DISSECTED ROCKSLIDE AND ROCK AVALANCHE DEPOSITS; TIEN SHAN, KYRGYZSTAN

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Abstract

Rockslides and rock avalanches in Northern and Central Tien Shan, that have been deeply dissected by subsequent erosion, or which internal structure was studied in trenches and road cuts, are described. Presence of intensively comminuted debris overlaid by coarse blocky material is found out in most of the case studies. At those cases, where different types of parent rocks outcrop in the rockslide scars, the resultant deposits are composed of the unmixed 'layers' of debris originated from these rock types. Such grain size distribution and unmixing of debris can be considered as typical features of large-scale massive rock slope failures. Basal sliding surfaces with different relationships between rockslide debris and underlying soil can be observed at several sites. Comprehensive study of deeply dissected deposits of rockslides and rock avalanches can shed light on mechanism of their rapid motion and of 'rock' → 'debris' transformation.

1. Introduction

The Tien Shan – one of the largest mountain systems of Central Asia – has many large (10^6-10^8 m^3) and giant ($\geq 10^9$ m^3) massive rock slope failures that form high natural dams and vast aprons of rock avalanches. Numerous rockslides occurred on slopes composed of several types of sedimentary, metamorphic and igneous rocks of Palaeozoic and Precambrian, rarely of Mesozoic and Neogene ages. Sometimes different lithologic units very in colours and can be easily recognised both in the scars and in the resultant deposits. It provides good opportunity to compare mutual position of various types of rocks before and after the emplacement. Some of such rockslides are of especial interest as far as they have been deeply dissected by subsequent erosion. These gorges form giant 'natural trenches', which allow detail study of the internal structure of rockslide deposits. In such cross-sections we can obtain comprehensive information

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about debris grain size composition and its distribution in the rockslide bodies as well as on the structure of basal sliding surface and other boundaries inside rockslide debris. Data that can be obtained by comprehensive study of deeply dissected deposits of rockslides and rock avalanches can shed light on mechanism of their rapid motion and of 'rock' → 'debris' transformation.

2. Case Studies

Hereafter data on the Kokomeren and the Inylchek dissected rockslides (the latter can be classified as rock avalanche), first described few years ago [28, 29] and of several other deeply eroded rockslides and rock avalanches (Figure 1) some of which still await detail research are presented.

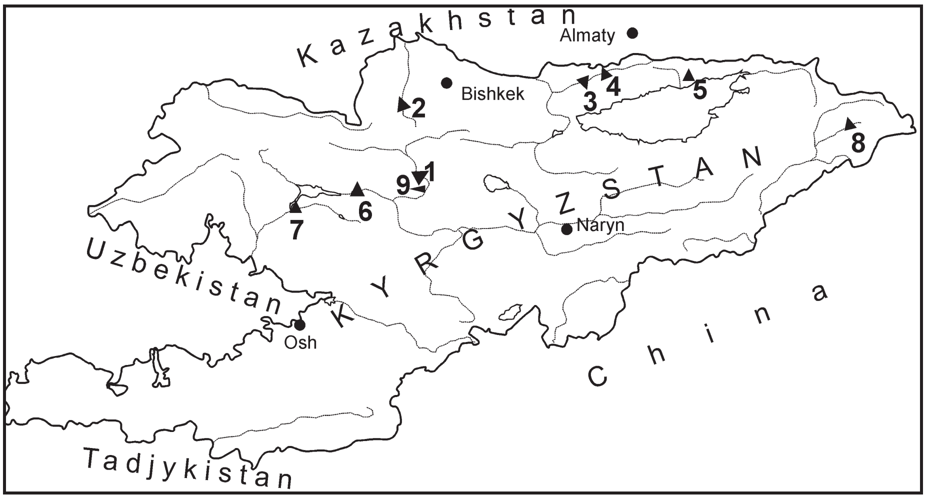

Figure 1. Location of rockslides and rock avalanches in the Kyrgyz Tien Shan described in this paper. Black triangles – rockslides and rock avalanches: 1 – Kokomeren, 2 – Aksu, 3 – Djashilkul, 4 – Bashi-Djaya, 5 – 1911 Ananievo, 6 – Djusumdy-Bulak, 7 – Karakul, 8 – Inylchek and Atdjailau, 9 – "Ancient".

