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Late Quaternary catastrophic flooding in the Altai Mountains of south–central Siberia: a synoptic overview and an introduction to flood deposit sedimentology

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ABSTRACT

This paper provides an overview of the geography and palaeogeography of the Chuja (Chuya)–Katun river system in the Altai Mountains of south Siberia In addition, an introduction to the sedimentology of catastrophic flood deposits is provided Tracts of large gravel dunes and giant gravel bars in the Katun and Chuja river valleys of south-central Siberia are testimony to episodes of catastrophic flooding that occurred owing to the sudden emptying of the ice-impounded glacial lake Kuray–Chuja primarily during the Late Pleistocene (40 ka to 13 ka) Although today there are no substantial water bodies in the Kuray and Chuja basins, glaciolacustrine deposits attest to the former presence of large ice-proximal lakes, whereas multiple strandlines at various elevations around the basin margins indicate former lake levels Floods were of a scale similar to that recorded for glacial-lake Missoula in North America. A large flood down the main Chuja and Katun river valleys deposited huge quantities of coarse and fine gravels within back-flooded tributary mouths and other valley-side embayments Today these deposits form giant bars that blanket the valley walls and block each tributary entrance for a distance of over 70 km While the bars were being deposited, the base of the main valley was infilled to a depth of 60–90 m by coarse-gravel traction deposits. In particular coarse gravel bedload and hyperconcentrated-flow units prograded down-valley beneath flood waters several hundred metres deep. Locally, steeply cross-stratified units, each several decimetres thick attest to steep bar-front progradation similar in style to a Gilbert-type delta

During individual floods, fine gravel and coarse sand, mostly transported in suspension, was deposited by multiple flood pulses in the entrance to flooded tributaries The resultant giant bars, up to 5 km long and 120 m in height, temporarily impounded lakes in the tributaries, indicated by local small-scale limnic deposits Subsequently, tributary streams cut through the bars, draining the small lakes and incising the lacustrine deposits Later floods down the main river valley again blocked the tributaries with flood gravels such that lakes reformed.

INTRODUCTION

Extensive catastrophic Pleistocene (46 ka to 13 ka) floods in south-central Siberia have been documented recently (Rudoy, 1988, 1990, 1998; Rudoy *et al*., 1989). These floods produced a suite of diluvial ('great flood') landforms, including large gravel dunes (Carling, 1996a,b), giant bars and flood-scoured channelways on a scale similar to that associated with the draining of glacial Lake Missoula in North America (Baker, 1973; Baker & Bunker, 1985). The morphology and sedimentology of these landforms may be diagnostic of catastrophic floods, and thus detailed description may aid in the interpretation of other ancient landscapes and stratigraphical successions. The sources of the Siberian floods were vast ice-dammed lakes impounded within the intermontane basins of the Altai and Sayan mountains (Fig 1) Evidence for

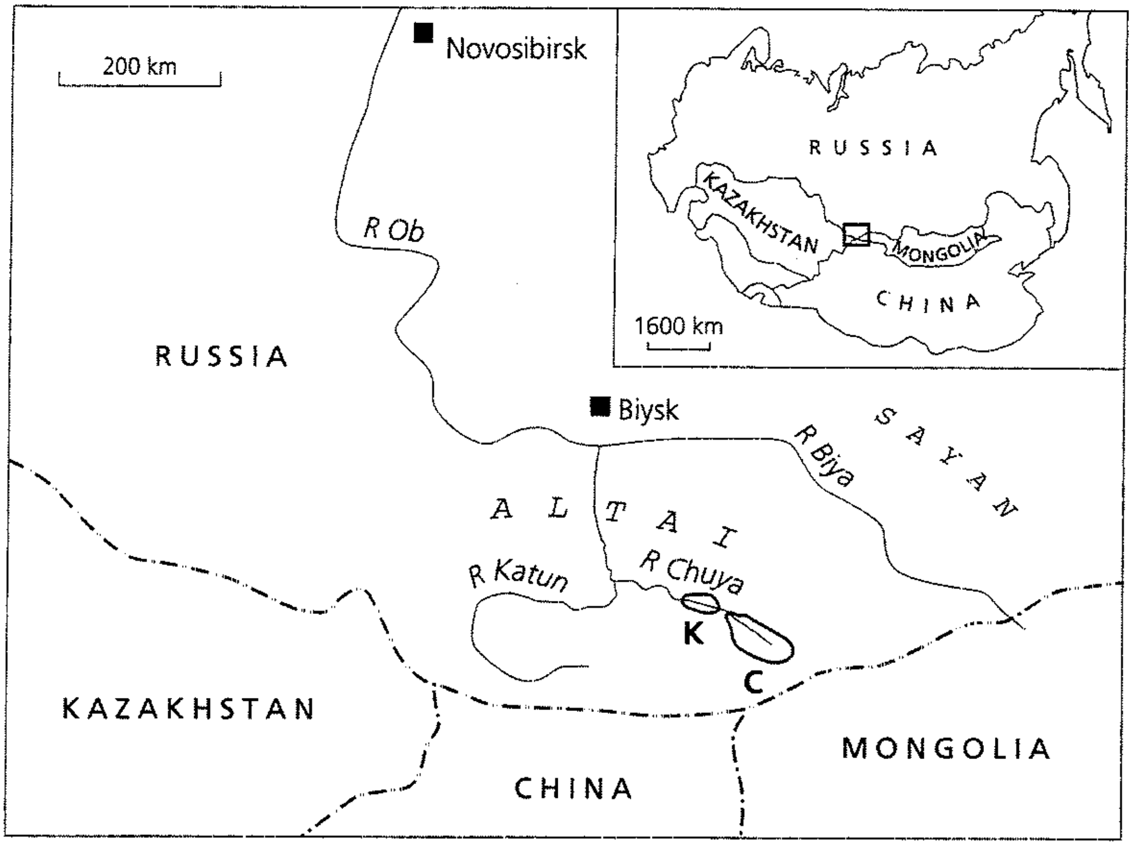


Fig. 1. Location map of study area in southern Siberia. The Kuray (K) and Chuja (C) basins are shown in the headwater of the River Chuja.

catastrophic floods has been noted within the headwater valleys of the rivers Ob and Yenisei. For example, the Chulym, Chulyshman, Bashkaus, Biya, Chuja (Chuya) and Katun river valleys, amongst others (Grosswald & Rudoy, 1996; Frechen & Yamskikh, 1999), show evidence of superfloods, but only the Chuja–Katun system has been studied in any detail. The River Chuja, a tributary of the Katun, was the routeway for several very large floods. Brief descriptions of these outburst floods, which emanated from glacially dammed lakes in the Kuray and Chuja basins (Fig. 1), have been provided by Baker *et al.* (1993) and Rudoy & Baker (1993). Baker *et al.* (1993) concluded that there was one major Kuray–Chuja flood and a number of minor floods; the peak flow of the largest was apparently consistent with the sudden collapse of an ice-barrier.

This paper provides a more detailed overview of the region and the palaeogeography, together with an introduction to the sedimentology. Localities mentioned in the text are identified in three ways: by local place name; by latitude and longitude (degrees, minutes and decimal seconds—determined using GPS) and by reference to kilometre road markers (e.g. *km 672*) that give the distance from Novosibirsk. This degree of detail should help other scientific visitors find key localities. The primary objectives are to elucidate the detail of the flood dynamics of the Kuray–Chuja floods, and to define the temporal and spatial sequence of flooding.

