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GRAIN SIZE COMPOSITION AND AGE OF ALLUVIAL SEDIMENTS IN THE TISTA VALLEY FLOOR NEAR KALIJHORA, SIKKIM HIMALAYA

INTRODUCTION

The lower part of the Sikkim Himalaya, called the Darjeeling Himalaya, is elevated from 200 m a.s.l. in the valley bottoms to 2,000–2,500 m a.s.l. on the watersheds. It is built of resistant Darjeeling gneisses overthrusted on the Daling metamorphic shales and quartzite, and then on less resistant Damuda sandstones and shales. At the sharp front of the mountains there is a narrow belt of sandy Siwalik zone (Gansser 1964). Especially, deeply incised canyon with steep sides (30–50° and more) was formed by the transfluent Tista river draining the whole Sikkim Himalaya (c. 7,000 km^2).

The mean annual uplift is calculated between 1–4 mm·a^{-1} (Nakata 1972, Iwata 1987). In the valleys of the marginal zones old gravels were found at the 700 m high Gorbathan surface, connected with the middle Pleistocene (Nakata 1972). There are also flattenings along the Tista and Rangit valleys, elevated at c. 900–1,000 m and at 600–700 m a.s.l. (200–300 m relative height) as described by N. R. Kar (1968) and L. Starkel (1972). These data indicate that the mean incision of the valleys could be of the order of 50–100 m during the last 10^5 years.

The annual rainfall in the Darjeeling Himalaya fluctuates between 2,000 and 4,000 mm, and in particular years may exceed 6,000 mm (Starkel 1972, Froehlich and Starkel 1987). Two to four times in a century, the extreme continuous rainfalls of the order of 600–1,500 mm are recorded (Froehlich et al. 1989), causing a simultaneous transformation of slopes by various mass movements and floods in the valley floors. During the last event in October 1968, the water level of the Tista river rose by 18–20 m (Starkel 1972) and caused local aggradation in the channel floor up to 5–7 m but during the next 15 years of relaxation its lowering by 1–5 m (Froehlich and Starkel 1987). That time, the river discharge reached c. 18,000 m^3·s^{-1}. There were formed extensive bars, several metres high, built of boulders. During every rainy season

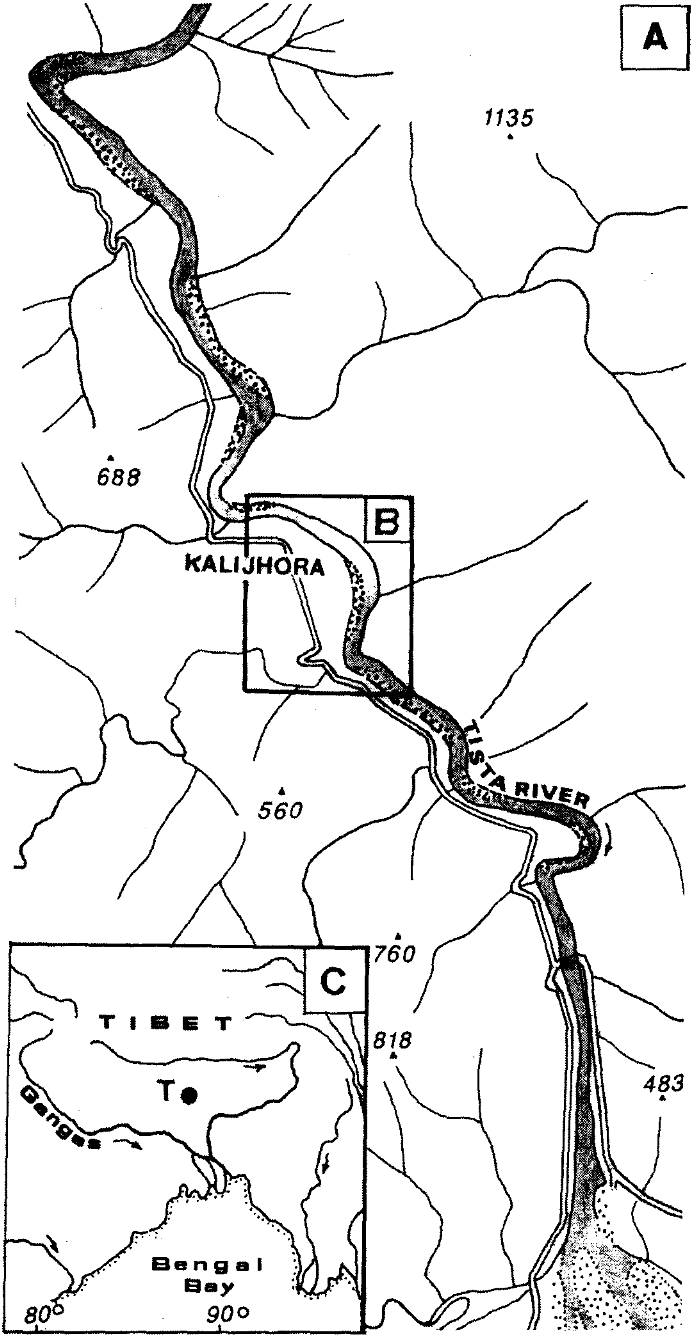


Fig. 1. Lowest reach of the Tista river gorge ending with alluvial fan. Along channel are single bars. Insert B was studied in detail (see Fig. 2.)

Ryc. 1. Dolny odcinek kanionu Tisty, kończącego się stożkiem napływowym. Wzdłuż koryta są pojedyncze odsypy. Okienko B zostało zbadane szczegółowo (patrz ryc. 2)

