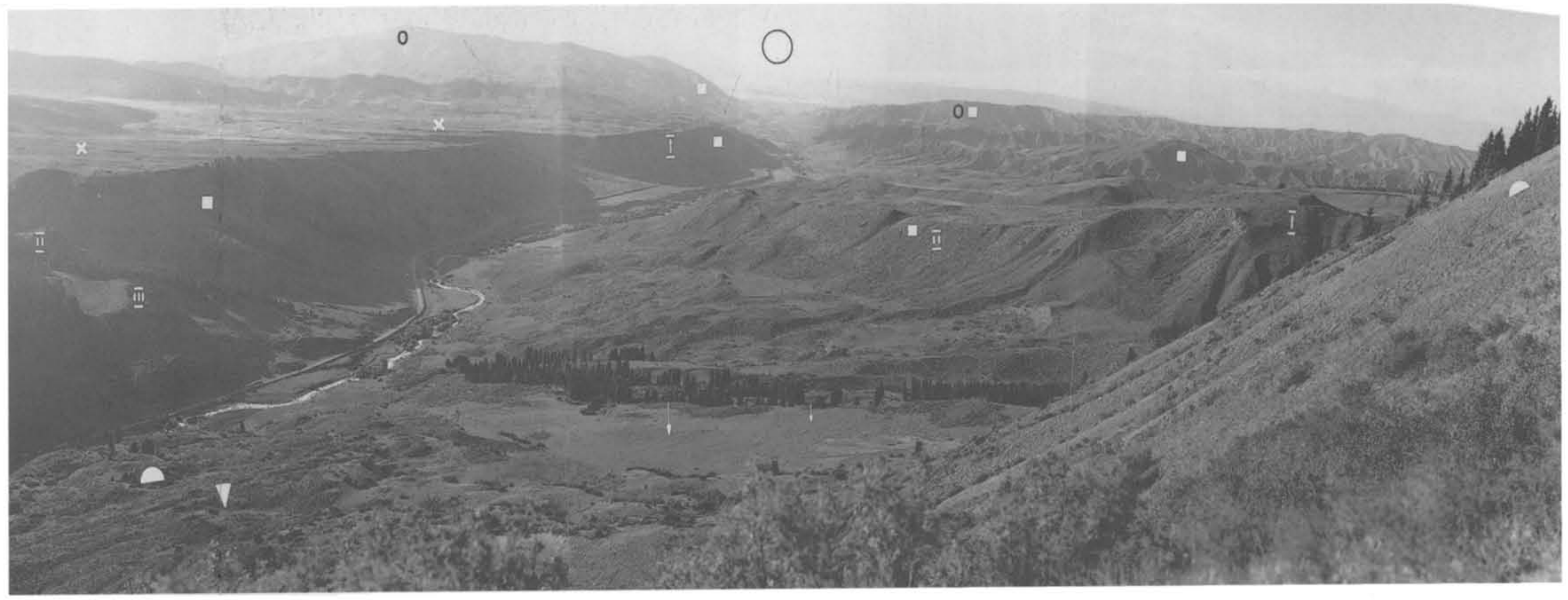


Fig 11 ▼
View from the orographic right-hand valley flank of the Chon Kyzylsu (or Tschon Kisilu) at 2290 m asl, facing S up into the valley (Fig 1 right-hand of No. 1). In the foreground medium-sized to very large light-coloured erratic blocks of granite (●) have been deposited by this Late Glacial outlet glacier of the Tian Shan ice-cap on the glacigenically polished rock flank (◖), which consists of greenish, metamorphic sedimentary rock (phyllites) (cf. Fig 12). The largest of these blocks is 5 m long, 4 m wide and 3 m deep (for comparison of size see the 1.75 m tall person). Corresponding to these erratica deposits, the Late Glacial lateral moraine terrace (□ III) is visible as a wooded, flattened area on the opposite side of the valley on the orographic left-hand side (cf. Fig II, III). The erratica lie 130–150 m above the present drift floor of the valley. The Main Ice Age level of the ice stream network (- - -), which can be reconstructed on the basis of the increasing absence of glacigenic flank polishings (◗◢), runs above the timber-line (2850–3050 m asl), and thus c. 1000 m above the valley floor. Far down (□ IV), another and more recent Late Glacial ledge of lateral moraines is visible (Sirkung stage). No. 2 = 4000 m-high peak with satellite rocks; No. 1 = 3985 m - high peak; both these mountains are ice-covered. Locality: 42°17'N/78°08'28"E; Photo: M. Kuhle 12. 9. 88.

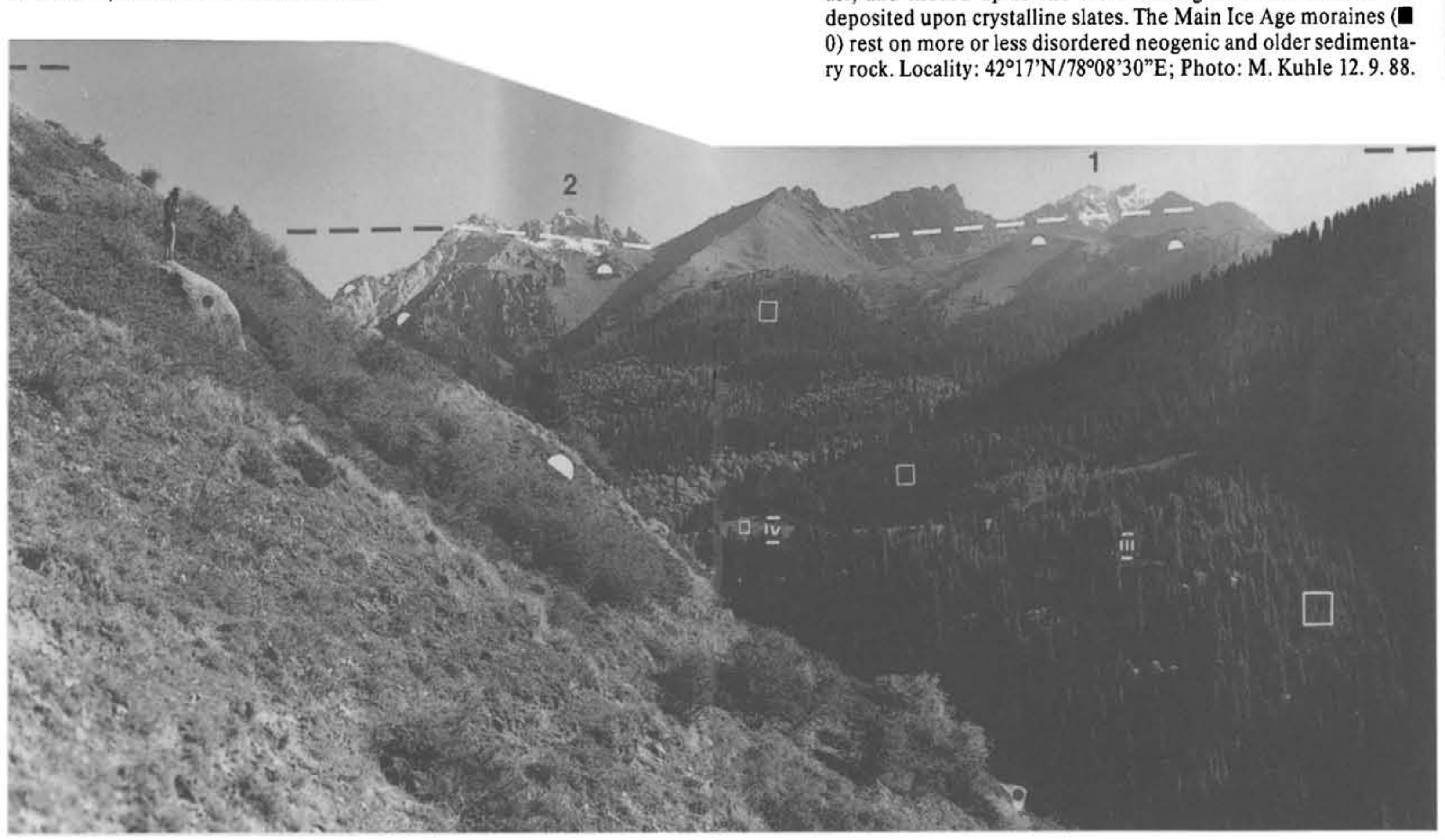


Fig 13 ▶
View from the valley bottom of the upper Chon Kyzylsu at 2700 m asl towards the S, looking into its valley-head with the confluence area of three headwaters on the NNE slope of the Terskey Alatau (Fig 1 on the right, below No. 1) (cf. Fig 14–17). As the evidence of flank polishings (◖◗) on the bedrock gneisses and metamorphites show, the main valley and its tributaries had been filled with glacier ice up to c. 4000 m (- - - -). At least two different ice-scour limits, ie prehistoric glacier levels, can be discerned: the lower one (- - - - below) is definitely from the Late Glacial period, but even the upper ice-scour limits marked here (- - - - above) are likely to belong to the early Late Glacial time. The highest, ie Main Glacial, ice stream level cannot be reconstructed here. □ mark talus cones from post-Late Glacial rock falls from the glacially polished valley flanks. ∇ indicates a mudflow cone on the valley floor. No. 1 = 4590 m peak, still with substantial ice superstructure; No. 2 = its c. 4300 m-high satellite N-peak. Locality: 42°08'N/78°12'30"E; Photo: M. Kuhle 11. 9. 88.

Fig 14 ▲
View from 3150 m to the E into the orographic right-hand flank of the Chon Kyzylsu main valley in the confluence area of the tributaries near its valley head (Fig. 1 right-hand side, below No. 1), where bands of ice-scouring occur up to the very ridges (◓). Glacially polished to great altitudes, the cuspate-shaped mountain flanks have undergone periglacially concordant transformation. - - - - marks the minimum height of the Ice Age glacier level at 3700 m asl. At the bottom of the trough-shaped tributary valley, Late to Neo-Glacial dumped end moraines are found (□). The flattened parts of slopes in the main valley must be regarded as Late-Glacial lateral moraine ledges (■). Locality: 42°07'30"N/78°12'E (cf. Fig. 15). Photo: M. Kuhle 11. 9. 88.

Fig 15 ▲
View from 3200 m asl towards SW, facing up into the orographic left-hand headwaters (Chon Aschuto) of the Chon Kyzylsu (Fig 1 on the right below No. 1). This is a hanging valley, the bottom of which is joined to the main valley by a c. 400 m-high confluence step. Flowing down from the Tian Shan plateau, one of the numerous outlet glaciers of the last Ice Age inland ice caps transformed the valley into a classic trough valley. After the late Glacial deglaciation only smallish talus cones (∇) were formed below the glacial flank polishings (◓). - - - - marks a probably Late Glacial glacier level at 3700–3600 m asl. Due to the absence of unambiguously preserved ice-scour limits, there is no evidence of higher ice levels. No. 1 = c. 4000–4200 m - high glaciated secondary peaks of a northern Terskey Alatau secondary ridge. Locality: 42°07'29"N/87°11'59"E (cf. Fig 16); Photo: M. Kuhle 11. 9. 88.