PERSPECTIVE

The Altai mountains are part of an extensive, structurally complex succession of individual mountain ranges in central Asia stretching from the Tien Shan in the west to the Aldan range in the east. The Altai Mountains were up-thrust in the Eocene and early Oligocene and the majority of the area has been tectonically active to some degree throughout the Cenozoic (Tapponier & Molnar, 1979). As explained below, it is the distinctive tectonic history that set the scene for Quaternary catastrophic floods. Major subparallel faults trending north-west to south-east intersect subsidiary faults that trend roughly east–west. Increased lateral shearing in the Cenozoic resulted in pronounced off-sets in the north–south fault alignment (Nekhoroshev, 1966). The result is a series of ridges, such as the Kuray Range to the north and the North and South Chujski ranges to the south of the tectonic depressions of the Kuray and Chuja basins (Bogachkin, 1981) (Fig. 2). Vertical relative movement of the order of 2500 m took place, particularly during the Pliocene–Pleistocene transition, enhancing basin development. Further motion occurred again at the beginning of the Mid-Pleistocene and during the Late Pleistocene. During the latter phase, however, uplift in the Altai is believed to have been slight (Zyatkova, 1977; Serebryanny, 1984) and largely occurred following deglaciation (Nekhoroshev, 1966). Enclosed by north-west and east–west trending mountain chains, the depressions bounded by strike-slip faults now form spectacular enclosed intermontane basins. Sedimentation has resulted in up to 0.5 km of Neogene and Quaternary sediment fill in the Kuray Basin and over 1 km of fill in the Chuja Basin. The latter exhibits, in the Chagan River valley (N50°3′15.4″; E88°25′58.78″), one of the most complete and important sections of the Cenozoic within central Asia (Zykin & Kazanskii, 1995). Today these basins contain no significant water bodies and drainage is solely to the north-west via the gorge of the Chuja River (Fig. 3). During the Pleistocene, however, large ice-dammed lakes filled the depressions, as witnessed by lacustrine deposits and palaeoshorelines (Figs 3 & 4).

Within the modern Altai massif, short alpine glaciers, totalling some 909 km^2 in area, descend from small ice-caps around the margins of the intermontane basins of Kuray and Chuja (Fig. 2). Presently, most Altai glaciers are fed by moisture from south-westerly and north-westerly airstreams. However, during the Quaternary, a cold anticyclone developed over central Asia such that the prevailing winds were from the north and north-east (Velichko, 1984; Back & Strecker, 1998). The global Quaternary cooling coupled with the distinctive topography was important in controlling associated glaciations. However, it is not clear how many glacial cycles occurred in the Altai during the Pleistocene (Okishev, 1977). Local terminology varies but, in accord with the system adopted for other central Asian mountain glaciations, the Late Pleistocene may be divided into four units (Archipov, 1998). The oldest is the Kazantsevo interglacial (substage 5e of the ocean isotope scale) which followed a pre-150 ka glaciation: the Tazovo. Two Late Pleistocene glacial phases followed: the Ermakovian (*c.* 100–50 ka) and the Sartan (*c.* 22–13 ka). These latter distinct cold periods were separated by the Karginian mega-interstadial, during which climate ameliorated abruptly (Back & Strecker, 1998) but was punctuated by frequent cold phases (Yamskikh *et al.*, 1999). Together these three younger periods form the Zyriankan glaciation that corresponds to the Würm (Weichselian) of western Europe. During maximum glaciation ice descended to around 1200 m altitude (Vardaniants, 1938; Grosswald, 1998) such that ice-caps covered both mountains and intermontane basins, and the piedmont to the north of the Altai (Grosswald, 1998). The maximum extent of glaciation is well delineated by terminal moraines in the piedmont (Fig. 2). The climatic variability of the Karginian interstadial is seemingly complex; glaciation in the Altai Mountains may have been continuous, with ice retreating from the basin margins during the interstadial. Although Mid and Late Pleistocene ice surrounded the Kuray and Chuja basins, and glaciolacustrine sediment suites demonstrate that locally glaciers were proximal to the lake margins, nevertheless the basins remained ice-free throughout much of the Late Pleistocene (Svitoch & Khorev, 1975). For example, during the final Sartan cold stage, although persistent local ice-caps occurred at higher elevations (Okishev, 1977; Serebryanny, 1984), mountain valley glaciers descended only as far as the basin margins (Fig. 2). During the Late Pleistocene, ice did not extend below 1750 m altitude in the Chuja Basin (Rudoy, 1998). The Sartan stadial maximum occurred around 18 ka when coldest-month temperatures were about –30°C (10°C lower than present), warmest-month temperatures were about +10°C (4°C lower than present) and annual precipitation was about 200–300 mm (around 300 mm lower than present, Tarasov *et al.*, 1999). The associated biome was mainly tundra, but cold steppe and cold deciduous forest occurred locally (Tarasov *et al.*, 1999). From this stadial maximum, the retreat of valley glaciers was punctuated by eight readvances. The sketchy glacial chronology for the Altai is in accord with that for the neighbouring Sayan Mountains and with the detailed chronology from the region around Lake Baikal to the east (Back & Strecker, 1998) and the Tien Shan to the west (Grosswald *et al.*, 1994). On this basis the continental-dominated climatic system for central Siberia shows close similarity to that of west Siberia

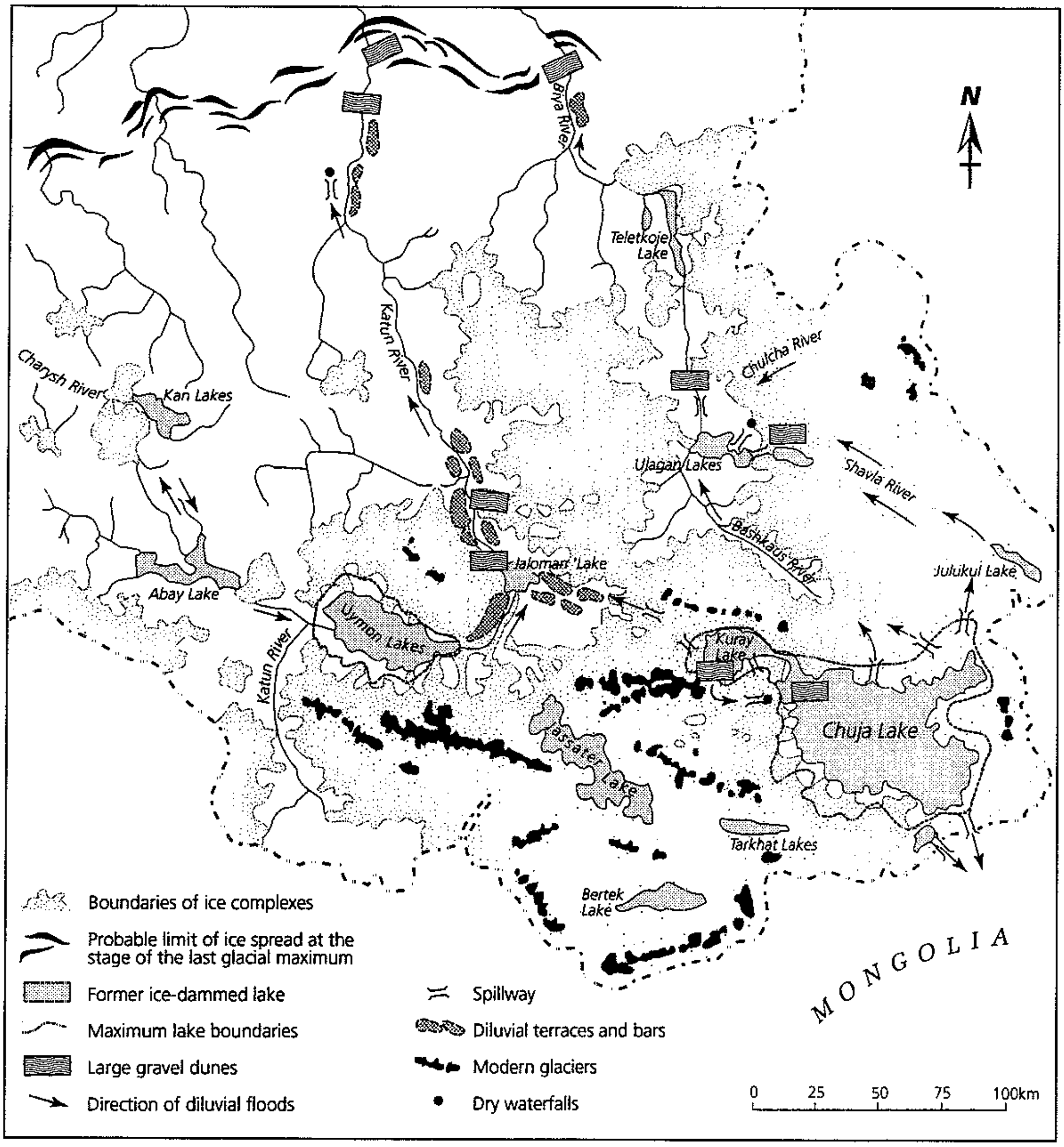


Fig. 2. Schematic palaeogeography of the Altai region during the Late Quaternary (after Rudoy, 1998). Approximate extent of ice-impounded lakes is based on strandline evidence and locations of glaciolacustrine sedimentary complexes. Maximum potential highstands are constrained by the modern altitude of potential outflow channels (spillways) without any correction for tectonic adjustments. Features in the Katun, Chuja and upper Bashkaus valleys and in the Kuray and Chuja basins have been verified by the authors. Note: dunefield in the upper Bashkaus valley reported by Rudoy (1998) could not be located by the authors and appears to be gullied terrain. Maximum extent of ice sheets during the Sartan is based on several Russian studies modified by Rudoy (1998). The Kuray and Chuja basins were ice-free