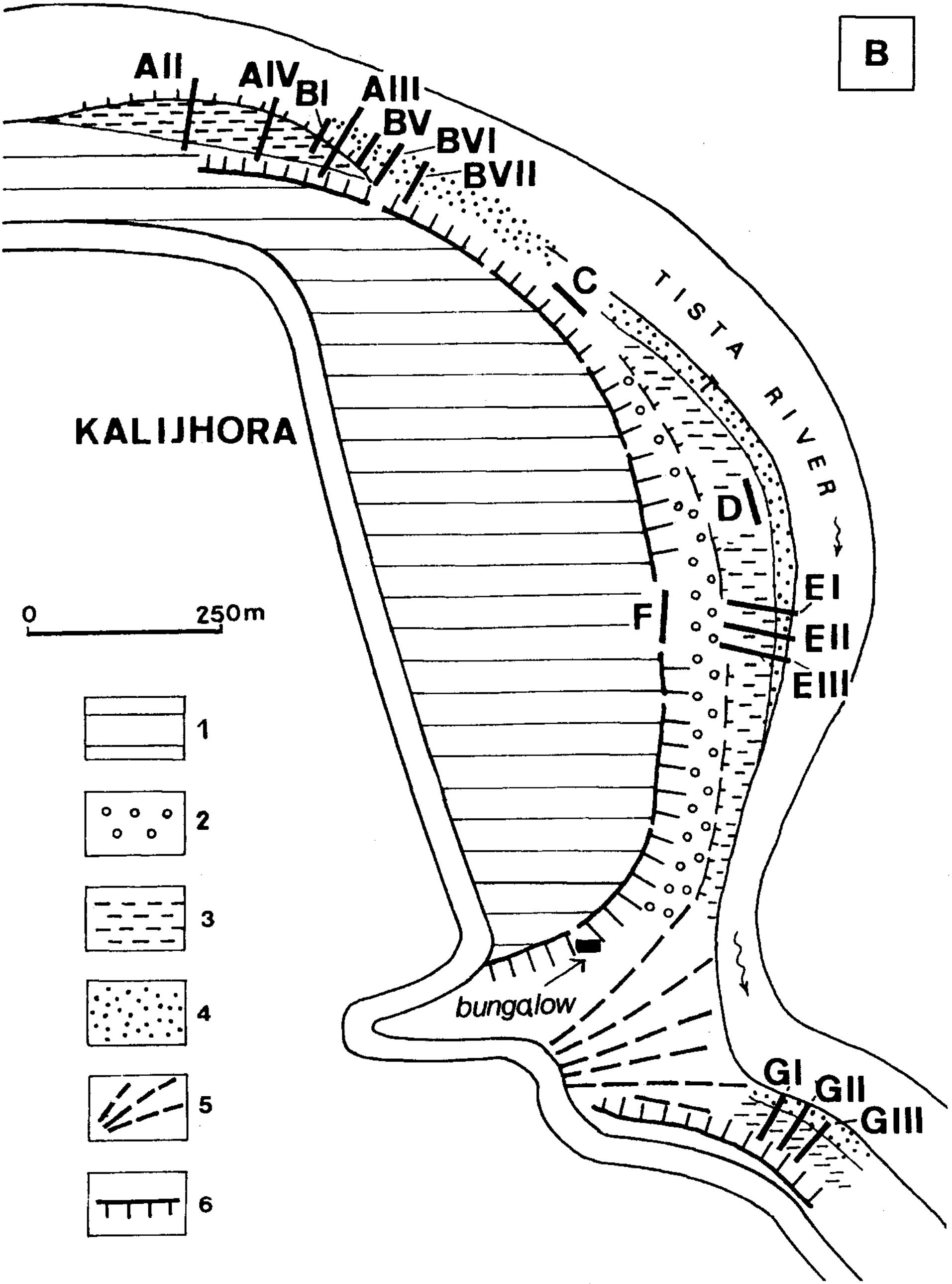


Fig. 2. Location of investigated cross-sections and profiles A–G (by L. Starkel). 1 — 60 m high terrace, 2 — 15 m high terrace, 3 — 5–7 m high terrace, 4 — bars and channel sites with boulders, 5 — active alluvial fan of Kalijhora creek, 6 — high scarps

Ryc. 2. Położenie badanych przekrojów i profilów A–G (oprac. L. Starkel). 1 — terasa 60 metrowa, 2 — terasa 15 metrowa, 3 — terasa 5–7 metrowa, 4 — odsypy i brzegi koryta z głazami, 5 — aktywny stożek napływowy potoku Kalijhora, 6 — wysokie krawędzie the water level of the Tista rises to 5–6 m and the discharge to 1,800–2,500 $m^3 \cdot s^{-1}$. Every 5–10 years, the water level may rise even to 7–10 m (cf. Froehlich and Starkel 1987). The repeated survey of the Kalijhora alluvial fan reaching the Tista river channel has shown a continuous transformation of a fan surface as well as of bars accompanying the Tista channel.

AREA AND METHOD OF STUDY

The 2 km long, studied segment of the sinuous Tista river valley is located near the outlet of the right hand side tributary, called Kalijhora (Kali creek). In this reach, a fragment of the 60 m high, up to 400 m wide, terrace (Fig. 1) is developed. Below a steep scarp, the following low terrace steps may be distinguished: 15–16 m high terrace, above the low (winter) water level (water level mark of the 1968 flood is elevated c. 18 m, i.e. 2–3 m higher); the 5–7 high terrace and lower bars on the river sides. The 50–100 m wide channel itself is paved with boulders and coarse gravels.

Based on the previous characteristics it might be expected that the channel bars should be reworked several times in a year, the 5–7 m high terrace is reworked or built up every year, and the 15–16 m high terrace was within the extent of the 1968 flood. This was confirmed during several visits between 1984 and 1991. The age of the 60 m high terrace should represent the upper Pleistocene (last cold stage?).

In January 1993 L. Starkel and T. Kalicki with assistance of R. Soja measured several cross-sections of the channel side and the right bank, low terrace, trying to characterise the grain size composition of coarse alluvia. For this purpose, the method described by J. Rutkowski (1995) was adapted. The method is based on measuring the long axes of gravels and boulders on the transects at fixed distances. The measurements were made every 25 cm on the surface of cross-sections passing through terrace plains and scarps. In the vertical exposures, similar measurements were carried out at 12.5 cm intervals. The generalised diagrams present the percentage of various grain sizes for different terraces and bars. Gravels were assigned to phi classes increasing every phi, if the gravels varied from -1 φ to -5 φ, and to the classes increasing every 0.5 φ, if the gravels were coarser. Sand and silt were measured separately (below the O line).

There were measured 5 transects of the low channel bar at the site B, and 9 transects of the channel bank at sites A (3), E (3) and G (3). The 5–7 m high terrace was sampled at site A (3 transects), E (3) and G (3). In the scarp of the 7–8 m high terrace, 8 vertical sections (site D) were measured. A similar vertical profile was surveyed at 5 m high terrace built of consolidated coarse alluvium (site C). The 15 m high sandy terrace covered totally by vegetation reached site E.

The aim of this study is to characterise the young alluvium of the Tista river in relation to the annual and extreme water level fluctuations. For comparison, the alluvial sequence of the 60 m high terrace (site F) was described. From the depth of 2 m and 37.3 m (bottom part) two samples were taken for termoluminiscence dating. They were examined by A. Bluszcz from the Department of Radioisotopes, Institute of Physics in Gliwice (Poland).

GRAIN SIZE CHARACTERISTICS OF SURFICIAL ALLUVIAL DEPOSITS

The surficial survey of grain size composition was made at sites denoted A, B, E and G (Fig. 2, 3, 4).

At site A represented by cross-section AI and AII (Fig. 4, 7) the scarp and the plain of 6 m high terrace were distinguished. The scarp (30% gradient) changes into a gentle channel floor built of coarse pavement. This part shows the dominance of coarse boulders between 25 and 150 cm, the steeper edge above is formed by gravels and boulders between 12.8 and 76.8 cm. The terrace plain is more than 100 m wide, only in its marginal part is not revegetated and coarse boulders are buried there by sands deposited during the last flood season.