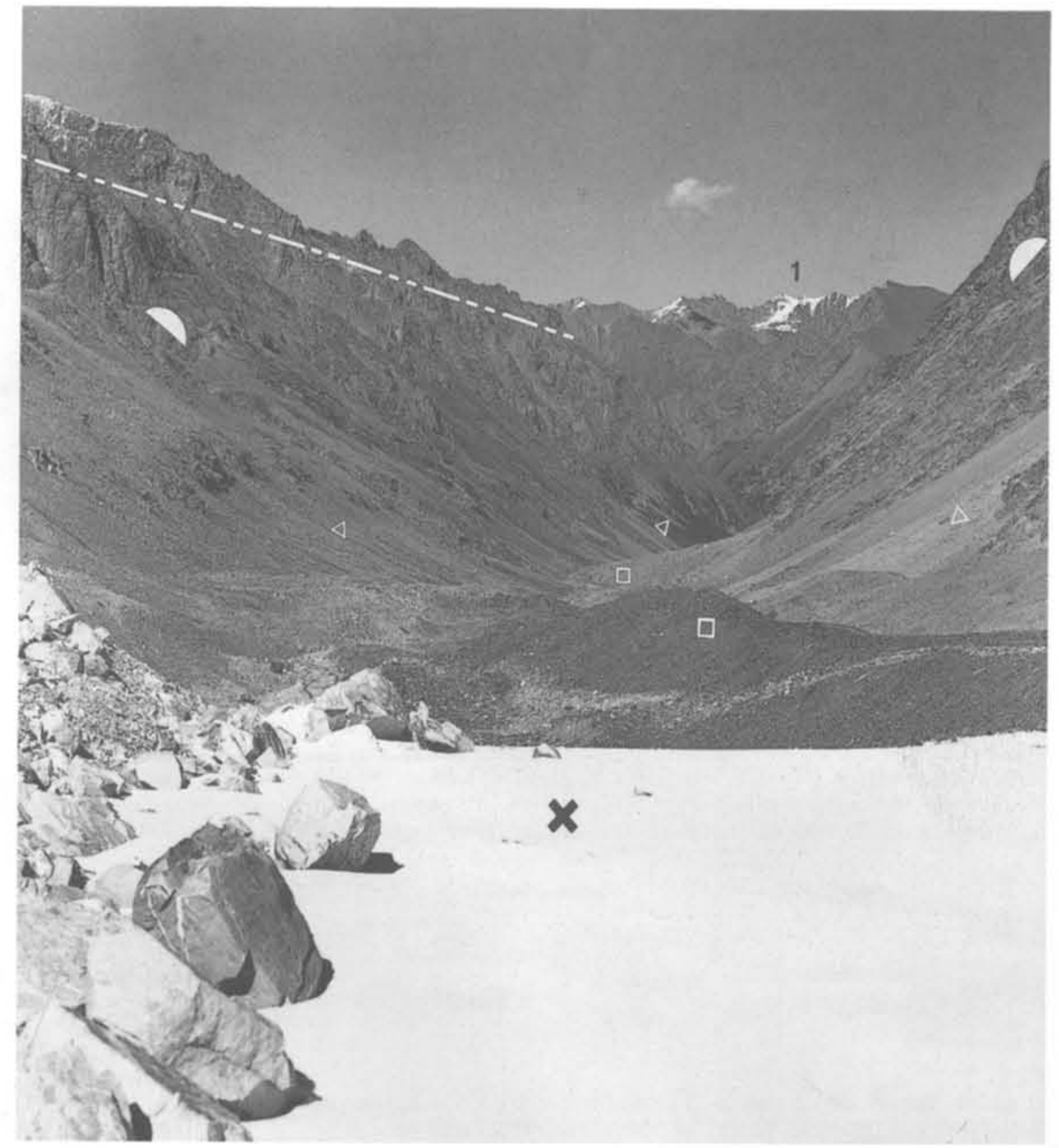


Fig 16 ▲
View from 3650 m asl, from the tongue of the Aschuto glacier (X) which is still under snow, towards the NNE down the Chon Aschuto valley (Fig 1 on the right, below No. 1). No. 1 = 4000–4200 m-high, only just glaciated northern peaks of the eastern Terskey Alatau chain. This trough valley has been scraped out (cf. Fig 15) by a northern outlet glacier of the Tian Shan ice cap (Fig 2) which flowed across the Aschuto transfluence pass (cf. Fig 17). The well preserved Late Glacial flank polishings (◓),with an ice scour limit at 4000–3750 m asl in the bedrock metamorphic rocks are evidence of a prehistoric glacier level (- - - -). The main Ice Age glacier level was noticeably higher. ∇ marks post-Glacial talus cones. □ (small sign further back) points to an historic ice margin location (Little Ice Age?) at 3300 m asl. The next younger ice margin location with a dumped end moraine, which is still likely to be holding some dead ice (□ larger sign more to the front) lies at 3400 m asl. The present glacier tongue ends at 3480 m asl, and is covered by debris (not visible, as it is in the blind spot of the exposure). Locality: 42°05'N/78°12'20"E; Photo: M. Kuhle 11. 9. 88.

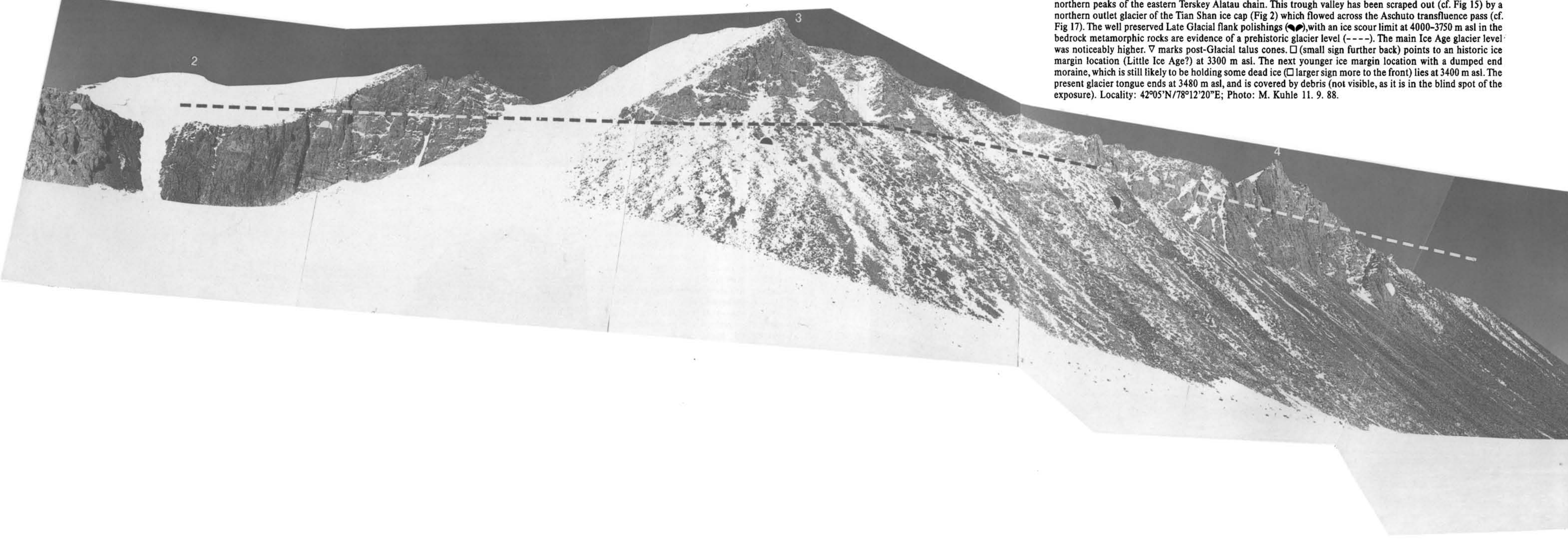


Fig 18 ▲
View from the southern edge of the town of Pakrovka near the south bank of Lake Issyk Kul in the area of the valley exit of Chon Kyzylsu (♦) in 1700 m asl towards the SE to three Main (?) to Late Glacial ice margin indicators (■) (Fig 1 right-hand of No. 1). The tongue of the Chon Kyzylsu outlet glacier emerged from the Terskey Alatau mountains and entered the mountain foreland (♦). Here, outside the hitherto lowest end moraines (cf. Fig 10) a renewed advance led to hammerhead-shaped spread. The three kame terrace-like moraine levels (■ or IMR levels) were built up during this process. In the three levels, which are laid down here, their edges bordered on the same number of glacier surface levels. The extreme steepness of the edge gradients (towards the right) is evidence that these were deposited along the edge of a glacier or against it (remnants of alluvial fans would have a much gentler slope). The glacier tongue may have reached Lake Issyk Kul (though persisting uncertainty on this point argued against an entry down to Lake Issyk Kul in Fig 2). X marks the locality of the sample described in Fig 19. Locality: 42h19'N/78°00'E; Photo: M. Kuhle 10. 9. 88.

Fig 17 ▼
View from the Ice Age transfluence Pass (Aschuto Pass, No. 11) from 4100 m asl across the Terskey Alatau main ridge (Nos. 1-4), which formed the NNW boundary to the ice cap cover of the Tian Shan plateau (Fig 1 on the right, below No. 1; cf. Fig 2 in the right-hand corner). The outlet glacier of the Chon Kyzylsu flowed over this pass. Some of the ice persists to this day (cf. Fig 16X), though only locally, over some kilometres to the north and south. This panoramic view has been taken from NE (Nos 2 and 3) to SE to SW (No. 1), showing the central Tian Shan plateau and above it, culminating at 5125 m asl, the Ak Shiyrak mountains (Nos. 5-10). The massif (Nos 2-4) is 4590 m-high (the main peak is out of view). The visible peaks at the Ak Shiyrak massif (Nos 5-10), 20 km away, are 4500-5100 m high. This massif is the presently most heavily glaciated area of the central Tian Shan plateau (glacier area c. 400 km²), and has five up to 15 km - long valley glaciers (Petrov glacier, c. 60 km²) (▼). Peak No. 1 is c. 4800 m high. The Tian Shan plateau (X) was covered by a c. 1000 m - thick ice cap. This minimum thickness has been reconstructed on the basis of glacier polishings of mountain spurs (≷). During the main Ice Age the ice level there (- - - -) was at about 4500-4700 m, asl. The Tian Shan plateau is covered by thick ground moraine (X). The transfluence thickness of the Chon Kyzylsu outlet glacier above this pass was at least 300-400 m, so that its surface level reached 4400-4500 m asl (- - - -). Some glacial flank polishings and smoothings have been preserved in the coarse crystalline rocks of some small areas to this day (◥◢). Locality: 42°03'20"N/78°09'E; Photo: M. Kuhle 11. 9. 88.