2.1. THE KOKOMEREN ROCKSLIDE

The Pleistocene Kokomeren rockslide (Figure 1, No 1; 41.92º N, 74.23º E) about 1.0 km^3 in volume descended from the left bank of the Kokomeren River 5-7 kilometres downstream from the Kyzyloi intermountain depression and formed a dam up to 400 m high (Figure 2). Subsequently it was dissected by the Kokomeren River that almost completely removed its distal part. It allow to conclude that the lowermost part of rockslide crest was at or near its front, contrary to many other high Tien Shan rockslide blockages, which have been dissected at their proximal parts due to lowering of dam's crests at the feet of the scars from which they descended. Such morphology when distal part is higher, corresponds to the 'primary' morphological type proposed in [30]. Similar 'primary' debris distribution characterises numerous high blockages in Karakoram Himalaya [18, 20], and other well-known rockslide dams such as Köfels in the Tyrolean Alps [16] and Usoi in Pamirs [12].

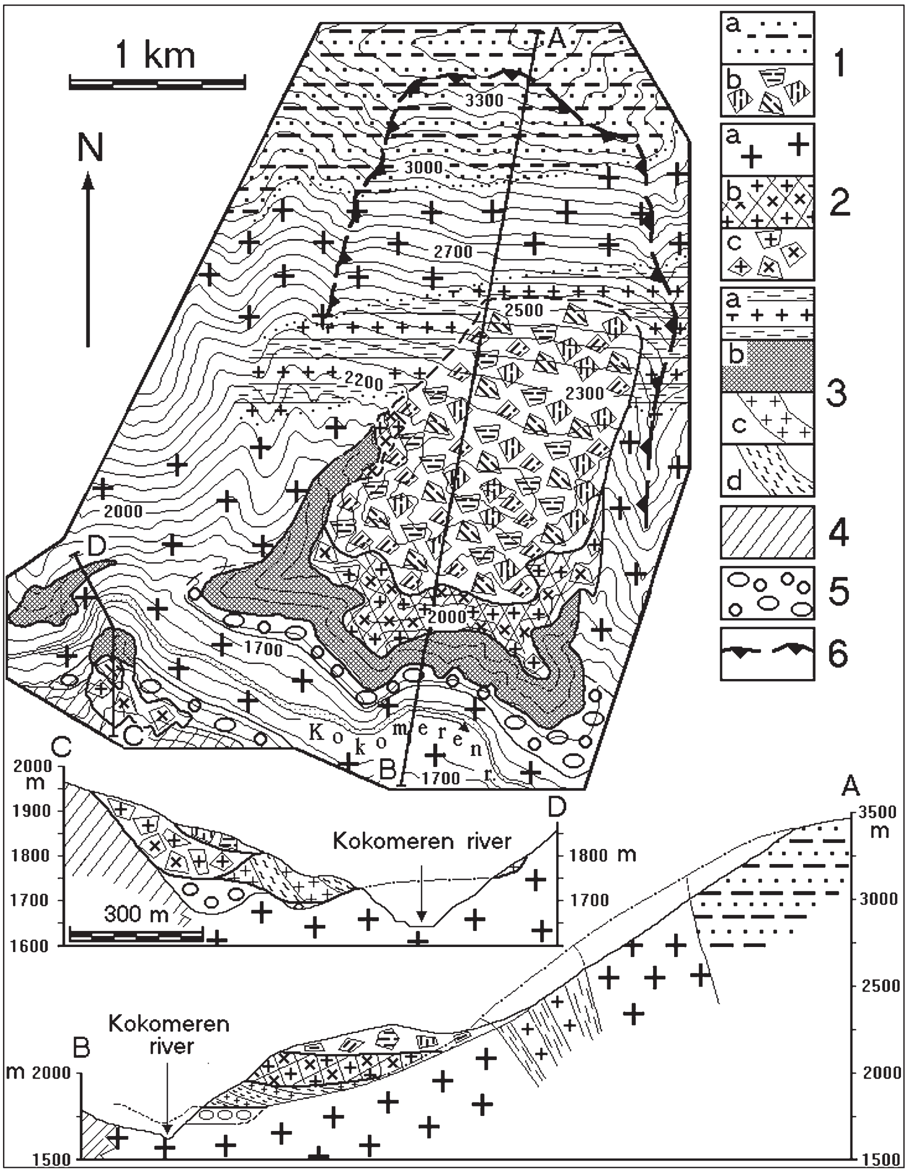

Figure 2. The Kokomeren rockslide (after [28]). Key to legend: 1a - sandstone, 1b - sandstone fragments in rockslide debris; 2a - granite, 2b, c - granite in rockslide debris, forming a huge massif (b) and composed of angular boulders (c); 3a – alternating granite and sandstone, 3b-d - shattered granite and sandstone in rockslide deposits (b - on the map, c, d - on the cross-sections, c - shattered granite, d - shattered sandstone); 4 - limestone, schist and diabase alternation; 5 - alluvium; 6 - rockslide scar.