A different picture is presented in the cross-sections at site B (Fig. 3, 7) where on the convex channel bend there was exposed a 20–25 m wide, about 200 m long, point bar raising only 1–1.5 m above the low water level in January 1993. It is built of gravels, 2–30 cm in diameter, and the depressions over the bar are filled with a thin sandy or silty cover. Single boulders on the surface were probably derived from the deeper parts of the channel or from the terrace edge. This bar is probably a product of a previous year flood (1992), contemporaneous with the sandy blanket on the 6 m high terrace (cross-sections AI and AII). The next lower flood waves from the end of the 1992 monsoon season are recorded in sandy and silty horizons preserved on the large boulders, on exposed rocky benches downstream as well as in the shallow depressions over the point bar itself.

The cross-sections at site E are located in the gentle straight reach of the Tista river and the exposed river bank inclined to 20% is built of finer gravels (comparing with site A) between 3 and 40 cm (Fig. 5, 8), culminating between 10–20 cm. Above it, a 5–8 m high terrace, rewashed by flood waters, extends. The terrace is built of similar gravels but with single large boulders, 80–100 cm in diameter, partly revegetated. Only in its marginal, 5–12 m wide part there is a blanket of overbank sands (Fig. 5, 8). Farther to the valley side there is the 15 m high sandy terrace with single buried boulders and with shrubs and trees several metres high. Its surface is only 2–3 metres below the mark of the 1968 high water level (18 m above the low water level) near the state bungalow.

Downstream of the alluvial fan of the right bank Kalijhora creek, on the convex bend of the river, closely to the rocky walls there is preserved the

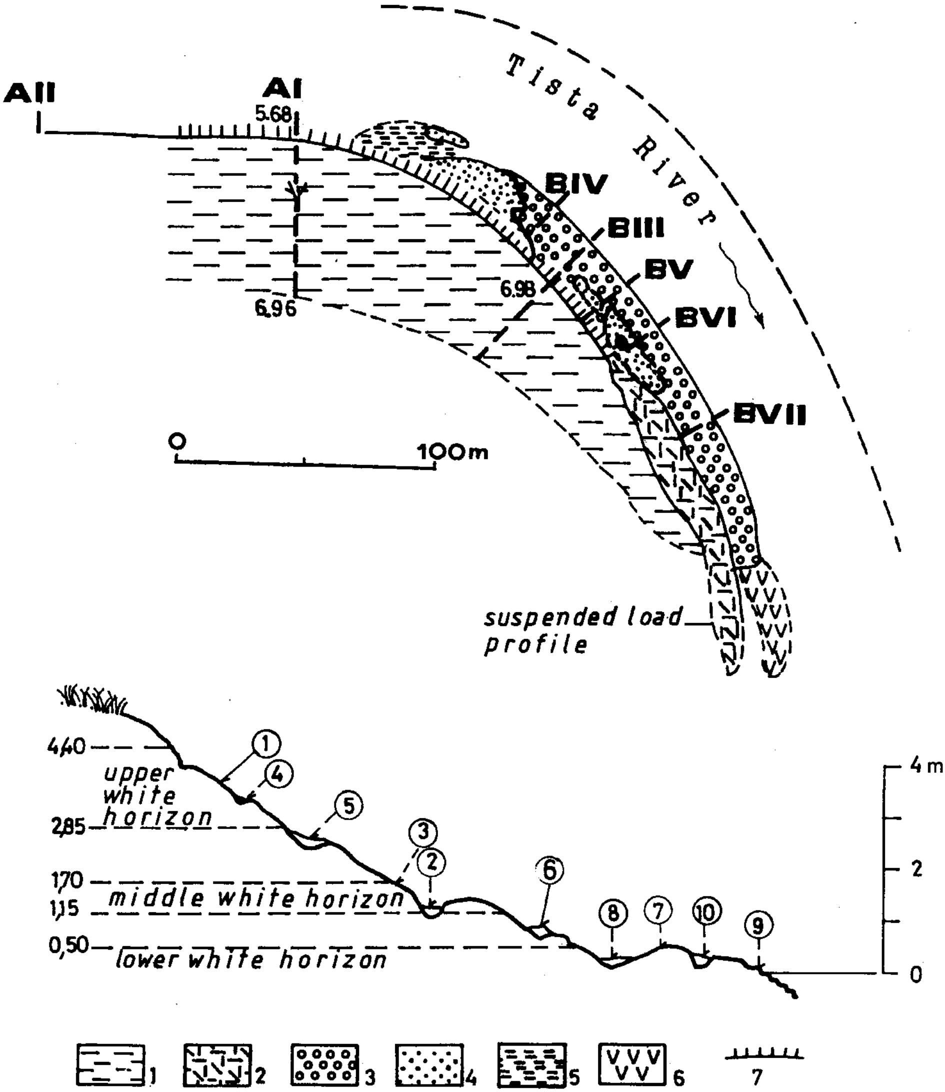


Fig. 3. Above sketch of the 1.0–1.5 m high bar within B transect and below rocky channel bank with silty white horizons of suspended material (by L. Starkel). 1 — 6 m terrace plain, 2 — gravels with silty cover, 3 — gravel bar with single boulders, 4 — sands in depressions, 5 — silty-sandy deposits submerged, 6 — gravel bar submerged, 7 — terrace edge

Ryc. 3. Powyżej szkic odsypu o wysokości 1,0–1,5 m w obrębie przekrojów B, poniżej skalisty brzeg koryta z pylastymi, białymi smugami z zawiesiny (oprac. L. Starkel). 1 — równina terasy 6 m, 2 — żwiry z cienką powłoką pylastą, 3 — odsyp żwirowy z pojedynczymi głazami, 4 — piaski w zagłębieniach, 5 — pylasto-piaszczyste odsypy zalane, 6 — odsyp żwirowy, podwodny, 7 — krawędź terasy