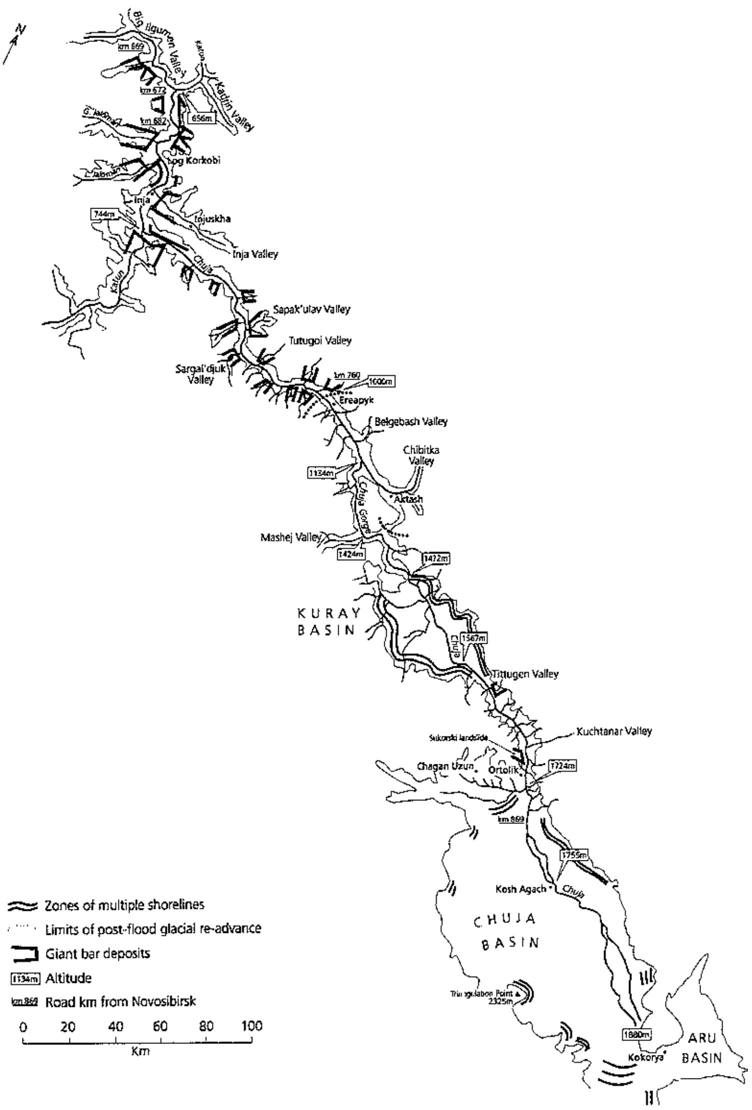


Fig. 3. Map of study area showing key locations and geomorphological features.

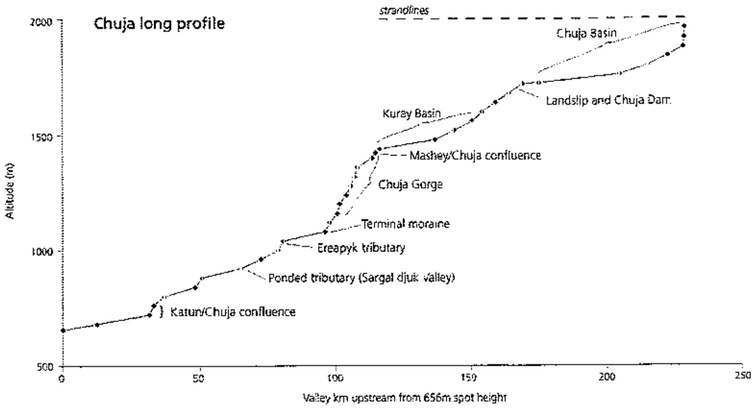


Fig. 4. Long-profile showing altitude of key locations and geomorphological features.

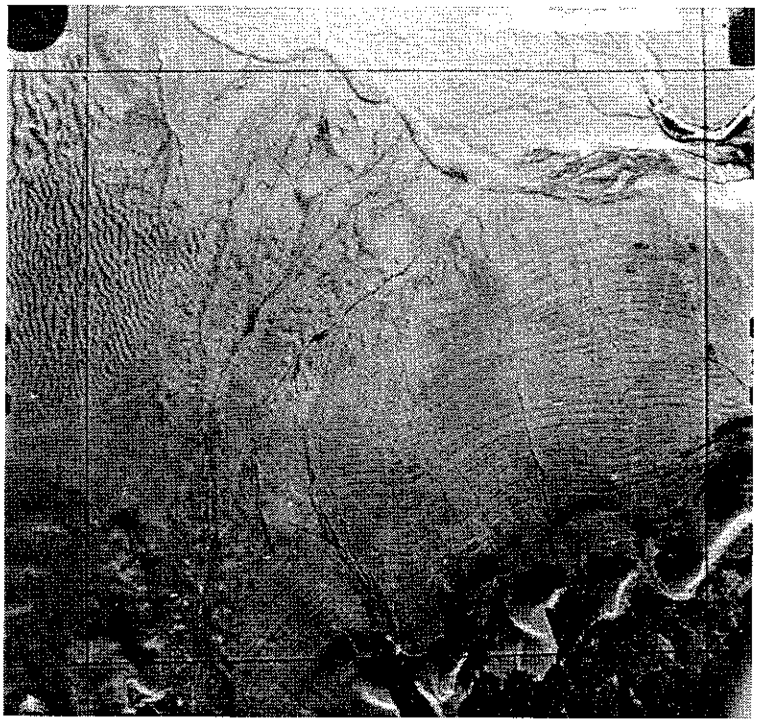


Fig. 5. Aerial view of portion of southern margin of the Kuray Basin Tree-covered (bottom right) and treeless ridges (bottom left at an altitude of around 1700–1800 m) represent local bedrock outcrops and glacial end-moraines of former valley glaciers, which descended from the Chujski Range to terminate around the basin margins The altitude of the basin floor (top) is around 1500 m. The subparallel lines (centre and right at an altitude between 1550 and 1650 m) are multiple strandlines representing fluctuations in the level of glacial Lake Kuray The eastern extremity of the Kuray gravel dunefield can be seen at the top left (Carling, 1996a). Scale: horizontal distance is approximately 5.0 km

and Europe during the past 130 ka (Archipov, 1998; Frechen & Yamskikh, 1999)

Using a variety of geomorphological evidence, including remnants of moraines (Rudoy, 1998), Baker *et al* (1993) concluded that the Chuja gorge had been blocked periodically by ice-sheet lobes or large valley-glaciers, which coalesced in the vicinity of the Belgebash, Chibitka and Mashej valleys (Figs 3 & 4). The substantial ice-barriers impeded the only drainage line exiting from the Kuray and Chuja basins, causing the development of a temporal series of large ice-dammed lakes. Numerous wave-built strandlines testify to variation in the lake level and, being best developed on south and south-west basin margins, attest to the direction of the prevailing northerly wind during the Quaternary (Figs 3 & 5)