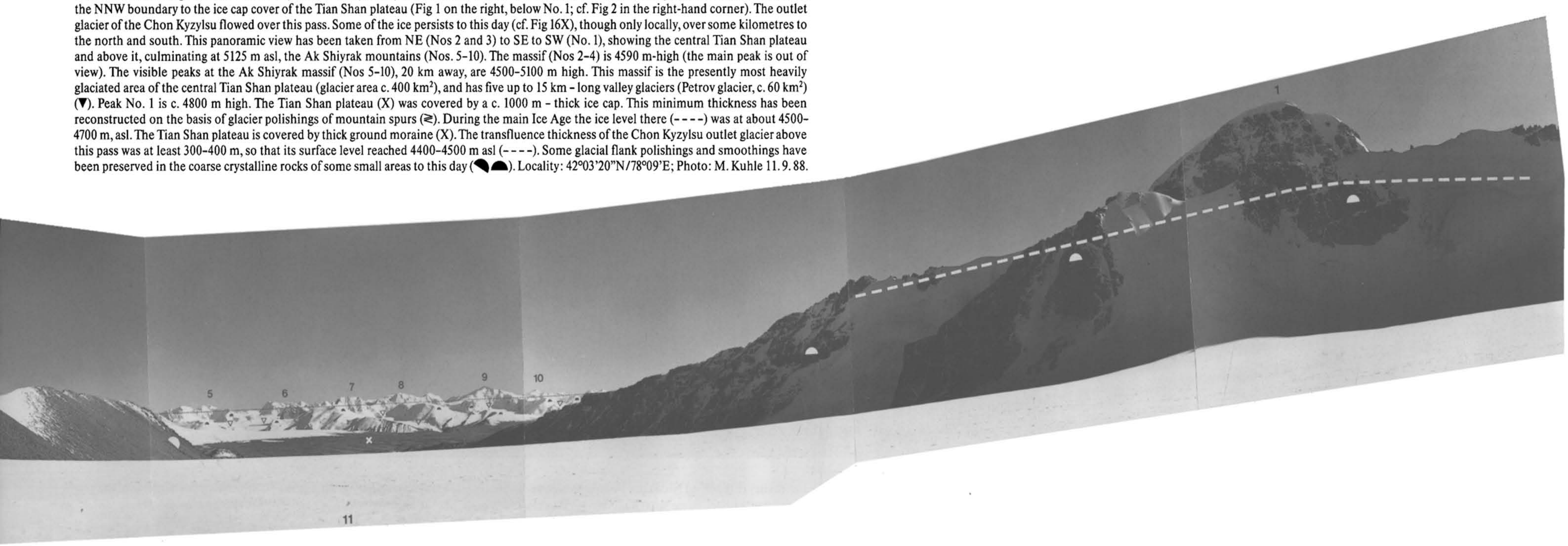


Fig 22 ▲
View from the northern foreland of the Terskey Alatau near the S shore of Lake Issyk Kul at 1630 m asl towards the S to the exit of the Barskaun valley (Fig 1, No. 3). Nos 1–3 = 4200–4550 m-high peaks of the northern Terksey Alatau chain. - - - marks the surface of the Ice Age Barskaun outlet glacier of the Tian Shan ice cap (Fig 2), which can be reconstructed on the basis of glacier polishings (◗). Lateral and end moraines in the highest locations (■O) belong to the Main Ice Age piedmont glacier, which calved into Lake Issyk Kul. ■ I and II belong to the Late Ice Age (Ghasa and Taglung stages). Even at that time the glacier tongue spread like a hammerhead into the foreland to c. 1650 m asl. The Main Ice Age moraines (■0) are of the ice marginal ramp (IMR) type, while the Late Glacial moraines (■I and II) leant against the inner slopes of the ice marginal ramps in the form of narrow lateral moriane ledges. ● indicates a more recent (than I and II) Late Glacial drift floor, which had been laid down by a glacier cave that already receded far back into the valley (cf. Fig 23). O marks corries and hanging valley heads. Locality: 42°09'50"N/77°39'E; Photo: M. Kuhle 13. 9. 88.

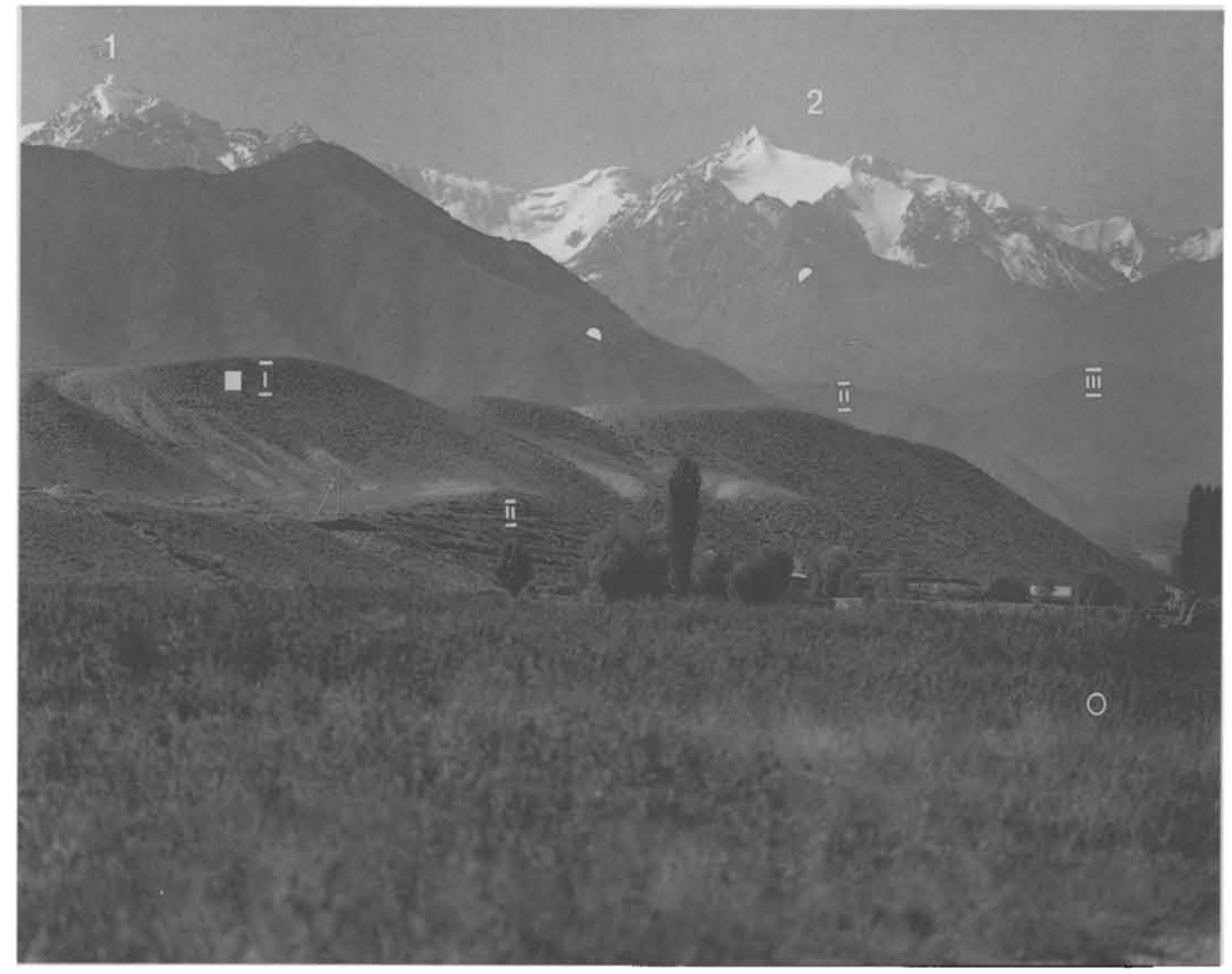


Fig 25 ▲
View from 10 km S of the shoreline of Lake Issyk Kul at 1800 m asl towards the SE into the Tok valley and over to the Terskey Alatau chain (Fig 1 No. 5). No. 1 = main or western subsidiary peak of the 4509 m massif; No. 2 = 4023 m peak on the E side in the 4478 m-high massif. Above the late Late Glacial drift floor (O = sander), the Late Ice Age lateral moraines (■) of the Taglung stage (II) and the Ghasa stage (I) are to be differentiated. ◖◗ mark the Main Glacial flank polishings. The corresponding piedmont glacier calved into Lake Issyk Kul (cf. Fig 2). III indicates the location of the ice margin of the Late Glacial Dhampu stage (III), which remains within the valley. Locality: 42°07'15"N/76°56'E; Photo: M. Kuhle 13. 9. 88.

Fig 24 ▲
View from a Late Glacial drift floor (outwash plain) surface (●) near the south bank of Lake Issyk Kul at 1640 m asl towards the SSW (No. 3) up the Tosor valley (Fig 2; Fig 1 No. 4) No. 1 = 4672 m-high peak; No. 2 = c. 4400 m-high western satellite peak; No. 3 = eastern satellite peak of the 4509 m-high massif, all of which belong to the Terskey Alatau chain and continue to be ice-covered. ◖◭◗ mark the Ice Age polishings on rock ridges and flanks up to the ice scour limits (- - -). ■ 0 refer to the main Ice Age piedmont moraines and IMRs of the same period. ■ I are the corresponding Early to Late Glacial forms (Ghasa stage). The former extend as far as into Lake Issyk Kul. ▼ indicate talus cone-like, Late Glacial glaciofluvial drift floors. Locality: 42°10'N/77°25'E. Photo: M. Kuhle 13. 9. 88.

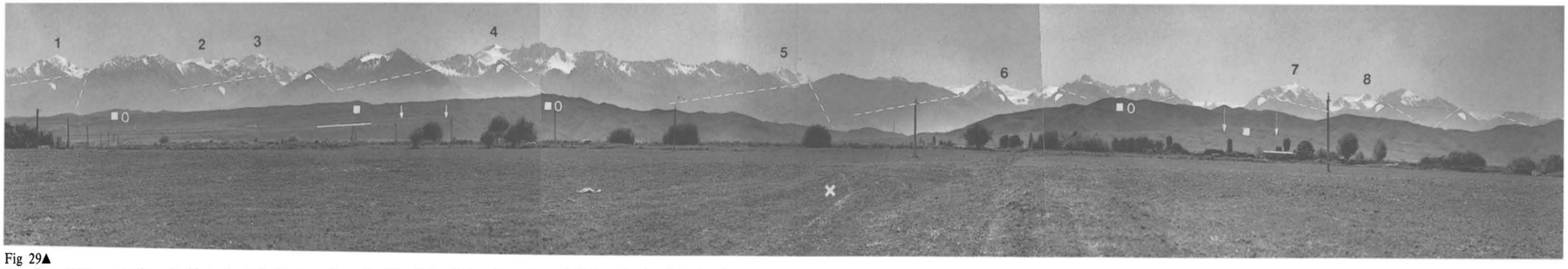


Fig 29▲
View from 1800 m asl, 10 km S of Lake Issyk Kul to the outer wall of the 300 m-high end moraines. Laid down by the Akterek valley piedmont glacier, they are of the ice marginal ramp (IMR ■0) type (Fig 1 between Nos 6 and 5; Fig 2). Panorama taken form SE (No. 1 = 4478 m-high massif) via SSE (Nos 2 and 3 = 4763 m-high massif, the highest feeder area of the immediate Akterek outlet glacier), S (No. 4 = W satellite of the 4763 m-high massif), SSW and SW (Nos 5 and 6 = 4159 to 4200 m-high peaks) to approximately WSW (Nos 7 and 8 = c. 4250–4300 m-high peak). ---- mark the levels of Ice Age valley glaciers of the Terskey Alatau chain, which entered the foreland. The preserved glacial flank polishings extend to these altitudes. The central outlet glacier tongue found its way through the gap between the two main glacial ice marginal ramps (between ■ 0 on the left and ■ 0 on the right) and down to Lake Issyk Kul, into which it calved (cf. Fig 2). ↓↓ point to runnels in the IMR outer slopes. They are the result of meltwater which had reached over the upper edge of the moraine. The outer slopes of the IMR (—) have a 7°–15° incline. X marks drift-covered ground moraine. Locality: 42°11'50"N/76°41'10"E; Photo: M. Kuhle 13. 9. 88.

Fig 30 ▲
View from the N bank of Lake Issyk Kul at 1615 m asl towards the NE across a mountain foreland on to the Kungey Alatau mountains (Fig 1 No. 11). This is the area of the Chok valley mouth, where the main glacial ground moraine (X 0), with its large granite blocks which are "swimming" (●) in a fine matrix, reaches the lake with a 42 km-wide front (cf. Fig 31). This was the W edge of the widest glacier calving front into Lake Issyk Kul (Fig 2). The oldest Late Glacial moraines (■ I = Ghasa stage) are to be found in the immediate valley exit. All the mountain ridges which are visible from here were polished by the glacier as it entered the foreland. Locality: 42°36'50"N/76°46'30"E; Photo: M. Kuhle 10. 9. 88.