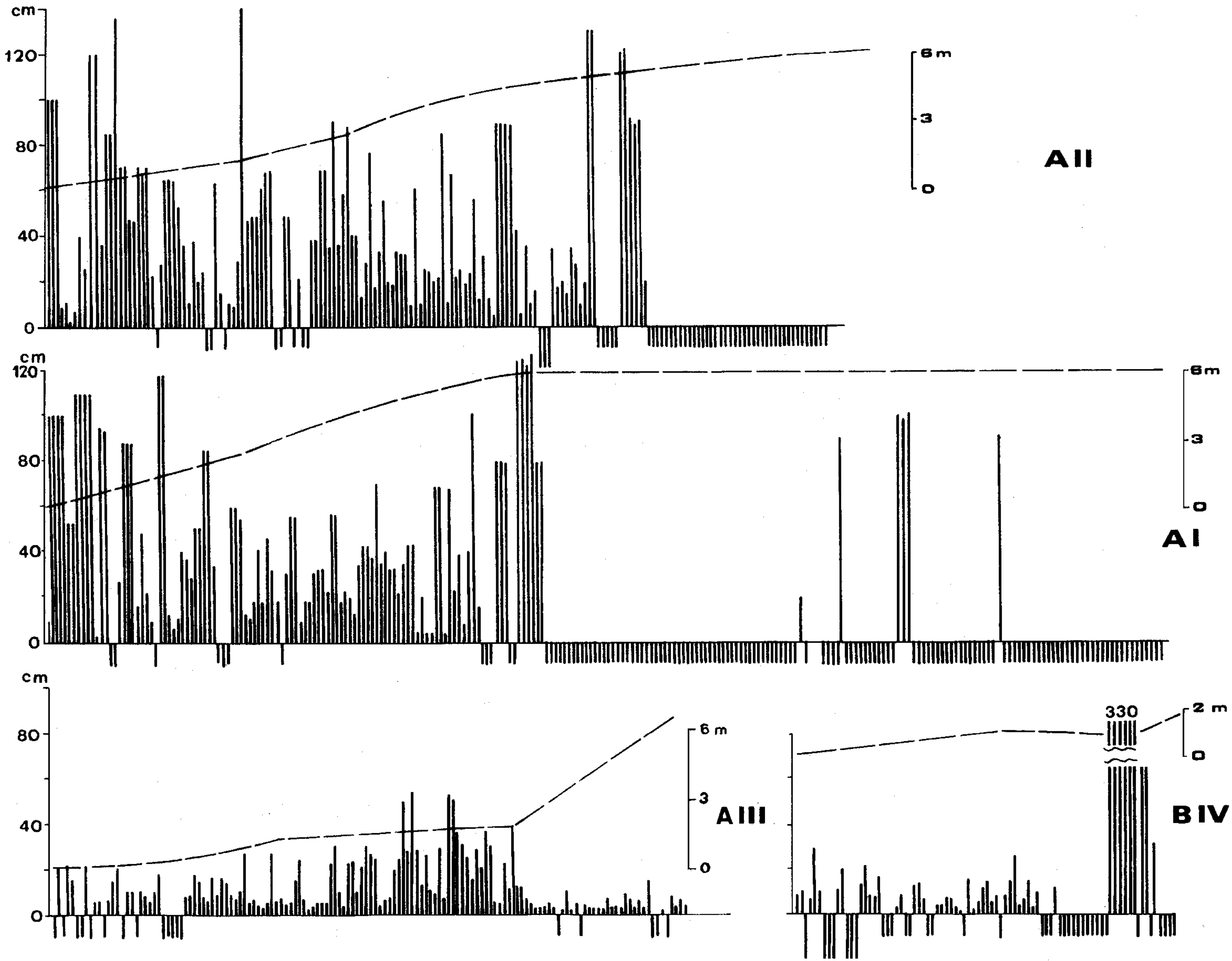


Fig. 4. Cross-sections and gravel or boulder diameters over them (by T. Kalicki, L. Starkel). AI and AII — terrace 5–7 m high, AIII and BIV — active bar. On the left scale of gravel diameters, on the right elevations above the river level

Ryc. 4. Przekroje poprzeczne i średnice żwirów oraz głazów na przekrojach AI, AII — terasa 5–7 m, AIII i BIV — współczesne odsypy (oprac. T. Kalicki, L. Starkel). Po lewej średnica w cm, po prawej wysokość nad poziom rzeki w m

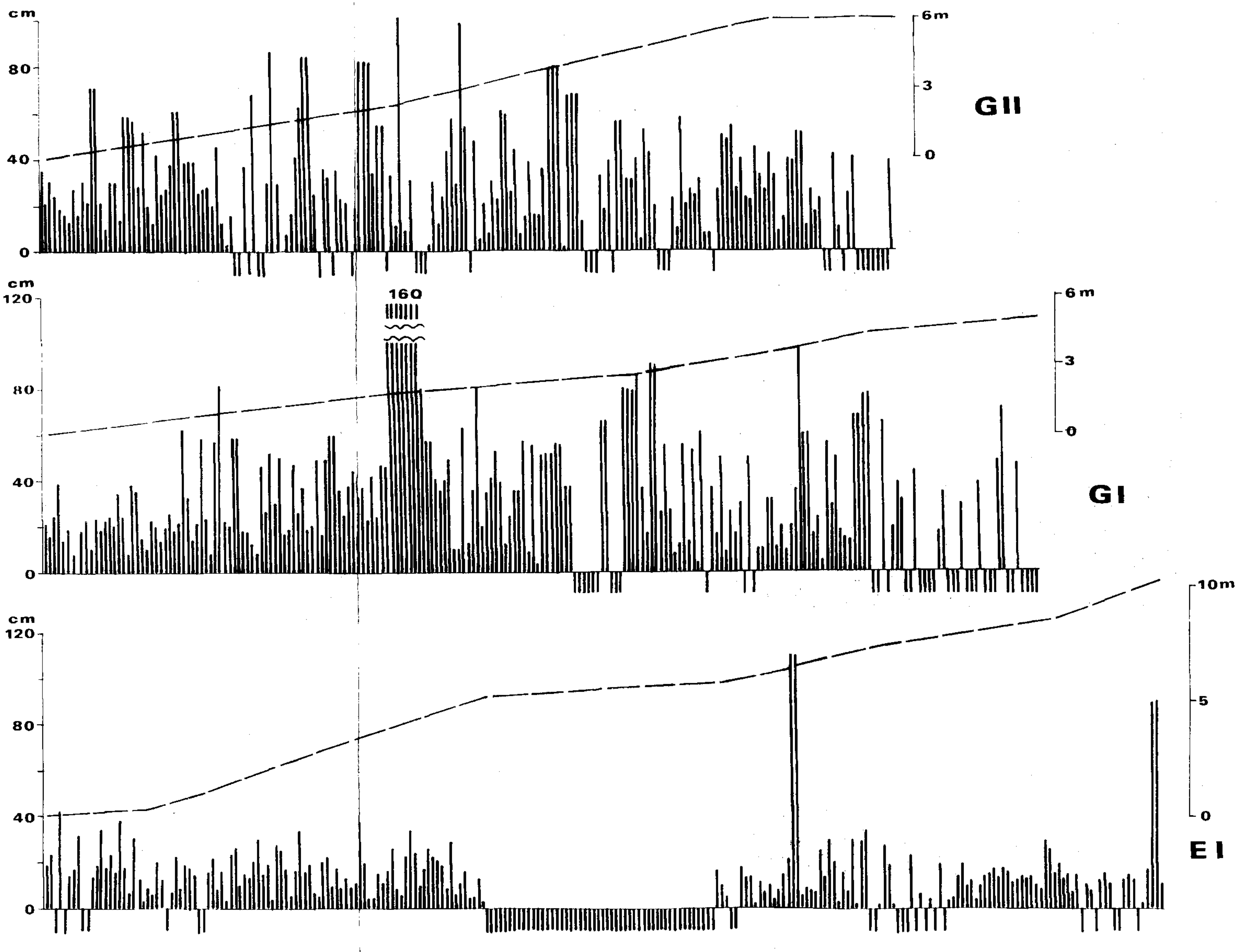


Fig. 5. Cross-sections and gravel or boulder diameters over them (by T. Kalicki, L. Starkel). EI and GI–GII — terrace 5–7 m high and their slope to river channel. On the left scale of gravel diameters, on the right elevations above the river level