In the Chagan valley (Fig. 3), thermoluminescence (TL) dating of the most ancient glaciolacustrine moraine complexes (N50°1′7 6″; E88°17′11.25″) indicates a Mid-Pleistocene age (380 ka to 266 ka). More recent glaciolacustrine deposits have been dated at 145 ka and between 32 ka and 25 ka using ^{14}C assay (Svitoch & Khorev, 1975); the latter deposits overlie moraine dated at 58 ka. In addition, the presence of lacustrine dropstones at a number of locations (e g near Kokorya: N49°56′49.69″; E89°4′15.97″) and strandlines on the 58 ka moraine attest to the former presence of glacial lakes that were contemporaneous with, or post-date, some glaciolacustrine successions Notwithstanding tectonic adjustments, strandlines at a range of elevations show that lake levels fluctuated greatly, occasionally attaining depths of several hundred metres. The lowest strandlines (below about 1940 m altitude) in the Chuja Basin are faint, are developed on gently sloping terrain and are widely held to be Late Pleistocene Distinctive strandlines occur at higher elevations on the northern side of the basin and are most prominent on 'headlands' along the southern margin. Here recurved spits at several elevations show that longshore drift was universally from north-west to south-east along this southern shore (Fig 6). The altitude and longshore gradient of a suite of Chuja strandlines have been surveyed below a triangulation point (*c* 2137 m N49°48′; E88°56′) located in the south-east of the basin (Fig 3). Seven distinct accretionary strandlines range between *c*. 2105 m and 1960 m, although locally the elevations are indicated by notches cut in weak bedrock Several pits dug in the strandlines together with two ground-penetrating radar (GPR) profiles (one shore parallel and one shore together this evidence is interpreted to represent unsteady downstream migration of two-dimensional dunes, about 2 m in height in an aggradational setting

As well as the dunefields described by Carling (1996a), additional dunefields were located in 1999 and 2000. Two gravel dunefields occur near Baratel (N50°15′35 84″; E87°44′47.51″) within minor side-valleys close to the Chuja gorge. At an altitude of 1710 m, these bedforms indicate strong currents moving towards the lake outlet into the Chuja valley. At the same location, but at a slightly higher altitude, strandlines terminate abruptly, close to where the ice-dam would have existed Within the Chuja valley, weakly developed dunes occur on top of a giant bar at Iodro (N50°23′46.5″; E86°59′9 9″) In addition, a group of six immense flow-transverse gravel bedforms (antidunes?) occurs within the exit to the Chuja Basin at *km 861*, close to the village of Chagan-Uzun (Fig 3); the largest bedform is 20 m high and 300 m long in the direction of the palaeoflow An extensive field of gravel dunes also occurs at Kam-Sugi (*km 869*)—both these sets of bedforms indicate flow from the Chuja Basin through the corridor to the Kuray Basin. Speransky (1937) and Lungershausen & Rakovets (1958) correctly identified the bedforms in the Kuray Basin as dunes. Latterly many Soviet geologists believed incorrectly that these structures were rogen moraine (or parallel-gullied outwash) owing to the distinct 'ribbed' or 'rippled' planform characteristic of this type of glacial moraine (Hättestrand & Kleman, 1999) Considered together the various bedforms of the Kuray and Chuja basins attest to the former flow direction of lake waters emptying rapidly into the Chuja and Katun river valleys. These floods can be traced into the lower piedmont zone of the Katun River (Fig. 2), where extensive fields of fossil subaqueous gravel and sand dunes have been identified on river terraces (Butvilovsky, 1993) For example, some 2 km to the south of the village of Surtaika, large dunes consisting of fine sand occur on both sides of the road (N52°12′27.5″; E85°53′44.4″) Road-side sections, including a gravel pit at the confluence of the rivers Isha and Katun, show that the dunes overlie a gravel terrace and are themselves covered by up to 0.5 m of loess Along the course of the River Katun, gravel dunes are found as far north as the town of Chemal Here a well-defined dunefield (N51°21′9.91″; E86°2′47″) occurs on the top of a giant flood bar close to the confluence of the tributary River Tolgoek and the River Katun (Okishev, 1997; his fig. 2).

Giant bars

Downstream of the Chuja gorge a series of prominent diluvial gravel bars occur within the Chuja River valley from *km 760* near the village of Erbalyk and along the course of the Katun River until *km 672* (Fig 3). At this point the Katun River turns abruptly to the east into a narrow gorge and the valley width is halved In addition, the Kadrin River valley (Fig 3) is known to have contained a glacier, which on occasion extended into the valley of the Katun River Thus passage of any large flood-wave would have been impeded at this point by the valley constriction (and possibly by the Kadrin glacier) causing temporary 'ponding' of flood water for several kilometres upstream The surge from the flood in the Katun valley would have run directly into the tributary Big Ilgumen valley (Fig. 3), such that diluvial 'run-up' deposits extend to the north-west at an altitude of 800–840 m near *km 669*.

The most massive of the diluvial bars (N50°21′48 3″; E86°40′44.1″) blocks the Katun River valley at the Chuja River confluence, which demonstrates that the greatest floods came down the Chuja valley from the Kuray Basin These bars either infill small alcoves that flank the main valley (Fig 7); or form barriers across larger side-valleys (Fig 8); or occur on the inside of main valley bends in a similar position to point-bars within river channels (Fig 9) These bars have steep (outer) margins (see Fig. 11) facing the main valley (typically 20° to 35° slopes; Fig. 7), rise 80–120 m above the highest river terrace, and individually are up to 5 km in length. Often 'run-up' deposits are found (tens of metres higher than the elevation of the bar-top) on the downstream side of the tributary where flood waters surged against the valley flank (see Fig 11a) In the Chuja valley, distinct benches are cut in the outer margins (e g at the Satakular and Tutugoi valley locations; N50°22′39.6″; E87°2′39.8″; Fig 7) Where bars developed across the entrances to tributary valleys, temporary lakes often formed in the impounded tributaries, as witnessed by lacustrine deposits The tributaries subsequently cut through the barriers, thus draining the small lakes However, a small lake still exists behind an intact bar in the Sargal'djuk valley (N50°19′41.1″; E87°3′28 5″; Figs 3 & 4) Later, further main valley floods entered the embayments and deposited more gravel in the areas behind the original bars. These later gravel deposits may be intercalated with lacustrine deposits within the side-valleys

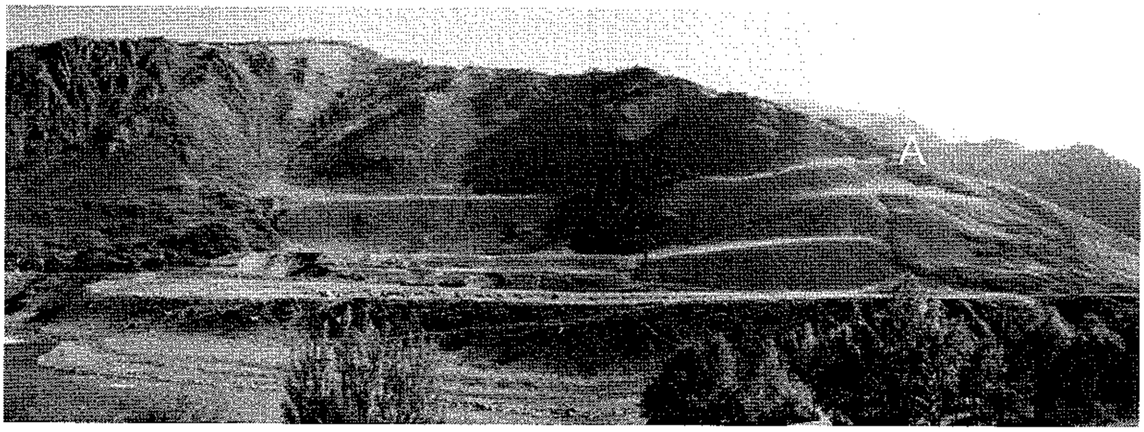


Fig. 7. Distinct benches cut in a giant gravel bar flanking the Chuja valley (flow right to left). At the extreme right a wedge of (light-coloured) flood gravels (A) can be seen partially filling a right-bank tributary valley. Flood sediments are thin on the rocky ridges, but the benches are well developed in the small alcoves between the ridges. In the centre foreground is the Chuja River incised into the boulder-strewn 'Inja' terrace.