Fig 31 ▲
View from a place adjacent to the one used for taking the photograph for Fig 30 at 1615 m asl, facing SE towards Lake Issyk Kul (O) (Fig 1, No. 11). The Main Ice Age ground moraine (basal till) (X 0) with its large granite blocks (●) is submerged beneath the surface of the lake waters (0). Locality: 42°36'48"N/76°46'31"E; Photo: M. Kuhle 10. 9. 88.

Fig 34 ▶
View from an end moraine ridge (■ 0) in the area of the same ice margin location as Fig 33 (Fig 1 No. 12) at 1770 m asl, facing north as far as the S-foot of the mountain range, when the glacially polished, bedrock rock is visible. Further down a several hundred metre-thick mass of moraine material (■ I = Ghasa stage) has been pushed up against it. The end moraines of the Main Ice Age (■ O) are separated from them by a several km-wide tongue basin (◊). Here they form an island of median moraines (Fig 2, on the right-hand side of Choktal) between the two glacier tongue ends which calved into Lake Issyk Kul. The largest blocks (● granite) have been left in the highest positions on the moraine ridge – a typical feature in the construction of end moraine walls. The surface of some of these blocks shows signs of weathering and exfoliation (desquamation) (● right-hand side). Locality: 42°39'59"N/77°11'59"E; Photo: M. Kuhle 10. 9. 88.

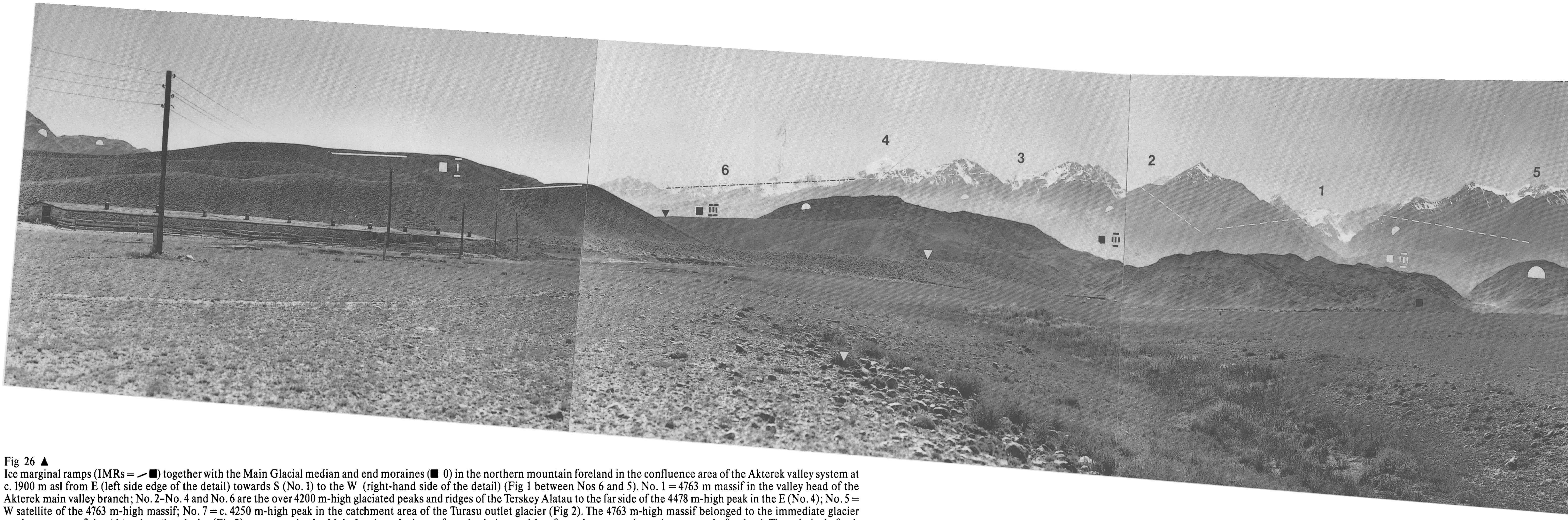
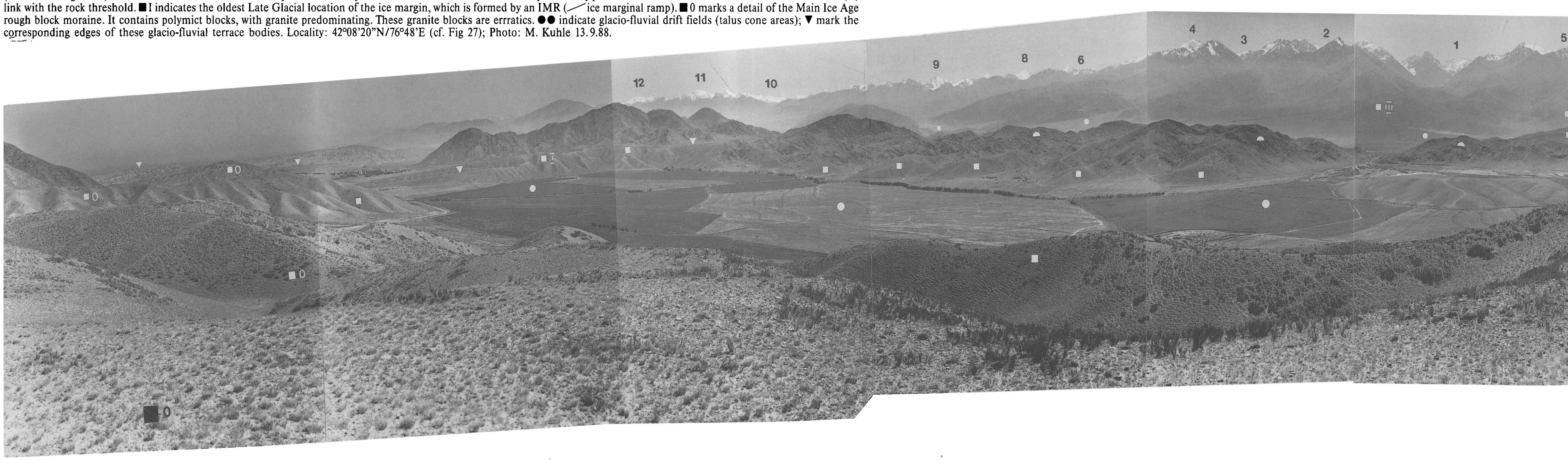
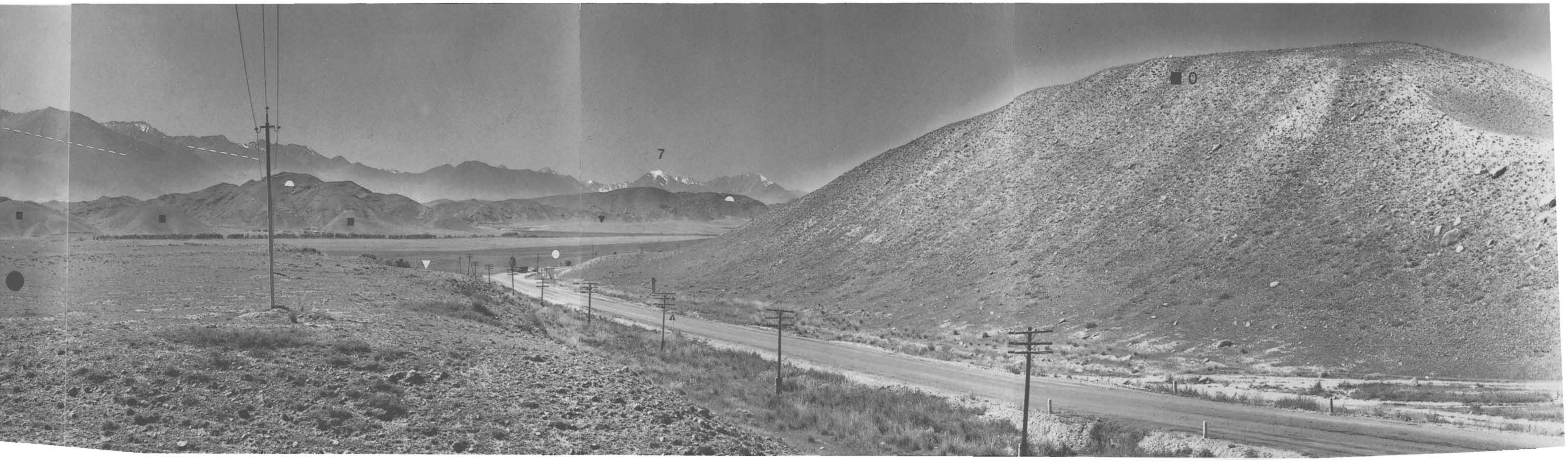
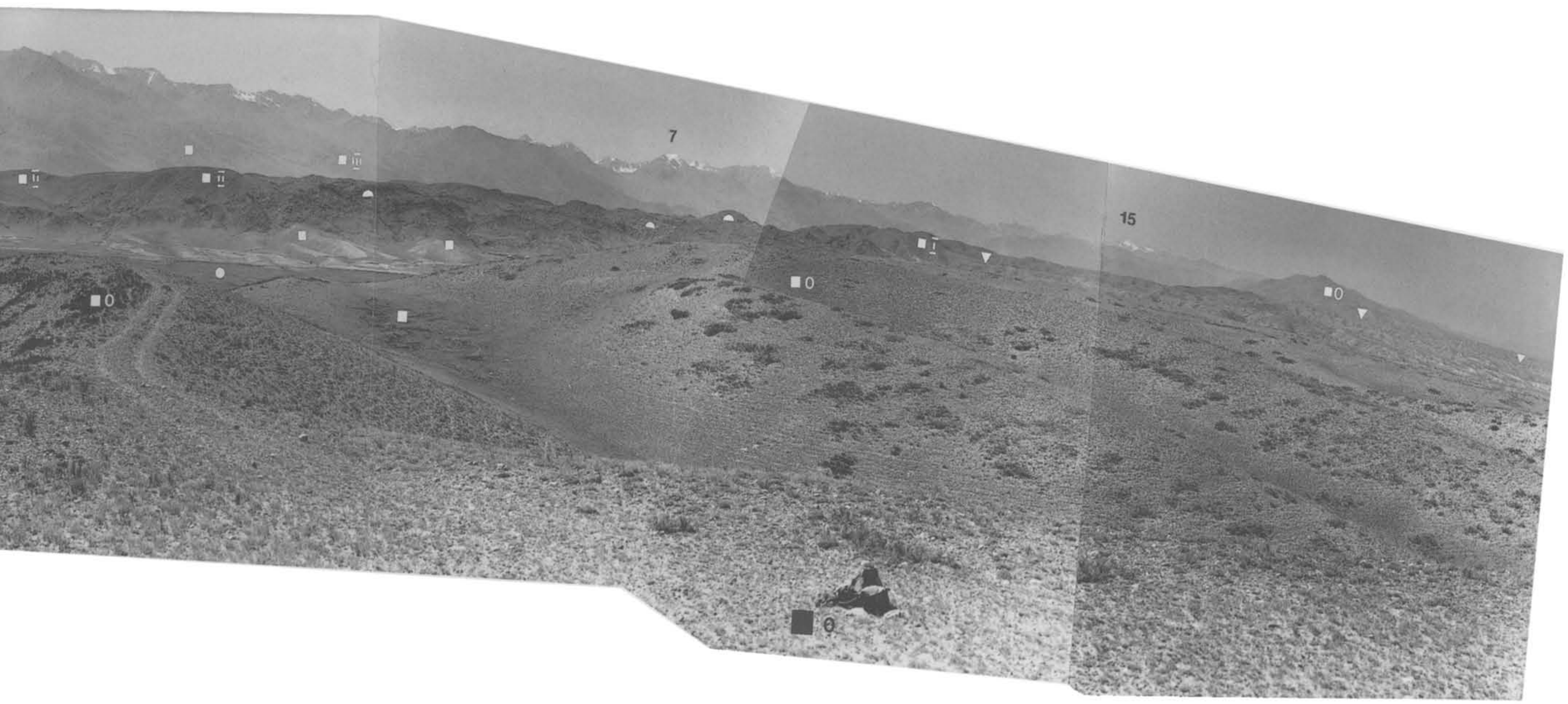