Ryc. 5. Przekroje poprzeczne i średnice żwirów oraz głazów na przekrojach EI i GI–GII — terasa 5–7 m i jej skłon do koryta (oprac. T. Kalicki, L. Starkel). Po lewej średnica w cm, po prawej wysokość nad poziom rzeki w m fragment of the 5–6 m high terrace, partly revegetated and covered with sandy patches at its margin (site G — Fig. 5, 8). Its up to 45 m long slope is inclined only 12% towards the river and is built of coarse imbricated gravels and boulders which due to a higher gradient of the river could be removed during normal floods. Fraction between 12.8 and 76.8 cm dominates here, but single boulders reach 100–160 cm. At several levels the sandy lenses indicating the late water rises of the 1992 flood season (similar to those observed at site B) are visible.

GRAIN SIZE CHARACTERISTICS OF TERRACE EXPOSURES

At sites C and D the deposits of terrace plains are undercut (Fig. 2, 6, 9). At site D, in vertical 2–2.5 m section, the structure of a part of the 7–8 m high revegetated terrace built of non-consolidated deposits was exposed.

The upper sandy part of the scarp was covered by vegetation. The exposure was restricted to the middle part (4.5–6.5 m above water level) where mixed gravels, 2–10 cm in diameter, with coarser boulders to 40–65 cm at the bottom dominated. These gravels represent probably the channel bar that was formed during a large flood in the 1968 and was built up when the water level was falling.

Site C presents a similar mixed gravel body of the terrace bench only 5 high. But on the contrary these gravels are consolidated and represent much older event. In the 2.5 m high exposure one may distinguish 3 layers (Fig. 6) indicating the fluctuations in water discharge and sediment transport. The upper

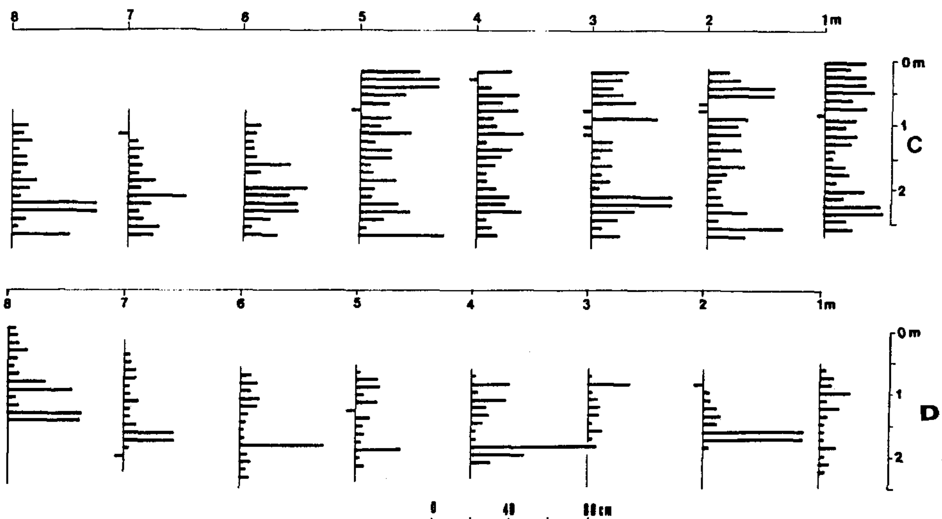


Fig. 6. Granulometry of alluvia in vertical exposures C and D (by L. Starkel)

Ryc. 6. Granulometria aluwiów w pionowych odkrywkach C i D (oprac. L. Starkel)

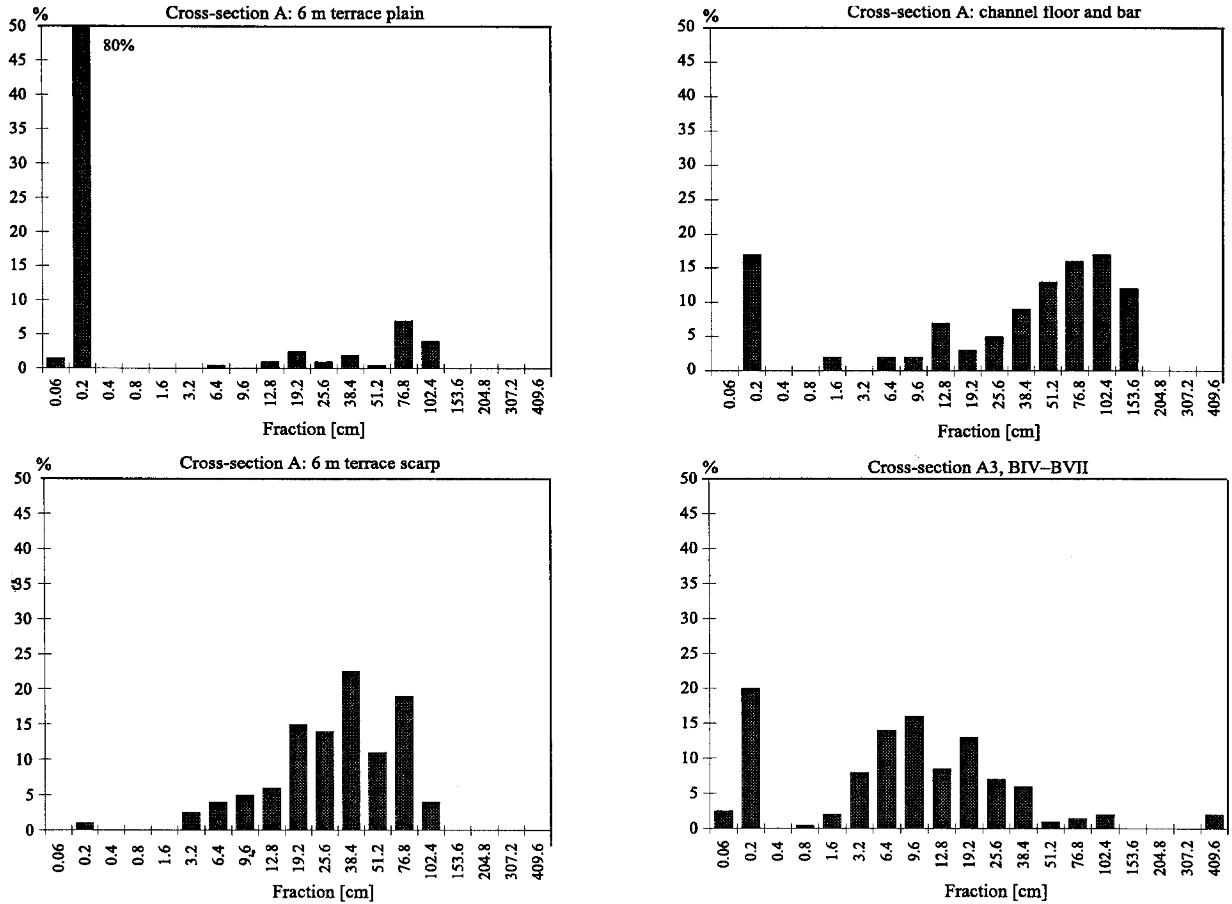


Fig. 7. Grain size distribution of surficial deposits on the A and B transects (by T. Kalicki)
Ryc. 7. Rozkład uziarnienia osadów powierzchniowych w przekrojach A i B (oprac. T. Kalicki)