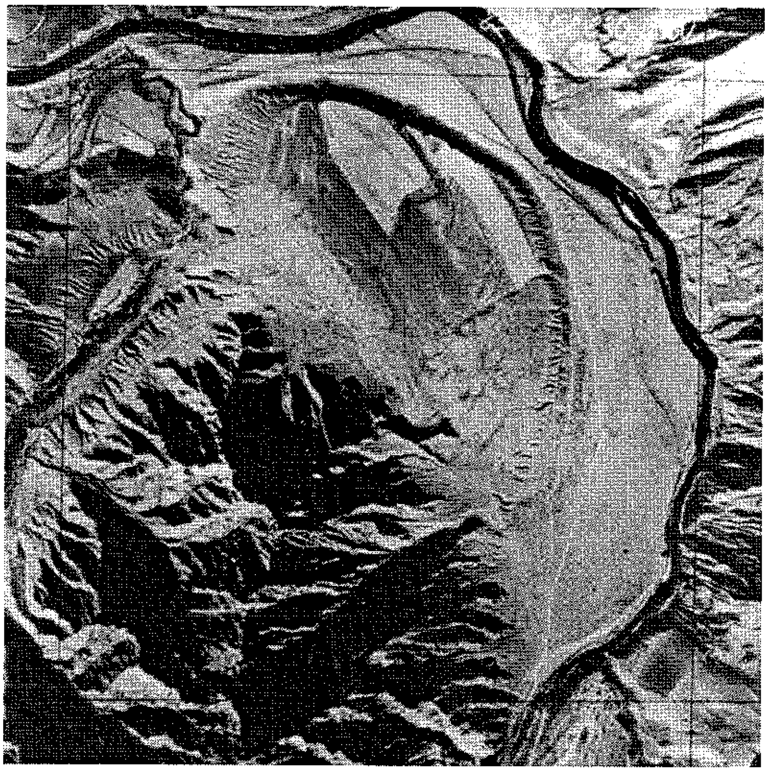


Fig. 8. Aerial view of the Little Jaloman giant bar. Mountain massifs are present far right and bottom left. The Katun River flows northwards from bottom right to top left. A left-bank tributary, the Little Jaloman River, joins the Katun River from centre far-left. The ovoid mass in the centre of the image is the Little Jaloman giant bar developed on the inside curve of the valley. Originally the bar extended across the entrance to the Little Jaloman valley filling the tributary with flood gravels. The tributary has trenched through these deposits, which are now heavily gullied, both along the course of the Little Jaloman River and along the outer margin of the bar within the Katun valley. Pock-marks and sinuous features on the bar top are kettle holes and associated drainage gullies, which resulted from melt-out of stranded ice-blocks (partially obscured by cultivation). Scale: horizontal distance is approximately 5.0 km

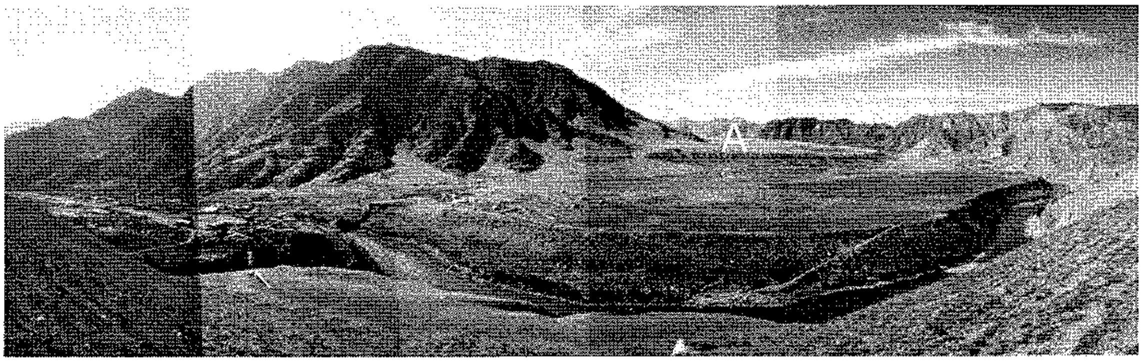
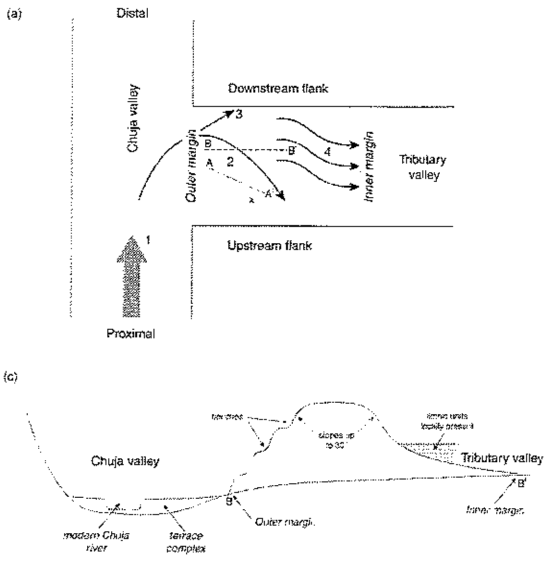


Fig. 9. View from the top of the giant bar blocking the right-bank tributary to the Katun River at the village of Inja (far left). The Inja River breaches the giant bar in a deep narrow defile below the electricity pylon (arrowed). The Katun River in the foreground flows from left to right entrenched in the Inja terrace. Centre-right, the upstream portion of the Little Jaloman giant bar may be seen (A), developed above the terrace level, in the lee of the dark mountain massif (Fig. 8). The 20-m-high pylon and habitation provide scale.

There are two styles of bar deposition related to whether the bars are proximal or distal with respect to the flood source. Bars within the Chuja valley consist largely of deposits of pebble gravels, some 100 m thick, although cobble- or boulder-beds also are very common (Fig. 10). Within each tributary valley, the bars consist primarily of stacks of multiple, subparallel gravel sheets, each some decimetres to 2 m thick. Within the Satakular bar (Fig. 3), individually the sheets form planar surfaces that dip towards the main valley and thus are inclined upwards, and obliquely, into the tributary valley. A well-developed, preferred pebble imbrication also indicates that bedload transport was from the main valley obliquely into the tributary. Together, these observations indicate that the bar was built up by sheets of bedload entering the tributary valley from the flood in the main valley in separated, recirculating flow-cells (Fig. 11). As the bar developed in height, flood water would have continued to wash over the bar top so that some deposits in the inner part of the bar should reflect this overwash process. However, the structure of the inner margins of these Chuja bars is not known, owing to poor exposures, but the present-day inner margins occasionally are extremely steep (including angle-of-repose), forming impressive barriers tens of metres high across the tributaries. Thus, the process of deposition is analogous to that of a barrier-bar process, whereby sediment moves across a planar, low-angle outer-margin to be deposited on a steep overwash lee-side. The Chuja valley is steep and narrow, such that flood velocity would have been very high (Baker *et al.*, 1993). This control, together with the fact that the bar outer-margins dip towards the main valley, probably indicates that the bar sediments never prograded far towards the centre of the main valley. Consequently, the modern morphology of the bars is essentially the same as immediately after the flood episode. However, some benches on the outer-margins of many Chuja bars probably are erosional, reflecting stillstands in the recession of the flood wave (Figs 7 & 11c).

Fig. 10. Proximal bars, within the Chuja valley, consist largely of deposits of pebble gravels some 100 m thick, although cobble- or boulder-beds also are common. This section is marked as (x) in Fig. 11a, and is about 70 m above the Chuja River within the giant bar that blocks the tributary Satakular River (Fig. 3). The view is from the upstream flank (Fig. 11a) of the tributary looking obliquely downstream towards the Chuja valley. The bar consists primarily of stacks of multiple, subparallel gravel sheets, each a few decimetres to 2 m thick. Individually the sheets form planar surfaces that dip obliquely towards the main valley (Fig. 11b).