Fig 26 ▲
Ice marginal ramps (IMRs = ⟋■) together with the Main Glacial median and end moraines (■ 0) in the northern mountain foreland in the confluence area of the Akterek valley system at c. 1900 m asl from E (left side edge of the detail) towards S (No. 1) to the W (right-hand side of the detail) (Fig 1 between Nos 6 and 5). No. 1 = 4763 m massif in the valley head of the Akterek main valley branch; No. 2–No. 4 and No. 6 are the over 4200 m-high glaciated peaks and ridges of the Terskey Alatau to the far side of the 4478 m-high peak in the E (No. 4); No. 5 = W satellite of the 4763 m-high massif; No. 7 = c. 4250 m-high peak in the catchment area of the Turasu outlet glacier (Fig 2). The 4763 m-high massif belonged to the immediate glacier catchment area of the Akterek outlet glacier (Fig 2). ---- marks the Main Ice Age glacier surfaces in their transition from the mountain to the mountain foreland. The relatively fresh glacial flank polishings (◠◠ in the background) stop at this altitude. The Late Glacial end moraines (■ III = Dhampu stage) in the valley exits below are of much more recent origin. ◠◠ (in the middle ground) indicate a rock threshold of metamorphic sedimentary rocks which has been flowed over and polished by piedmont ice. In the flow shadow small moraine "tails" (■) link with the rock threshold. ■ I indicates the oldest Late Glacial location of the ice margin, which is formed by an IMR (⟋ ice marginal ramp). ■ 0 marks a detail of the Main Ice Age rough block moraine. It contains polymict blocks, with granite predominating. These granite blocks are errratics. ●● indicate glacio-fluvial drift fields (talus cone areas); ▼ mark the corresponding edges of these glacio-fluvial terrace bodies. Locality: 42°08'20"N/76°48'E (cf. Fig 27); Photo: M. Kuhle 13.9.88.







◄ Fig 27

View from the 200 and more metre - high Main Ice Age end moraines of the IMR type (■ 0) at 2100 m asl across the very extensive tongue basin of the Akterek outlet glacier. It is in the northern Terskey plateau foreland (Fig 1 between Nos 6 and 5; see Fig 2) (cf. Fig 26). This is a panorama which extends over 100 km from E (on the left side edge of the detail) via ESE with the 4672-high massif in the upper Barskaun valley (No. 12) and some peaks (Nos 11–9) to the 4509 m-high massif (No. 8) SE, showing the peaks of the 4478 m-high massif (Nos. 6, 4, 3), via S with the mountains of the 4763 m massif (No. 2, 1, 5), via SW with the c. 4250 m-high massif No. 7 in the catchment area of the Turasu outlet glacier, towards W with the 4502 m-high peak (No. 15), the most westerly glaciers of which flowed from the Terskey Alatau down to the Chu valley. The central Akterek glacier emerged from the valley under No. 1, and joined parallel valley glacier branches in the foreland to form one large piedmont ice. There are late Late Glacial end moraines (■ III = Dhampu stage) in the valley exits with corresponding talus cones of the same period just below (● background). ▲▲ mark a bedrock metamorphic rock threshold which the foreland ice has polished and rounded. Superimposed upon it are earlier Late Glacial moraines (■ II), which are classified as belonging to the Taglung stage. At the foot of the mountains (■ in the background) as well as at the rock threshold (■ middle-ground) Main to Late Glacial moraine "tails" are deposited in the flow shadow of the glacier. On the outside they are followed by the main glacial tongue basin with the glacio-fluvial drift fields (● talus cones, outwash fans) filled in by the Late Ice Age. ■ I marks old Late Glacial (Ghasa stage) ice marginal ramps (IMRs). Their lee-side ramps consist of outwash slopes with a 7–15° incline (▼). In the foreground the Main Ice Age end moraine or IMR edge can be seen (■ 0) running along the northern edge of the tongue basin. Once close to it, the edge of the glacier has given way to small meltwater valleys, which start here (■ in the middle foreground) and lead N down to Lake Issyk Kul (cf. Fig 28 and 29). The piedmont ice surface of the Akterek outlet glacier is entered in Fig 26 and 29 (- - - -). Locality: 42°07'20"N/76°45'E; Photo: M. Kuhle 13. 9. 88.

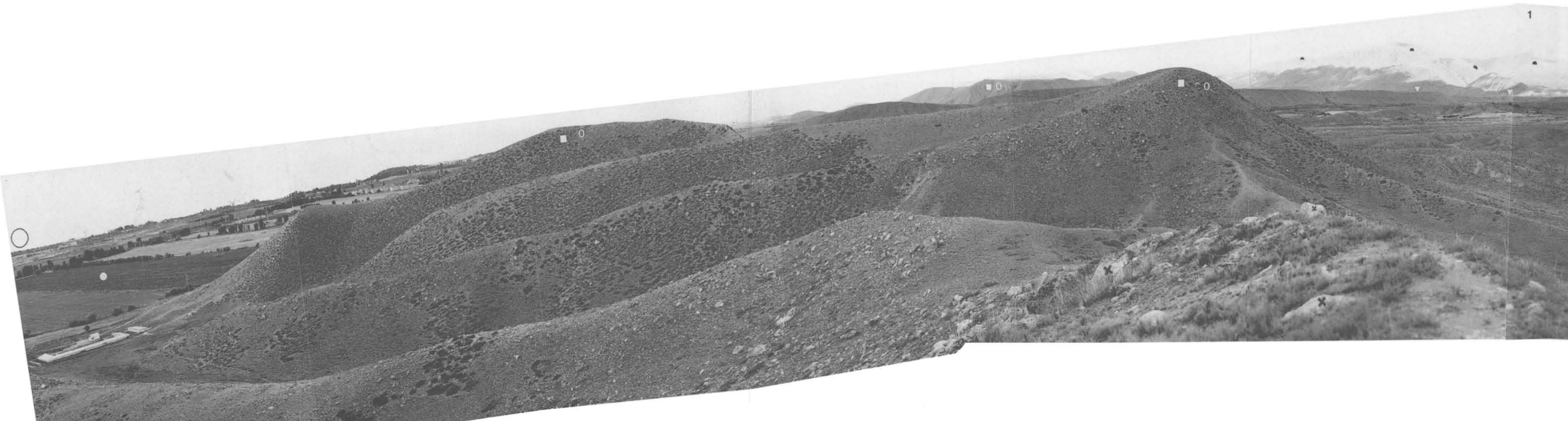


Fig 40 ▲
View from the second lowest Late Glacial lateral moraine (■ II) in the Chon Kemin valley at 1730 m asl across the Late Glacial tongue basin (●). The latter faces W, and its lowest ice margin position reaches down to 1500 m asl (Fig 1, right-hand of No. 8; Fig 2). The lowest lateral moraine terrace (IV) in this valley cross-section occurs at 1670 m asl. The Main Glacial ice margin position was more than 20 km further down-valley at 1200 m asl (on the far right outside this detail) and reached the Chu river (Fig 2; Fig 1 between Nos 8 and 10). The view of the panorama extends from ENE to the 4124 m-high massif (No. 1; northern Kungey Alatau chain) via E up-valley, further to ESE to S and across the southern Kungey Alatau (No. 2 = 3828 m-high peak, No. 3 = 3967 m-high massif, No. 4 = 3540 m-high massif) into the orographic left-hand valley flank to WSW down-valley. The tongue basin contains late-Late Glacial to Holocene glacio-fluvial drift which is divided into a maximum of three terrace levels (▼▼). The river in this valley cross-section runs at 1550 m asl. The bottom terrace is 2 m high, the middle one 5–8 m, and the third and last is 20–25 m high (▼▼). This is topped by a black soil floor (chernozem) on a loess base. ■ I (1950 m asl), ■ II (1850 m asl), ■ III (1730 m asl), and ■ IV (1670 m asl) (cf. Fig 41) mark the four Late Glacial moraine and kame terraces of the Ghasa, Taglung, Dhampu and Sirkung stages, while ---- show the corresponding glacier levels. Here, in a southern exposition, the ■ III moraine terrace (far left and far right) is only 1.5 km wide. ◖◓ indicate the valley shoulders, rock terraces, mountain spurs and glacigenic cuspate slopes (◖ below No. 2) the Last Ice Age glacier cover polished, truncated and rounded. Now under periglacial climatic conditions, the corries (○) present post-Glacial solifluidal moving drift covers with a large proportion of blocks. Locality: 42°47'N/76°07'15"E; Photo: M. Kuhle 13. 9. 88.