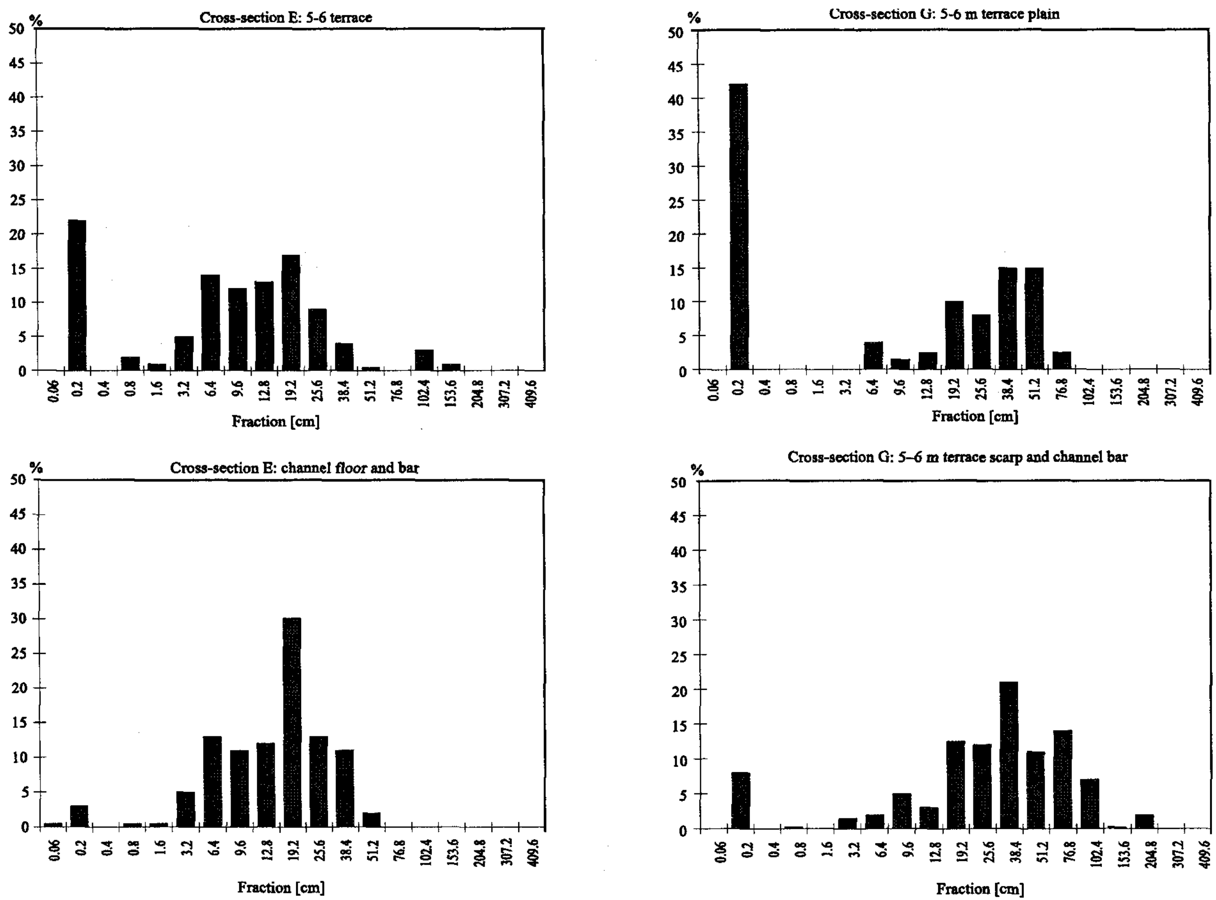
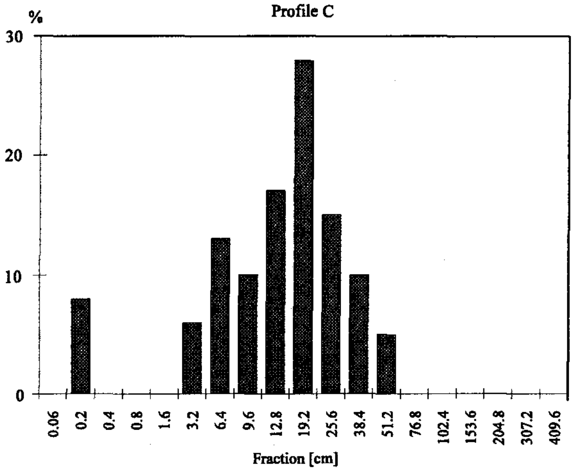


Fig. 8. Grain size distribution of surficial deposits on the E and G transects (by T. Kalicki)
Ryc. 8. Rozkład uziarnienia osadów powierzchniowych w przekrojach E i G (oprac. T. Kalicki)



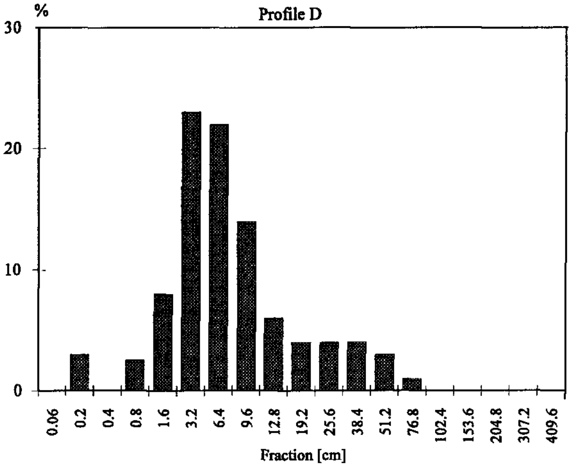


Fig. 9. Grain size distribution in vertical sections C and D (by T. Kalicki)
Ryc. 9. Rozkład uziarnienia w profilach pionowych C i D (oprac. T. Kalicki)

layer includes gravels between 10 and 40 cm in diameter, the middle, 1–1.5 m thick layer — only those of 5–20 cm while the lower layer — again those up to 30–45 cm.