The largest bars occur in the Katun River valley close to the villages of Inja and Little Jaloman (Fig. 3)



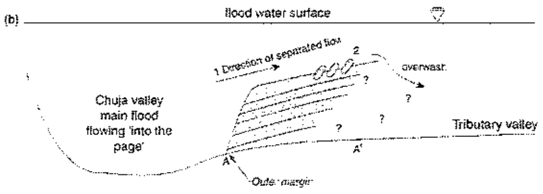


Fig. 11. Cartoon depicting the mechanism by which giant bars were deposited within tributaries to the Chuja River. (a) The flood wave in the main valley (1) generated a giant eddy into the tributary (2) as well as 'run-up' deposits (3) high on the downstream flank Coarse gravel deposition was confined initially to the immediate tributary mouth, latterly sediments were washed over (4) the developing bar into the ponded tributary valley. (b) The section A–A′ (Fig 11a) demonstrates how the separated flow (1) within the eddy resulted in primary bedding and imbrication (2) dipping obliquely across the entrance to the tributary Lateral trimming of the outer margin of the bar caused over-steepening of the outer margin. (c) The section B–B′ (Fig 11a) shows the characteristic, flat-topped bar-form seen today, characterized by steep inner and outer margins Benches (Fig. 7) developed on the outer margin during flood draw-down The effective blocking of the tributary resulted in the development of a small lake, indicated by limnic sediments

The Inja bar forms a barrier across the Inja River valley (N50°27′25″; E86°38′1.8″) in which there are three lacustrine deposits separated by units of flood gravels. The Little Jaloman bar forms a broad 'point-bar' that extends across the entrance to the Little Jaloman River valley in which there are no lacustrine deposits (Figs 8 & 9). Distinctive cone-shaped hollows with associated drainage gullies on the top of the Little Jaloman bar (Fig. 8), as well as on other bars, are ascribed to melt-out of stranded ice blocks (Maizels, 1977; Syverson, 1998). These features are similar to kettle-holes, and concentrations of large angular boulders in the upstream portions of the bars are indicative of flood flow tearing bedrock from the adjacent valley walls.

In contrast to the coarse pebble gravels in the Chuja valley, down-system fining is such that the Katun valley bars, near Inja and Little Jaloman, consist mainly of fine pebbles and granules. Average grain size further decreases down-valley to granules and sand near *km 672*. In the vicinity of Little Jaloman and Inja, the valley gradient is reduced (Fig. 4), the valley widens, and here the largest bars are found. These bars tend to have steep truncated outer margins (Fig. 8), although the bedding in the outer margin is near-horizontal, or dips gently towards the main valley centre. This stratigraphy indicates that the outer margins originally extended towards the centre of the main valley, but subsequently have been cut back to some degree by lateral erosion.

In contrast to the Chuja valley bars, the bars in the Katun valley often have gentle inner margins, with deposits extending some thousands of metres up the tributaries (Figs 12 & 13). Trenching by streams has resulted in good exposures of the bar sediments at locations near the outer and inner margins of bars within the tributary valleys. The bar-top surface and major bedding planes dip into the tributary valleys at angles of a few degrees to 10°. As a result, deposits pinch-out up-tributary at a distance of some 2 km. Beds are thickest (10–20 m) proximally at the base of the bar, and thin distally, reaching a minimum thickness of about 1–2 m (Fig. 14). The sediment, consisting of fine pebbles and granules, tends to show constant grain size or fines distally, as trough cross-bedded coarse angular sands and granules commonly replace gravels up-tributary.

The bar deposits at Little Jaloman consist of 11 distinct successions (Fig 15). The facies characteristics of each succession are fundamentally identical one with another except in terms of thickness and local detail. The lowest successions within the proximal deposits (Fig 14) can be 10–20 m thick, but this decreases

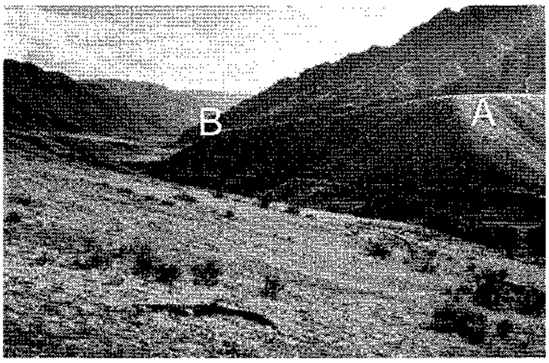


Fig. 12. Oblique view, into the tributary, of the gravel infill on the downstream flank of the Little Jaloman valley. The river has cut a deep defile through the giant bar. The steep outer margin of the bar (A) is sun-lit on the right beneath a 20-m-high pylon. The bar top, on the true left flank of the tributary, slopes back into the valley at a uniform gradient before steepening beyond a second pylon. The inner margin is at (B)

both vertically and towards the inner margin. In view of the distinct repetition, successions can be termed *rhythmites*. The monotonous repetition of the facies in each superimposed succession implies a repetitive flow control rather than vagaries in sediment supply. Within the lower to mid-sequence of the rhythm (not shown) massive coarse gravels give way to smaller scale coarsening or fining-upward sets of subparallel laminae and beds of granules and pebbles, 3 mm to 400 mm thick. Isolated cobbles and boulders in fine gravels are common. Higher in the sequence undulating-, sigmoidal- or cross-beds of very coarse sand and granules occur beneath a cap of coarse fluvial gravel/debris flow deposits (top of Fig. 15 and see Fig. 16).

Lacustrine successions

Giant bars temporarily impounded small lakes in some of the tributaries until the tributaries cut down

Fig. 13. Oblique view, into the tributary, of the gravel infill on the upstream flank of the Little Jaloman valley (viewed from beneath the pylon in Fig. 12). The bar top is out of sight to the left, from which direction flood water would have entered the tributary from the Katun valley. The sedimentary surface (A) (abutting the flanking mountains), and the bedding of the deposits, slope into the valley at about 10°, finally pinching out 2 km upstream (Fig. 14). Originally the fill would have constituted a continuous surface but the tributary subsequently cut through the deposits.

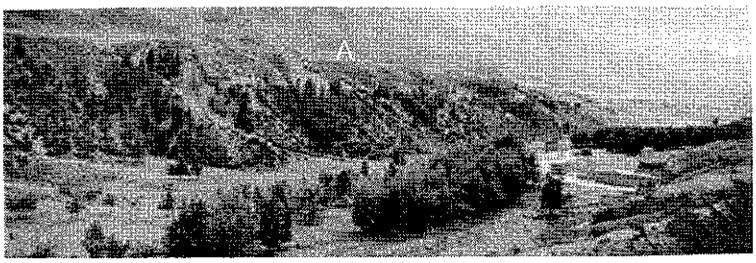
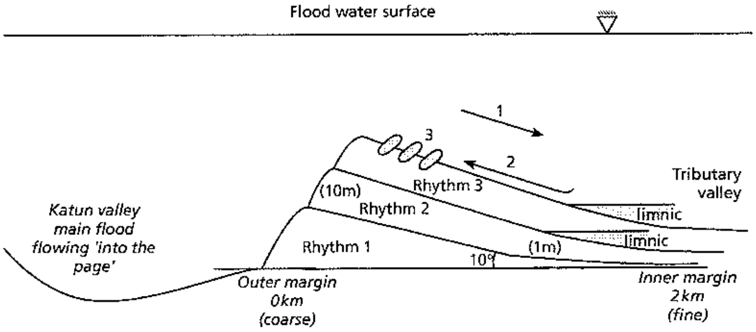


Fig. 14. Cartoon depicting mechanism by which giant bars were deposited within tributaries to the Katun River. Section extends from the outer margin adjacent to the Katun valley to the inner margin within the tributary. Bedding is often self-similar, forming a series of stacked rhythms (of which only three are depicted here). These rhythms thin distally and in some tributaries interbed with limnic deposits. The separated flood flow (1) entered the tributary above an accreting bar-form, evidence for return currents (2) is weak and flow-direction indicators, such as particle orientation (3), suggest up-tributary flow