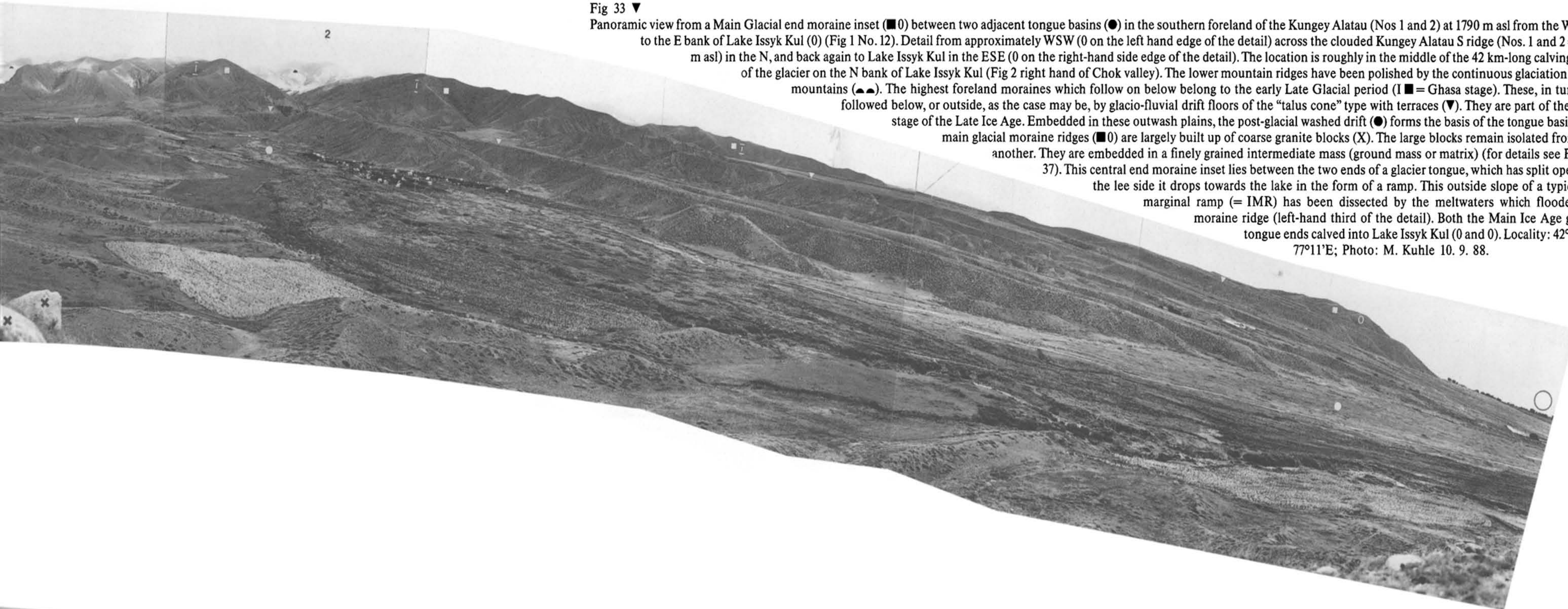


Fig 33 ▼
Panoramic view from a Main Glacial end moraine inset (■0) between two adjacent tongue basins (●) in the southern foreland of the Kungey Alatau (Nos 1 and 2) at 1790 m asl from the W bank to the E bank of Lake Issyk Kul (0) (Fig 1 No. 12). Detail from approximately WSW (0 on the left hand edge of the detail) across the clouded Kungey Alatau S ridge (Nos. 1 and 2 = 4771 m asl) in the N, and back again to Lake Issyk Kul in the ESE (0 on the right-hand side edge of the detail). The location is roughly in the middle of the 42 km-long calving front of the glacier on the N bank of Lake Issyk Kul (Fig 2 right hand of Chok valley). The lower mountain ridges have been polished by the continuous glaciation of the mountains (▲▲). The highest foreland moraines which follow on below belong to the early Late Glacial period (I ■ = Ghasa stage). These, in turn, are followed below, or outside, as the case may be, by glacio-fluvial drift floors of the "talus cone" type with terraces (▼). They are part of the same stage of the Late Ice Age. Embedded in these outwash plains, the post-glacial washed drift (●) forms the basis of the tongue basin. The main glacial moraine ridges (■0) are largely built up of coarse granite blocks (X). The large blocks remain isolated from one another. They are embedded in a finely grained intermediate mass (ground mass or matrix) (for details see Fig 34–37). This central end moraine inset lies between the two ends of a glacier tongue, which has split open. On the lee side it drops towards the lake in the form of a ramp. This outside slope of a typical ice marginal ramp (= IMR) has been dissected by the meltwaters which flooded the moraine ridge (left-hand third of the detail). Both the Main Ice Age glacier tongue ends calved into Lake Issyk Kul (0 and 0). Locality: 42°41'N/ 77°11'E; Photo: M. Kuhle 10. 9. 88.

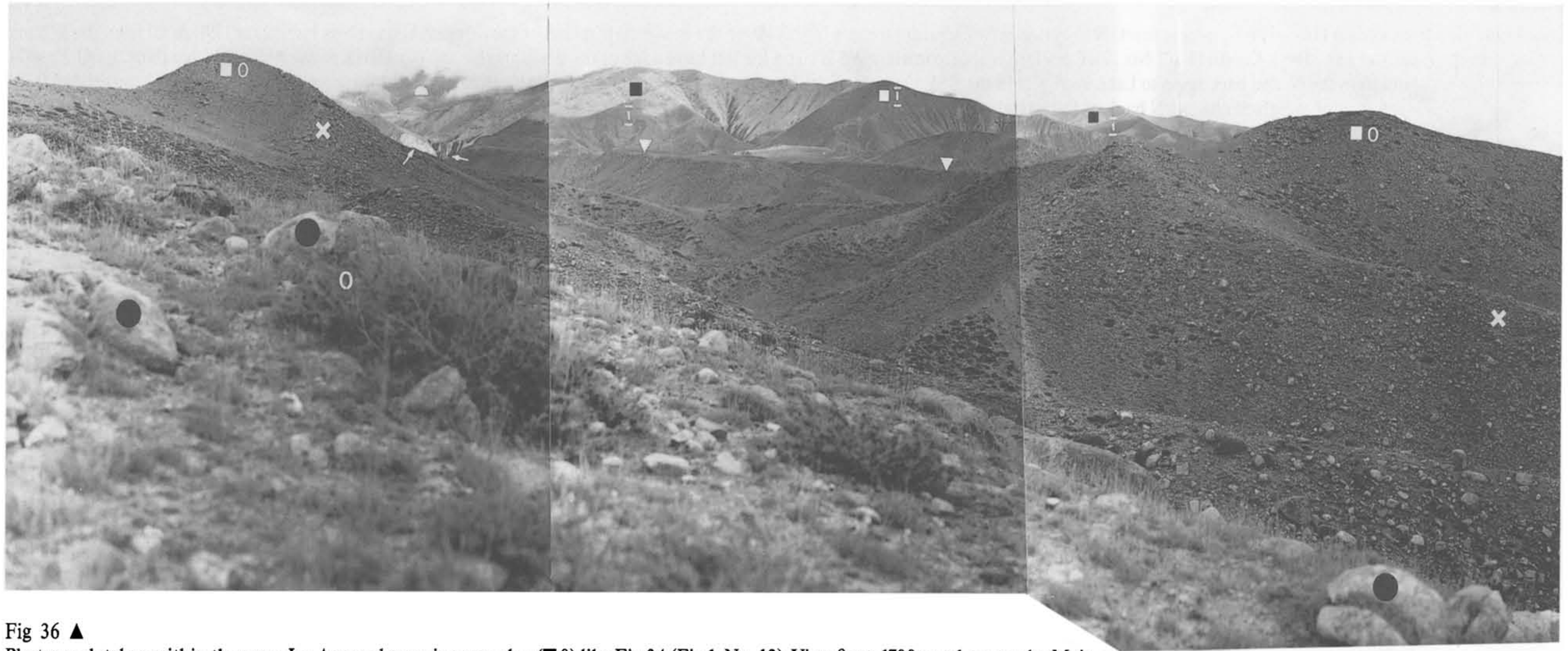


Fig 36 ▲
Photograph taken within the same Ice Age end moraine complex (■ 0) like Fig 34 (Fig 1, No. 12). View from 1700 m asl across the Main Glacial tongue basin with the Late Glacial drift floor terraces (outwash plain terraces) (▼) on to the early Late Glacial end moraines (■ I = Ghasa stage) and the lower, glacially polished mountain ridges to the south. ↑ marks the glacio-fluvial dissection of the Late Glacial moraines (■ I) in the valley exit. ● are blocks of granite (cf. Figs 32 and 35), which have been transported over long distances. X indicates a more recent Main Glacial ice margin, evidence of which is shown in a moraine ledge deposit. A glacier tongue passed a somewhat older moraine complex here before descending to Lake Issyk Kul (Fig 2 right of Choktal). Locality: 42°39'59"N/77°12'01"E; Photo: M. Kuhle 10. 9. 88.

Fig 38 ▼
View from the N bank of Lake Issyk Kul in the S mountain foreland of the Kungey Alatau at 1630 m asl towards the N across the extensive ground moraine areas (X 0) (Fig 1 No. 13). The ground moraine contains large blocks of granite (●). It extends into Lake Issyk Kul, ie further down than 1600 m asl (Fig 2 right-hand of Choktal). The foot of the mountain has been glacially polished (☗). ▼mark late glacial drift floor terraces (talus cone terraces) which run down from the ice margin locations at the immediate mountainfoot. Locality: 42°39'20"N/77°13'E; Photo: M. Kuhle 10. 9. 88.

Fig 41 ▲
View from 1720 m asl on to the inner slope of the orographic right-hand lateral moraine terrace (■ III; Fig 40) with large polymict, rounded to facetted, in parts even striated blocks over unstratified crystalline blocks (X = granite and syenite) (Fig 1 on the right of No. 8). No. 1 marks the catchment area of the valley and at the same time the position of the valley head in the central Kungey Alatau in the E. ☗ mark orographic left-hand Late Glacial flank polishings. Locality: 42°47'N/76°07'15"E; Photo: M. Kuhle 13. 9. 88.

the other hand, our result is remarkedly close to the same parameter determined for the Tibetan plateau - 1180 m (Kuhle 1988). At it is becoming increasingly clear from mounting evidence, during the LGM snowlines were about one kilometer lower than they are today everywhere on the Earth. Their lowering shows no change between hemispheres and remarkably little change with latitude, on the wet side of the mountains and on their dry side, on the margins and in the interiors of continents. This conclusion, ranking among the major global generalizations, has been based on a wealth of research data from Europe, Americas, Africa, and the entire Pacific basin (Broecker and Denton 1989). Hence, reported here data on Central Asian LGM-snowline depression seem to be in line with corresponding glacial change in the rest of the world.

The LGM snowline lowering values, obtained in Lake Issyk-Kul area, were deducted from the present-day equilibrium line altitudes within the whole Northern Tian Shan, and the result compared with land topography, and a tentative, working map of LGM ice covers was compiled for further comparison with modeling experiment results. In the process, all available means of checking up the ice-marginal positions, such as airphotographs, information from field descriptions by Prinz, Fedorovich, Kalesnik and others, as well as by our own, were employed to verify and refine the map. After modeling, the map gave a state-of-the-art portrait of the glaciation and its growth history. In particular, of the size and thickness of specific ice covers, and of their true relationships with intermontane basins, rivers, Lake Issyk-Kul and smaller high-plateau lakes.

The southern margin of the ice cover extended to the lowest foothills of Kokshaal Tau Range, to the elevation of 1500 m asl, close to the bottom of the Tarim Basin; that elevation was assigned by Fedorovich to the Lower Quaternary ice margin. The northern margin reached the levels of 1100–1200 m in its eastern part (Kungey Alatau and Zailiysky Alatau Ranges), and 900–1000 m in its western part (Kirgiz Range). Over the plateaus of "syrty" the ice covers were continuous; the protrusions of nunataks were possible only where the alpine peaks rise, while all the plateau depressions, including the ones now occupied by the Sonkul and Chatyrkul lakes, were buried under a kilometer-thick ice.

Ice covers and Lake Issyk-Kul. The essence of that relationship, as depicted in Fig 2, can be reduced to the following facts: the mountain ice covers surrounded the basin and the outlet glaciers converged on its bottom. At least 25 outlet glaciers focused their flow into Lake Issyk-Kuk and discharged icebergs. We can speculate on the further fate of the icebergs: provided, the mean air temperature in the basin was below 0 °C (since today it is about 6 °C, and the above snowline depression translates into 7 °C to 9 °C of cooling) while the amount of heat stored in water was quickly spent on melting. Hence, there could be no ice melting in the lake, and the mass of icebergs was building up until, time permitting, a floating ice shelf formed.