ORIGIN AND AGE OF DEPOSITS IN THE VALLEY BOTTOM

The previous observations just after the 1968 flood (Starkel 1972), the repeated measurements of the shape of the Kalijhora alluvial fan (Froehlich et al. 1989) and the measurements presented above allow one to conclude that all the deposits and forms in the Tista gorge are under control of extreme and annual floods. The 15 m and 5–7 m high terraces represent the boulder bars formed during the 1968 event. The higher one was revegetated and only rarely was built up during higher floods. The lower one may be rewashed and built up again during every year flood. It is not excluded that the paved river channel was partly incised in the gravel-boulder body transported as a hyper-concentrated flows (Costa 1988). These coarse bars now form the channel banks and the main body of the 5–6 m terrace. Annual floods may displace smaller gravels over the channel pavement and form temporal bars (site B).

All these changes do not exclude the presence of older (centuries?, millennia?) residual alluvial fills (site C) or erosional benches. The presence of rapids and erosional kettles just upstream and downstream of this surveyed reach indicate that the downcutting in the river channel is still in progress.

STRUCTURE AND AGE OF THE 60 M HIGH TERRACE

On the right bank of the Tista river, upstream of the Kalijhora creek, a fragment of the 60 m high, about 400 m wide and more than 1,000 m long terrace extends. It is the largest fragment of the high terrace in the whole Tista

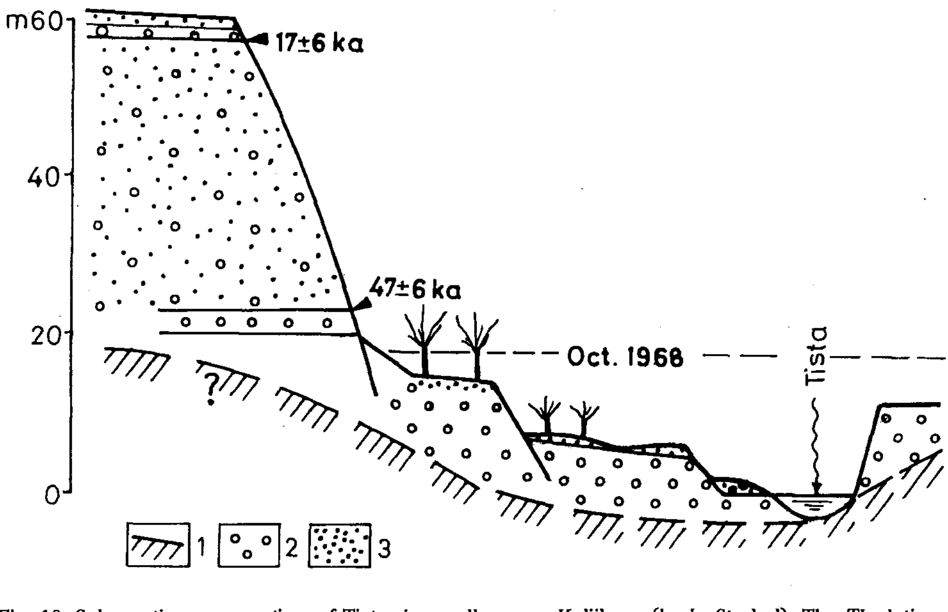


Fig. 10. Schematic cross-section of Tista river valley near Kalijhora (by L. Starkel). The TL datings, extend of 1968 year flood and revegetated portions are indicated. 1 — substratum, 2 — gravels and boulders, 3 — overbank sands

Ryc. 10. Przekrój schematyczny doliny Tisty koło Kalijhory (oprac. L. Starkel). Zaznaczono daty TL, zasięg powodzi 1968 r., części zarośnięte roślinnością. 1 — podłoże, 2 — żwiry i głazy, 3 — piaski facji pozakorytowej

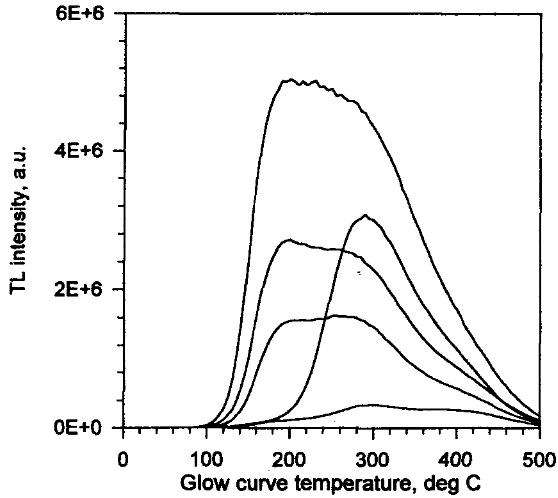


Fig. 11. Examples of TL glow curves taken for the sample K-2. The narrow curve in the middle is the natural TL. The lowest one is the natural TL bleached by the laboratory exposure to the light. The other curves are examples of TL regenerated by a gamma irradiation (by A. Bluszcz)

Ryc. 11. Przykłady krzywych świecenia TL dla próby K-2. Wąska krzywa w środku oznacza naturalną luminescencję. Najniższa krzywa to naturalnie TL zredukowane wybielaniem przez laboratoryjną dawkę promieniowania. Inne krzywe są przykładami TL regenerowanymi przez promieniowanie gamma (oprac. A. Bluszcz)

gorge downstream of the junction with the Great Rangit river. Following the general uplift-downcutting model the presence of the rocky terrace with a thin alluvium on the top might be expected. But in the contrary at its edge there is exposed a very thick alluvial sequence (Fig. 10).

Under 1 m of sandy soil a layer (depth 1–2 m) of sands with coarse gravels up to 10 cm in diameter occurs. Below, to the depth of 37.3 m, the member of sands with fine gravels (to 3 cm) and rare lenses of coarser gravels are found. Two samples of sand for TL dating were taken from the depth of 2 m and 37.3 m. Between 37.3 and 40.0 m there are exposed coarser gravels again. Below, the deluvial cover overlying the 15 m high terrace extends. Probably, somewhere 10–15 m above the present river channel the rocky erosional plain is located because along the river between sites B and D there are exposed steep rocks, several meters high.

THERMOLUMINESCENCE DATING

The TL dating of natural quartz grains contained by sediments under study. An intensity of thermoluminescence of these grains measured under the controlled laboratory conditions reflects the total dose *ED*, of ionizing radiation absorbed by them since the last exposure to the sunlight. The annual dose *d*, i.e. the dose absorbed during one year, depends on the natural radioactivity of the sediment (or the concentration of radioactive elements: U, Th and K).