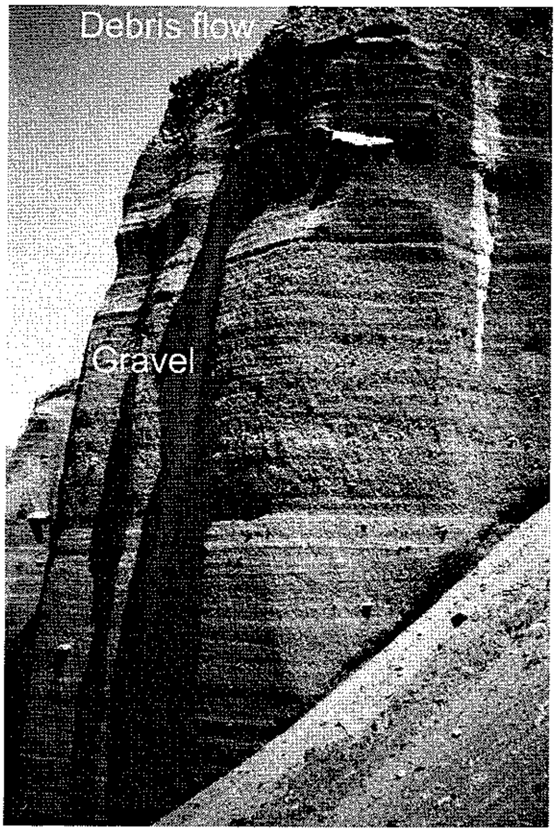


Fig. 15. Eight-metre-high section representing one rhythm of deposition in a stack of 11 self-similar units within giant bar deposits in the Little Jaloman River valley.

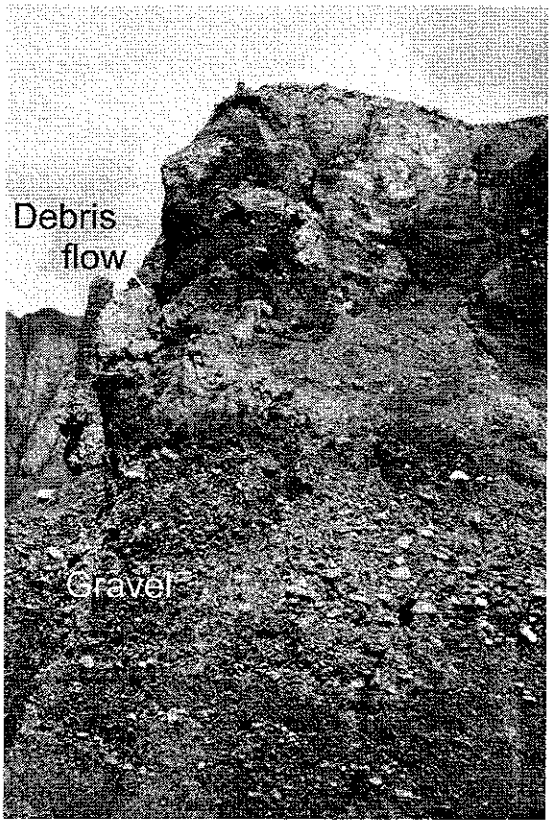


Fig. 16. Two-metre section of coarse fluvial gravel and debris flow deposits at top of rhythm shown in Fig. 15.

and drained the lakes (Figs 11c & 14). Within the Inja valley there is clear evidence for at least three lacustrine units separated by flood-gravel units. Gully sections in giant bar sediments in the Inja valley, adjacent to the village of Injuskha, expose the full 70-m thickness of the sediment pile. The sections show at least three flood-gravel units separated by three episodes of lacustrine deposition. The last and highest lacustrine unit forms the present-day horizontal surface behind the giant bar. The lake sediments are finely laminated or rippled white silts (Munsell 10 YR 8/1) with red staining (Munsell 10 YR 8/8) in some laminae. Worm trails are abundant in the upper lacustrine silts and fish bones have been reported (Ragosin, 1942). Convolution (Fig. 17) and local intercalation of the lacustrine deposits with reworked flood gravels reflect reworking of the earliest lake silts and flood gravels by subsequent floods. In addition, the sediment pile was unconsolidated and slumped as progressive downcutting by the tributary stream breached the bar and trenched the lacustrine fill. Until recently, the age of these Inja deposits was disputed. Ragosin (1942) suggested a Late Mesozoic or Tertiary origin, whereas Svitoch & Khorev (1975) and Svitoch (1987), using radiocarbon and luminescence dating, argue for deposition at the end of the Late Pleistocene during the Karginian interstadial (between 46 ka and 23 ka). Recently, however, the middle and the upper lacustrine units have yielded ^{14}C dates of 23 350 ± 400 yr BP and 22 275 ± 370 yr BP, respectively (Barishnikov, 1992). During this study an infrared stimulated luminescence (IRSL) date of 22.4 ka (± 2.3 ka) was obtained for the middle lacustrine unit by the Desert Research Laboratory in Reno, Nevada. Thus a Sartan stadial date seems appropriate.

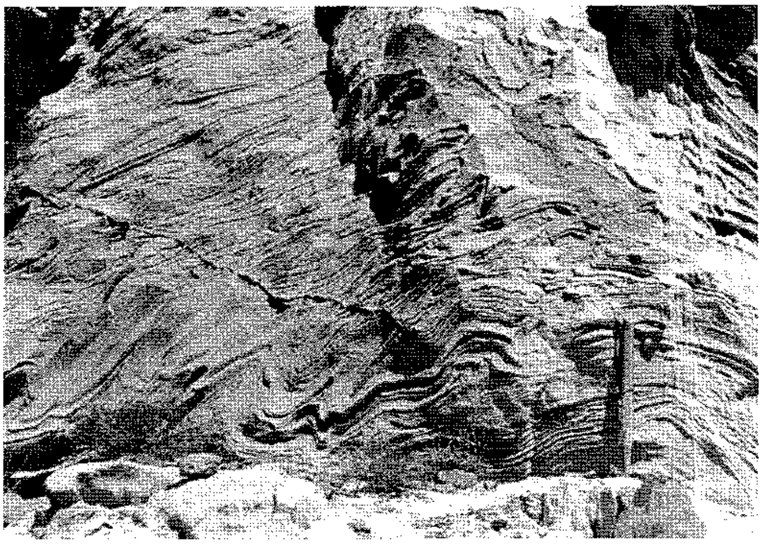


Fig. 17. Convoluted laminations of fine white lacustrine silts Axe is 50 cm long

Terrace successions

The terrace gravels have not been studied in detail and further stratigraphical and sedimentological investigation is needed To date only the basic relationships have been recorded. Near Little Jaloman village the sediment-fill in the Katun River valley consists of up to 90-m thickness of terrace gravel (Fig. 5), which thins upstream to less than 60-m thickness in the Chuja River valley (Fig. 6). The modern river has cut a deep narrow trench in this sediment. Two main terrace levels occur: one broad terrace primarily at 80 m above the modern river, is termed the Inja terrace, and another narrower terrace is 5–10 m higher. Minor terracettes, similar to those in braided rivers, occur on the 80-m level and up to six other discontinuous terraces occur along the trench walls. A single TL assay of questionable validity, 55 m above the river near the Chuja–Katun confluence, dates the Inja terrace to 148 ka (± 16.7 ka) such that it was formerly believed that the terrace sequence should be older than the Inja bar (Svitoch, 1978) Despite the TL dating, poor exposures of sediment sections at Log Korkobi and Inja demonstrate that the giant bar gravels extend beneath the terrace gravels towards the centre of the valley. A good exposure at the confluence of the Katun and Chuja rivers shows giant bar sediments on a bedrock surface at the modern river level with debris flow and terrace gravels above. In each example the contact is distinct and unconformable. Consequently, the bar sediments must pre-date the terrace sequences At Log Korkobi, and at some other locations, the lowest valley-fill, at the base of the terrace gravels, lies on bedrock and consists of a 1-m thickness of grey (Munsell 5Y 6/1) silty sand dated by IRSL to 47.2 ka (± 6.7 ka). This layer is overlain by a 3-m to 10-m thickness of cobbles with a distinctive cream-coloured (Munsell 10 YR 8/2) silt matrix Above is the rest of the terrace succession. This has not been mapped in detail but consists of trough cross-bedded braided river deposits, conformably and unconformably interspersed with several decametres of very poorly sorted, coarse gravel beds, which include numerous boulders up to 2 m in diameter These latter coarse beds are interpreted as large-scale grain-flow deposits. Throughout the succession of coarse gravels, several horizontally laminated fine sand and silt beds occur. These beds are up to 1 m thick but pinch-out laterally after several decametres These sandy units appear to represent temporary small ponds, formed by river inundation of hollows on former braidplain levels Near Great Jaloman, the terrace succession is capped by a massive boulder-layer consisting of well-rounded, half-metre size boulders forming a single bed up to 3 m thick Although most terrace gravels are horizontally bedded there are a few locations where a single, thick unit of cross-stratified gravel is in evidence For example, on the right bank of the Katun River, opposite the confluence of the Little Jaloman River, the terrace gravels consist of a single 30-m-thick unit of cross-stratified gravel in which individual foresets can be traced, dipping steeply (up to 30°) away from the valley margin A similar 10-m-high unit occurs just downstream of a bridge crossing the Chuja River at the village of Iodro (N50°24′1 0″; E86°58′22.8″). In both cases, the large-scale foresets lie on bedrock at the base of the terrace succession