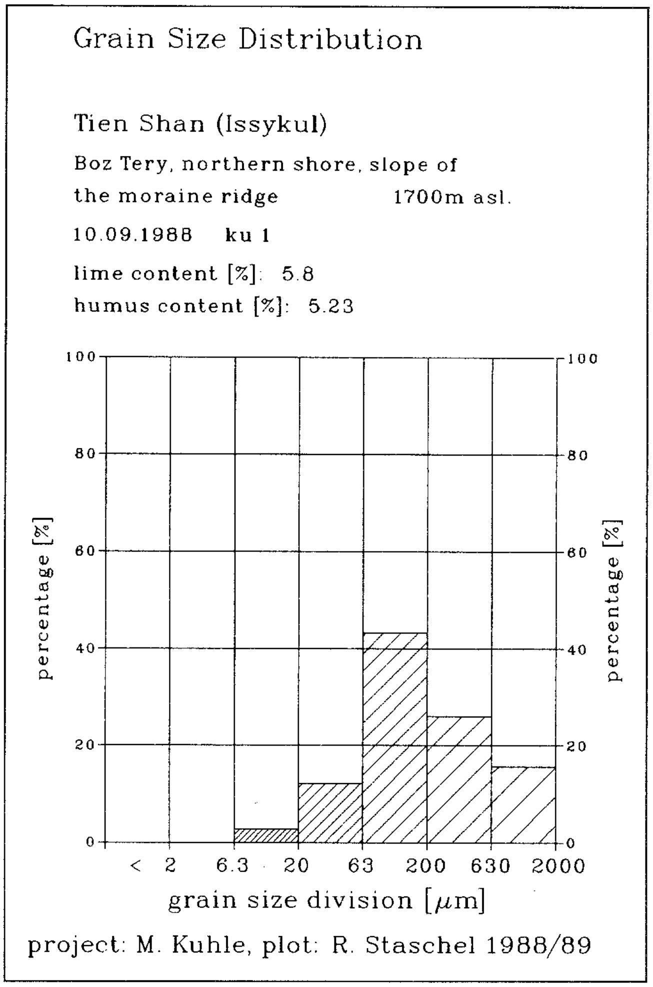


Fig 32 Taken from the surface of the end moraine ridge c. 100 m above Lake Issyk Kul, this moraine material (Fig 1, No. 12) is relatively coarse thanks to its high proportion of granitic sand. On the surface the fine material has moreover been washed out by excessive meltwater and rain-wash (however, cf. Fig 35). Locality of the sample origin: 42°40'N/77°12'E; (Fig 33).

The latter, being squizzed and dragged largely westward, in the direction of intermittent water flow, carried glacial debris to the outflow, built there an ice-raft delta pushing it into a dam. This mechanism of building the ice-raft deltas has been described from present-day glacial lakes (Gilbert and Desloges 1987). A group of hills built of deformed layers of ice-rafted sands and till lenses, called Bozbarmak, seems to be a remnant of the dam. Possibly, the deltaic sediments of Upper Chu River contributed to the dam also. In our view, the formation of that dam was one of the factors explaining the deflection of Chu River from Lake Issyk-Kul. The role of another factor was played by formation and deepening of Boam Canyon

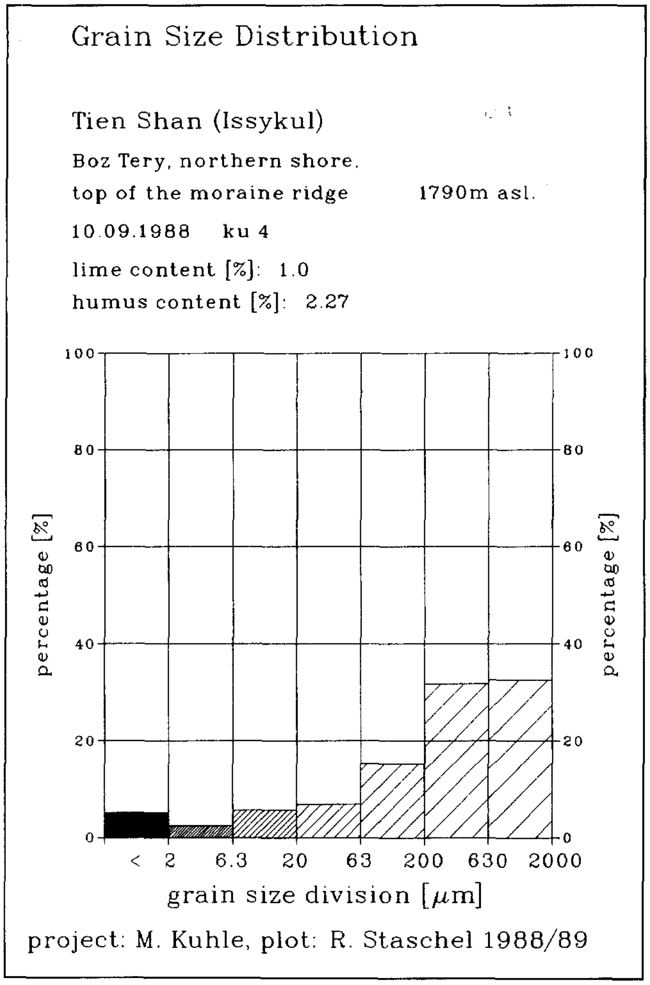


Fig 35 Main Ice Age moraine material from a depth of 20 cm (locality: Fig 1 No. 12; Figs 34 and 36), showing the typical "fine grain size peak" in the bimodal course of the graph of the columnar diagram. Locality where the samples were taken: 42°40'N/77°12'E.

which provided a channel for easy outflow, urging the river to take a shortcut.

Another alternative suggested by modeling experiments (see below) is the complete filling in of the basin by glacier ice. Indeed, it was in intermontane basins where ice thicknesses attained their maximum values which were well in excess of the lake's depth. If this was the case, some of the above evidence should be related to the sequence of deglaciation events, not to LGM.

Origin of Boam Canyon. The establishing of LGM ice-damming of Lake Issyk-Kul provides a natural explanation both for lake-level oscillations and mechanism of the Boam Canyon formation. The lake water balance during glaciation turned positive, which could have been a mere result of diminished (by ca. 50%) evaporation. Hence, the water discharge from the lake was inevitable. On the other hand, judging by the LGM situation in the basin as reflected in our map, the only way of this discharge was by breaking through the ice dams. This sort of lake outbursts are typically caused by rises in water level, while the specific rate of the rises depends on the ice dam height (Nye 1976). As the dam on the Kokpak-Kyrkoo profile had an estimated relief of about 350 m, the expected lake-level rises could reach 300 m, well in excess of the heights recorded in lacustrine terraces. The established fact of the past Lake Issyk-Kul ingressions in Kochkor Basin which now hosts Upper Chu River supports this estimate. Minimum elevations within the basin - 1900 m asl; nevertheless, the glaciers, which invaded the basin from the east, went afloat and produced icebergs.

Relatively high levels of "glacial" (or, rather, late-glacial) Lake Issyk-Kul have been suggested by the structure of above-mentioned ice marginal ramps, also. Judging by the sections studied between lower reaches of Turasu and Akterek rivers, in particular in the Kara-Ortok hill (Fig 1 and 2), the ramps are made up of gradedly bedded silts and sands, similar to the parallel-bedded deep-sea turbidites. It is probable, that those silt and sand masses were accumulated in underwater environment, which could only be possible if the lake level stood much higher than today.

The difference between the highest level of "glacial" or late-glacial Lake Issyk-Kul and the altitude of a rocky threshold in its outflow suggests that the volumes of water, which were repeatedly discharged during lake-outbursts, were equivalent to a 200–250 m water layer, ie amounted to about 1300 km^3. This implies that during the outbursts occurring at intervals of 100–150 years (another of our estimates), giant water discharges (on the order of a million m^3/s), and extreme flow velocities (equal to or exceeding 20 m/s), typical of such catastrophic events, did take place. This, in turn, implies very high erosional potential of the outbursts. Hence, it were the outbursts which can account for the canyon formation, making tradtional resorts to arguments of neotectonics superfluous. As for the debris, produced by hollowing the canyon, it went on building of an enourmous outwash fan which blankets the bottom of Lower Chu Basin. A section of the fan is exposed in a quarry near the Settlement of Ivanovka (Fig 1), 85 km west-northwest of the Boam Canyon mouth, where a sequence of cross-bedded gravel, loess and coarse-grained sands outcrop; their total thickness appears to be in excess of 80 m.

The above information gives a chance to see the geological "potency" of Tian Shan glaciation in proper perspective. Specifically, it makes us re-assess the part played by glacial and glaciofluvial deposits in sedimentary sequences of the region. For instance, we expect that upcoming detailed studies will result in re-interpretation of the sediment sequences from Lake Issyk-Kul bottom and coast, in acknowledging the important role played in the sequences by glacial debris.

Ice thickness and surface elevation. To determine thickness and surface elevation profiles of the ice cover, which formed on plateaus and ranges south of Lake Issyk-Kul, a finite-element program solving the continuity

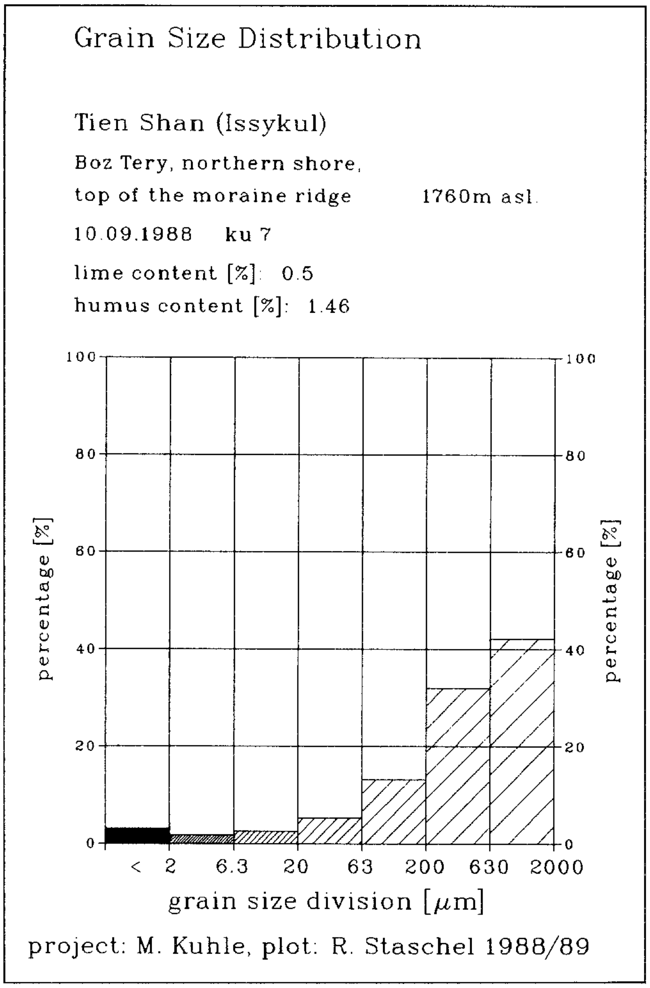


Fig 37 Somewhat richer in sand, but less well endowed with pelite (cf. Fig 35), this end moraine sediment belongs to the same Main Ice Age moraine complex as shown in Fig 36 (Fig 1, No. 12), with the bimodal course of the column levels, including a distinct "fine grain size peak" and a "coarse grain size peak" characteristic of moraine substrata. Locality where the sample was taken: 42°39'59"N/ 77°12'01"E.