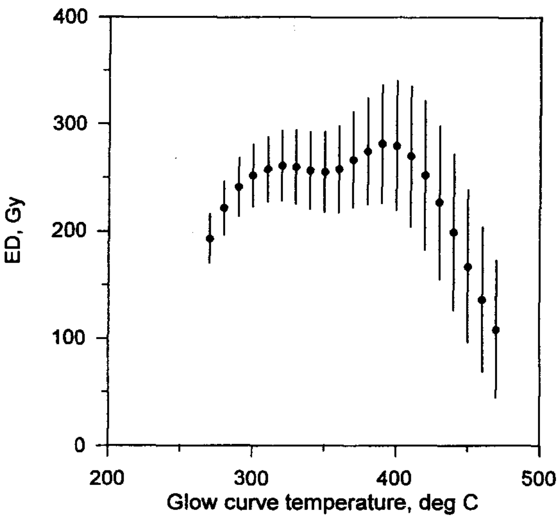


Fig. 12. The plateau test for the sample K-2. *ED* values are plotted against the TL glow curve temperature. The interval between 300° and 400°C gives a reasonably good plateau around 260 Gy (by A. Bluszcz)

Ryc. 12. Test plateau dla próby K-2. Wartość dawki równoważnej *ED* przedstawiono w ich relacji do TL krzywej temperatury. Interwał między 300° a 400° daje stosunkowo dobre plateau około 260 Gy (oprac. A. Bluszcz)

When both *ED* and *d* values are assessed then the TL age is calculated using the formula:

$$T = ED \cdot d^{-1}$$

The dating of sediments is possible because grains are sensitive to the light. An exposure to the sunlight, which usually takes place during weathering, transportation and sedimentation processes, erases the previously acquired TL signal close to the zero level. Thus the TL method dates the last exposure to the sunlight in the sediment's history. This particular moment is usually, but not always, closely related to the formation of the sediment.

The samples underwent the standard laboratory treatment procedures (Bluszcz and Pazdur 1985) preceded by the determination of radionuclides (i.e. U method applied here makes use of dosimetric properties Th, K). After radioactivity measurements were completed, 90–100 μm quartz grains were extracted and etched with 40% HF for 60 minutes at an ambient temperature.

For each sample the measured concentrations of U, Th and K radioisotopes were converted into values of annual doses (Aitken 1983). An attenuation effect of etching was taken into account (Fleming 1979; Mejdahl 1979), also an appropriate allowance for the cosmic ray dose was made (Yokoyama et al. 1982). The average water content, which was estimated on the basis of the measured actual water content, was also taken into account and finally the effective dose rate values (the annual doses) were calculated.

The equivalent doses *ED* were obtained by means of the regeneration method. The natural TL was bleached by an exposure to the laboratory lamp and then regenerated by an irradiation with known gamma doses from the ^{60}Co source. The thermoluminescence of quartz grains was measured by the automated Daybreak TL reader type 1,150. The Figure 11 presents examples of glow curves recorded during these measurements. Results of TL measurements were fitted with an exponential function of the form given below

$$\mathrm{TL}(D) = C - B \cdot \mathrm{e}^{-A \cdot D}$$

where:
TL(*D*) — the thermoluminescence of bleached grains irradiated with the dose *D*;
A, *B*, *C* — function parameters (*C–B* estimates the initial TL while *C* the TL saturation level).

The three parameters *A*, *B* and *C* were found by the non-linear least square regression. *ED* values were then calculated according to the formula

$$NTL = C - B \cdot \mathrm{e}^{-A \cdot ED}$$

where:
NTL — the natural TL value;
ED — the equivalent dose;
others as above.

Calculations of *ED* values were repeated for glow curve temperature intervals (10°C wide), from 270° to 470°C. Basing on these values the plateau tests (see the Figure 12) were constructed for each sample and for each bleaching time. Results which formed better plateau were chosen for further processing yielding the final *ED* values. The sample K-1, sampled at the depth of 2.0 m, gave the TL age of 17 ± 6 ka BP (GdTL-399) and the sample K-2, sampled at the depth of 37.3 m, gave the TL age of 47 ± 6 ka BP (GdTL-400).

The present TL datings indicate that the thick alluvial body of the 60 m high terrace may reflect the increased sediment load during the last cold stage. To explain the formation of such high alluvial terrace two factors should be considered. During the last cold stage the cryonival belt and upper tree line occurred to 1000 metres lower than at present. The production of debris as well as the extents of valley glaciers were much larger. But the formation of the 40 m thick sequence of fine sands and gravels in the lower reach of gorge subjected to uplift and incision, requires one to assume that the aggradation proceeded upstream from the Himalaya foreland. In such circumstances it is not excluded that this aggradation coincided with the phase of weakened or checked uplifting.

FINAL CONCLUSIONS

The characteristics and dating of various alluvial fills in the Kalijhora reach of the Tista river valley in the Darjeeling Himalaya show a very complex course of formation of these fills. In the valley floor of this high energy and narrow mountain river, all types of deposits and forms are affected by extreme floods and are modified by frequently operating processes. It was followed by a continuous formation and destruction of the floodplain adjusting either to frequent or extreme floods. These fluctuations are superimposed on the long-term tendency to downcutting.

The late Pleistocene, 60 m high terrace indicates that this tendency may have been stopped for a longer period, probably due to specific coincidence of increased production of sediments in headwaters and weakened uplifting in the marginal zone.

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STRESZCZENIE

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GRANULOMETRIA I WIEK OSADÓW RZECZNYCH W DNIE DOLINY TISTY KOŁO KALIJHORY, SIKKIMSKIE HIMALAJE

Wcześniejsze badania nad skutkami powodzi z 1968 roku (Starkel 1972) i nad zmianami stożka napływowego bocznego dopływu Kalijhora (Froehlich i in. 1989) wskazywały, że osady i formy w dnie przełomowej doliny Tisty są kształtowane przez ekstremalne i coroczne powodzie. Szczegółowe pomiary granulometryczne w 1993 roku wykazały, że zarówno terasę 15-metrową, jak 5–7 m budują żwiry i otoczaki niekiedy do 1 m średnicy, złożone jako odsypy w czasie wezbrania 1968 roku. Wyższa z nich została później zarośnięta i rzadko bywa nadbudowywana piaskami. Niższa bliżej koryta bywa przemywana, a jej powierzchnia nadsypywana piaskami w czasie corocznych powodzi. Te wezbrania na bruku na skłonach koryta wsypują żwirowo-piaszczysyte odsypy. Równocześnie spotyka się scementowane aluwia starsze, nie odbiegające składem mechanicznym od powstałych w 1968 roku. Cokoły występujące lokalnie w korycie wskazują na kontynuację pogłębiania.

Jedyną wyższą 60 metrową terasę na tym odcinku buduje najmniej 40 metrowa seria piasków i żwirów. Datowania TL wykonane w gliwickim laboratorium dały wiek 17 ± 6 ka BP z głębokości 2 m i 47 ± 6 ka BP z głębokości 37,3 m. Obie daty wskazują na związek z ostatnim okresem zimnym, gdy górna granica lasu i granica wiecznego śniegu były około 1000 m niższe i produkcja rumowiska znacznie wzrosła. Ale obecność tak miąższej i tak drobnoziarnistej serii w odcinku pogłębianym, blisko wylotu z gór, świadczy, że agradacja postępowała w górę doliny, co mogło być ułatwione przez zahamowanie ruchów tektonicznych podnoszących tą część Himalajów.