The distinctive large-scale gravel foresets noted near Little Jaloman and elsewhere are interpreted as originally constituting a largely unmodified Gilbert-type 'delta', similar to that described for fluvioglacial deposition into standing water (Clemmensen & Houmark-Neilsen, 1981; Smith & Jol, 1997; Plink-Björklund & Ronnert, 1999) This interpretation is reinforced by a distinct upward coarsening from the bottom-set through the foresets to the boulder top-set. The generally gradational contacts between the gravel beds indicate penecontemporaneous deposition of the complete cross-stratified succession

PRELIMINARY INTERPRETATION OF DEPOSITIONAL ASSOCIATIONS

The interbedded succession of flood gravels and limnic units in the Inja valley demonstrates that at least three large floods in the Katun River valley penetrated the tributary valley of the Inja River The two later floods overtopped the earlier bar deposits and added flood gravels to the local succession. On the basis of the evidence at Inja it is assumed that the complete suite of giant bars found along the course of the Chuja and Katun rivers are of a similar age range, and in many cases may be compound sedimentary bodies derived from several flood episodes.

The following sequence of events is envisaged The earliest giant bars were deposited around 23 ka, as indicated by the date of the earliest limnic unit in the Inja valley At this time the valleys of the Chuja and Katun rivers may have contained little sediment, or the initial flood surge scoured the main valleys to bedrock. The evidence is that only remnants of older deposits are to be found, such as the grey silty sand dated by IRSL to 47 2 ka These thin remnants are preserved beneath giant bar gravels, which largely sit directly on the bedrock surface close to the altitude of the modern river Over a total period of several thousand years a number of large floods, some 200 m or more in depth, coursed down the steep Chuja River valley depositing giant bars at each tributary confluence The primary source of the sediments was material eroded from fluvioglacial fans deposited within the Kuray and Chuja lake basins upstream, but local valley-side bedrock, scree and glacial deposits were also eroded and then redeposited in alluvial successions In the steep Chuja River valley, flood power was great and the primary sediment source close to hand Hence the giant bars tend to consist of coarse gravel Downstream of the confluence of the Chuja and Katun rivers the gradient of the valley is reduced, the valley widens and here flood power was reduced. In addition, flood waters were ponded temporarily by the valley constriction at *km 672* (Fig. 3) Consequently flood waters backed up in the Katun valley, between *km 672* and the Chuja–Katun confluence, depositing several large fine gravel bars, including those at Inja and Log Korkobi The backwater effect extended up the Katun River valley for about 15 km above the Chuja confluence, infilling the Katun valley with two large bar complexes, which extend from Sok-Yarik (N50°16′35.1″; E86°41′51.9″) to Komdodj (N50°22′26.6″; E86°40′5.1″)

The power of the flood could erode and transport blocks of many metres in diameter from the valley walls (Baker *et al*, 1993) However, most of the flood gravels in the Katun valley giant bars consist of pebbles and granules. Presumably large blocks were readily fragmented by the flood power (~ 10^5 W m^{-2}; Baker *et al.*, 1993) or were numerically insignificant compared with finer gravels On the rising limb of a flood, coarse cobble-sized gravels were rapidly deposited in the tributary mouths probably forming an initial deposit, typically 10–20 m high, similar to a coastal spit across each side-valley. As water depths increased during the main flood, the side-valleys became deeply flooded such that finer gravels were deposited above the cobble-sized deposits from a high-concentration suspension; these finer gravels extend further into the tributaries than the cobble gravels. The finer gravels form successions typically between 70 and 200 m high.

In contrast to the fine gravels in the bars, the terrace gravels are much coarser, generally consisting of cobble or boulder gravel, including debris-flow units and large-scale cut-and-fill sequences, the latter typical of braided river deposits The whole terrace succession often exhibits boulders concentrated at the terrace surface (Fig. 7). The stratigraphical relationship between giant bars and the terrace infill shows that the bars predate the terrace infill. However, the large-scale cross-stratification indicates that at least parts of the terrace succession were deposited as a steep depositional front consisting of Gilbert-type foresets moving down the main valley into a body of water. The best explanation is that some of the terrace infill, i.e the cross-stratified deposits, was deposited almost conformably with the giant bars While the giant bars were deposited in lateral locations, largely from suspension, a bedload dominated large-scale bar-front was prograding downstream into the back-flooded Katun River valley On the falling stage of the flood, and during subsequent periods, these bar-front deposits were extensively eroded and reworked. Subsequent flow events infilled the valley developing the main (Inja) terrace, such that the present-day terrace surface is most likely a composite of large flood deposits and later reworked material In time the river cut vertically and laterally forming the low-level terraces, before down-cutting once more to its present level on the bedrock The controls and timing of the phases of incision are not known

CONCLUSIONS

Gigantic gravel bars, some 120 m high and up to 5 km in length, developed across the mouths of valleys draining into the Chuja and Katun rivers as a result of Mid to Late Pleistocene superfloods that coursed down the Chuja–Katun system The origin of the flood waters was the ice-impounded glacial lake Kuray–Chuja, which filled and emptied repeatedly. Geomorphological evidence indicates that the lake was impounded by convergent glaciers in the vicinity of the town of Aktash, and possibly at Kuehtanar. At least three major floods occurred The first of these floods, for which we have good evidence, occurred around 23 ka and deposited a series of 'primary' bars. Through both erosion and deposition, subsequent floods have modified the bars so that some, such as at Inja, consist of multiple alluvial successions interbedded with limnic deposits. Often modification occurred by flood waters overtopping earlier bars, or by the deposition of additional minor bars set against the outer margins of primary bars. Additionally, where tributary river flow had, over time, breached the primary bars and drained any impounded small lakes, later flood waters entered the tributaries, depositing flood gravels as insets behind the primary bars within the tributary valleys However, further stratigraphical and sedimentological data, and dating control, are needed to demonstrate the detail of these events.

The overall character of the deposits demonstrates that the bars were formed by recirculating flow within back-flooded tributary mouths. Within the Chuja River valley, close to the ice-dam failure, bars consist of cobble and pebble gravels, but they fine downstream to pebble gravels, granules and coarse sand in the Katun River valley In the high-gradient Chuja system, bars often have flat tops, very steep inner margins and frequently exhibit benches on the outer margins In the lower-gradient Katun valley, bars show less evidence of benches, and have tops and inner margins that slope gently for up to 2 km into the tributaries Limnic deposits in some side-valleys show that the giant bars temporarily impounded tributary inflow after the flood waters had receded; tributaries subsequently cut down through the barriers, draining the small lakes.

The stratigraphical relationship of the giant bars to the sediment-fill within the main valleys is not clear. The main valley-fill locally consists of large-scale cross-stratified units reminiscent of Gilbert-type foresets that prograded down-valley These deposits have been fluvially reworked to give a series of terrace surfaces Further investigation is warranted.

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