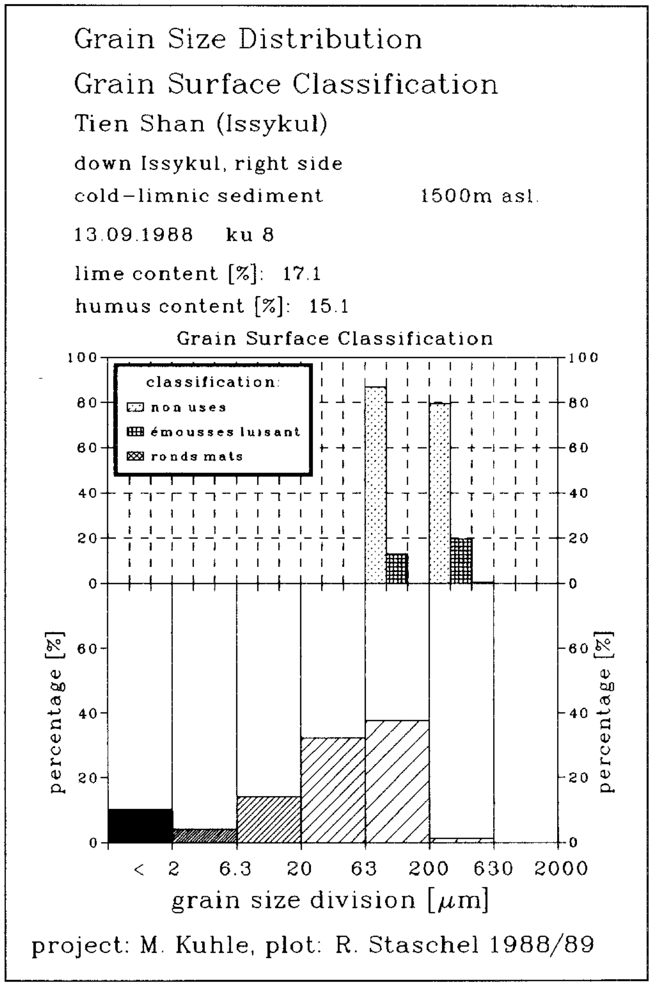


Fig 39 Held back by the glacier in the Chu valley above the Boam canyon, the lake sediments are tens of metres above the present talweg (Fig 1 on the left above No. 15; Fig 2). Their grain size distribution has the characteristics of till. A "fine grain size peak", or bimodal course, is shown in the columnar diagram. Under the key word "none uses" (ie not affected by fluvial or aeolian influence) the grain surface classification shows grains broken by glacier force as predominating in at least 80% of the sand fraction analysed here. 13–20% of the grains reveal fluvial influences, which can be explained by the involvement of glacio-fluvial dynamics. Locality where the sample was taken: 42°30'20"N/75°52'30"E.

equation for ice flow was employed. Input to the model consisted of the spatial coordinates of the nodal points and the values of each of the following material properties at the nodal points: bedrock elevation, flow law constant, sliding law constant, present ice surface elevation, accumulation rate and percent of the flow due to sliding. Output consisted of time-dependent ice elevations and isostatically adjusted bedrock elevations at each nodal point, as well as column-averaged ice velocities at the centro id of each element defined by a group of nodal points (Fastook and Chapman 1989).

The finite-element grid consisted of 4-node quadrilaterals with material properties defined at each of the nodal points. In this modeling experiment, the grid had 1735 nodes and 1639 quadilateral elements, with a grid spacing of approximately 16 km. The mechanism controlling the velocity was assumed to have been ice flow (without sliding), and the flow law constant was taken as 3.0 Bar m^{f}.

All nodes except those within the boundaries of Lake Issyk-Kul were assigned mass balance relationship typical of polar continental regions. They have an unadjusted equilibrium line at 312 m, a maximum ablation rate of −1 m/yr ice equivalent, and a peak accumulation rate of 0.26 m/yr at 650 m. Beyond this, the accumulation rate declines to less than 0.10 m/yr at elevations above 4000 m. This mass balance curve could be slid up or down to reflect local snowline elevations. Since snowline elevation is largely a function of latitude, we needed only define snowline adjustment at the pole and its slope (100 m per 100 km) to calculate the snowline elevation at any gridpoint. Knowing that, we could use the mass balance curve to obtain a net accumulation or ablation rate for the node.

The nodes within the boundary of Lake Issyk-Kul were assigned ablation rates of –5 m/yr, which reflected the calving mechanism of ice wastage. If the lake were to freeze solid or to be chocked with icebergs then this calving would cease and the lake nodes be assigned a mass balance similar to the one described above. In the light of Lake Issyk-Kul paleoclimate and geomorphology, the latter assumption looks realistic. Hence the modeling results, where they describe the lake basin, should be regarded as minimal.

Modeling experiments were conducted to test two climate scenarios - one with a gradual, and another with an abrupt change in the regional snowline elevation. In first experiment, the snowline was lowered in 200 m intervals every 1000 years, beginning with the present elevation of 4100 m, until the LGM value of 2900 m was reached at 6000 years. This value was maintained until the volume of the ice cover equilibrated at 19,000 years. Then, to simulate the deglaciation, the snowline was raised 200 m every 2000 years until its present value was reattained at 29,000 years. Again it was held here until it equilibrated at 33,000 years. Surprisingly, the ice cover at this point turned out more extensive than at present. The snowline was further raised to 4900 m, at which value the ice cover disappeared at 41,000 years. After that, the snowline was returned to its present level once more, allowing the ice cover (slightly larger than its minimum size) to equilibrate at 45,000 years.

In second experiment, the snowline was abruptly lowered to its LGM value and held at this level until attainment of equilibrium at 15,000 years. The snowline was then returned to its present position, and again held until equilibrium was attained at 22,000 years. Since this did not result in the ice cover shrinkage to its present configuration, the snowline had to be further raised to 4700 m, and held until the ice disappeared by 25,000 years (Fig 4).

The abrupt lowering of the snowline from 4100 m to 2900 m resulted in the widespread formation of a thin ice cover that then thickened and extended its margins gradually with time. At its equilibrium configuration, the ice cover was found to have increased in size to such an extent that it reached the limits determined by our field research. In particular, the experiments suggested, that it took the ice cover only 10,000 to 13,000 years of growth, depending on type of assumed scenario, to reach and intrude the water body of Lake Issyk-Kul. The maximum ice thicknesses localized over intermontane depressions where they reached 2500–3000 m, while over high plateaus ice grew to maximum thicknesses of 1200–1250 m (Fig 5 and 6).

In both the experiments, the time of ice-growth to *nearly* maximum volumes turned out about two times shorter than the time required for ice-cover equilibration. This is clear from comparison of ice-cover configurations 2 (7 ka after completion of snowline lowering) and 3 (a full equilibration which took another 6 ka). But in general, whichever scenario we may find more realistic, our modeling experiments warrant the conclusion that the time required for building the Tian Shan ice cover was sufficiently short to fit into the brackets set by the last ice-age chronology. The same can be said about the time of full ice-cover equilibration which took only 15 to 19 ka.

Tian Shan ice cover vs. Tibetan Ice Sheet. It may be argued that the ice cover of Tian Shan was a perfect paleoglaciological analogue of the great Tibetan Ice Sheet. There is a number of arguments favouring this contention. Indeed, both Tian Shan and Tibet have similar - dry and cold - climate; they have the same style of geomorphology with vast high-level plateaus lying at the elevations of 4000 and 5000 m, respectively; present-day snowline in both the regions goes some 300 m to 700 m above the plateaus getting in touch only with the higher ridges towering over the plateaus; the same rate of snowline depression during LGM, amounting to the mean value of 1200 m, characterized the regions. Hence, during the ice age, the snowline over both Tian Shan and Tibet lowered well below plateau surfaces making their continuous glacierization inevitable (Fig 7). Our modeling experiments aimed at simulating the Tian Shan glaciation seem equally applicable to Tibetan Ice Sheet, although the ice-sheet build-up and equilibration probably took some more time on Tibet than on Tian Shan.

In our view, the LGM Central Asian glaciation was represented by a continuous bow-shaped chaine of mountain ice covers and sheets, which semi-confined Tarim Basin with Takla Makan Desert on its bottom. Paleoclimatically, this setting strongly suggests that powerful winds born by the westerly jet-streams coupled with katabatic air-flows focused on Takla Makan and the neighbouring deserts (Fig 8). Which, in turn, implies that the deserts, first of all Takla Makan, were the source areas of the magnetic dust masses that were transported and deposited by wind to form the Chinese loesses. It seems improbable that Gobi Desert alone was that source area as believed by Kukla (1988); it is only natural to assume that, to account for as major a loess field as the Chinese, commensurately large ice sheets and corresponding wind systems were needed.

With all said in mind, we may further speculate that the history of the Central Asian glaciations, including ice-sheet inception and changes on Tian Shan and Tibet, had to be recorded in the Chinese loesses – just like the history of the Greenland and Antarctic Ice Sheets were recorded in bottom sediments of the surrounding oceans. If this inference is upheld by further studies, then the Chinese sequences which are containing the record of about 20 loess/paleosol alternations and are underlain by the Gauss/Matuyama boundary (ca. 2.43 my) should be considered a *curriculum vitae* of the Central Asian glaciations. The Tibetan Ice Sheet and its satellites appear to have been incepted simultaneously with the ice sheets surrounding the North Atlantic.

Conclusions

Judging by the authors' studies in Lake Issyk-Kul area, the horizontal and vertical extent of Würm glaciation in Tian Shan Mountains was an order of magnitude larger than shown by all previous reconstructions. At the LGM, continuous ice covers buried the systems of mountain ranges and plateaus, their outlet glaciers breached border ridges and descended to foothills, till elevations of 1500 m asl in the south and 900–1000 m asl in the north. The glaciers originated from high plateaus flowed into intermontane basins; as a result, in some basins ice thickness exceeded 2500 m; a number of glaciers from Terskey Alatau and Kungey Alatau Ranges focused their flow on Lake Issyk-Kul and invaded its basin with ice which led either to ice shelf formation or, possibly, to a complete ice filling of the basin.

The environmental impact of the glaciation turned out much stronger than it was formerly admitted, also. The past glaciers reshaped the mountains by scouring trough-valleys and glacial cirques and by breaching the ridges bordering high plateaus, while the glacially-derived debris were transported downslope to form moraines and ice marginal ramps, to fill in Lake Issyk-Kul hollow and the rest of intermontane basins. The glaciers interfered with hydrographic systems, too. In particular, they impounded Chu River and chocked Issyk-Kul with icebergs, which caused big-range lake-level oscillations, the formation of Boam Canyon (by the impact of lake outbursts), and the deflection of Chu River from Lake Issyk-Kul (by incision of the canyon and build-up of an ice-raft delta at the lake outflow).

The ice sheet/water basin interactions, as studied in Lake Issyk-Kul area, may help in understanding the ice-age behaviour of the variety of different basins surrounded by calving glaciers. In particular, they provide a working model for explaining the glacial evolution of Lake Baikal (and its unique faunas) or even the Arctic Ocean which got confined by grounded marine ice sheets.

The average LGM lowering of regional snowline in Tian Shan was found to equal 1200 m. Since the present snowline in Lake Issyk-Kul area has the altitudes of 4100–4200 m, passing only a few hundred meters above the high plateau surfaces, the Würmian snowline dropped well below the surfaces making their glacierization inevitable. An analogous snowline/earth surface relationships were characteristic of present-day and ice-age Tibet, which had to result in similar changes of glaciation. The whole history of the Central Asian glaciations seems to be recorded in the Chinese loess sequences. The beginning of the loess accumulation dating back to the Gauss/Matuyama boundary (2.43 my) may be considered as a milestone marking the onset of the Central Asian glaciations.

Judging by our finite-element model, ice covers would form and equilibrate on Tian Shan in 19,000 years (first climate scenario with a gradual change in snowline elevation) or 15,000 years of growth (second scenario with an abrupt lowering of the snowline). The modeling experiments yielded ice thicknesses (up to 2500–3000 m in intermontane basins and 1250 m on plateaus) and ice-marginal positions; the latters conformed to the results of the authors' field observations.

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