Thus, the Kokomeren rockslide which lowest part was nearer to the opposite bank of the valley could be considered as rather rare exception. Remaining part of rockslide debris rests on the left bank of the river on a terrace 150m above the riverbed. Frontal part of the dam filled the ancient valley, which was 40m above the present-day riverbed and now only its minor portion remains intact on the right bank of the river just above the road. This portion of debris is easily attainable, while study of the left-bank part of the dam requires crossing of the powerful Kokomeren River.

This rockslide is of particular interest because its internal structure can be investigated in detail due to different colours of rocks involved in the failure [28, 29, 31]. Its 1.6km-high scar exposes (from its top to foot) dark-grey sandstone, reddish granite and granite and sandstone alternation. The same sequence can be observed in the rockslide deposits on both banks of the river. On its left bank the upper part of the dams' body, up to 250 m thick, is composed of tremendous blocks and huge angular boulders of red granite, overlain, in turn, by a 'layer' of blocks and big fragments of dark-grey sandstone. The lower part, up to 150 m thick, consists of 'layers' of intensively comminuted alternating granite and sandstone (see section A-B on figure 2). The same succession occurs in the isolated segment on the right bank of the river (see section C-D on figure 2). The only difference is that at this part upper granite unit is composed of angular boulders up to 2 - 3 meters across while on the left bank – of large block hundreds meters in size (in the lateral direction). It should be pointed out that the boundary between the slightly and the intensively crushed rock units is abrupt, without any transitional zone.

Correspondence of the succession of debris varieties in the rockslide deposit to the lithostratigraphy in the scar, and retention of the bedrock structure show that lower part of the sliding mass, up to 150 m thick, moved as a single unit without internal mixing. Intensively comminuted granite sampled from the lower unit at the right bank of the river has grain-size composition typical of sand (Table 1) with specific gravity of 2.67 - 2.68 g/cm^3 and extremely low coefficient of permeability, comparable with that of clay. The latter was measured in the laboratory after compaction of small amount of debris. Separate particles are angular quartz and feldspar crystal fragments. The smallest particles are mainly the quartz scales, and some bigger quartz grains have conchoidal micro-texture that indicates high local stress in the process of rock crushing.

Table 1. Grain size composition of two samples of shattered granite from the lower zone of the Kokomeren blockage (right bank of the river).

Fractions (mm)	1.0-0.5	0.50-0.25	0.25-0.10	0.10-0.05	0.05-0.01	0.01-0.005	0.005-0.002	0.002-0.001	<0.001
Sample	Content (%)								
1 (M-A)	11,90	27,90	27,60	8,40	17,10	2,70	2,40	0,40	1,60
1(M-D)	6,90	31,60	27,60	10,50	14,10	3,70	0,40	1,60	3,60
2(M-A)	6,40	27,50	24,70	11,20	21,10	3,70	2,40	1,40	1,60
2(M-D)	7,80	24,00	22,50	15,30	17,10	4,60	1,40	2,50	4,80

M-A - micro-aggregate grain size composition (material is shaken in distilled water), M-D - grain size composition of maximum dispergated sample (material is boiled in water with sodium pyrophosfate).

Similar, though slightly coarser grain-size distribution and particle's shape was reported for the matrix of several Karakoram rockslide deposits [17, 18] and by for the lower part of Falling Mountain rock avalanche (M. McSaveney, Personal Communication, 2002). Such an extent of shattering significantly exceeds values calculated, according to formulas adduced by Azarkovitch & Pokrovsky [1] for blast-fill dams, that take into account the initial bedrock fragmentation and crushing caused by explosion, collapse and dynamic compression. Therefore we can assume that debris comminution in natural large-scale rockslides should be produced by some additional forces, more powerful than above mentioned, affecting thick lower portion of rockslide debris as a whole. Very small difference between micro-aggregate grain size composition and grain size composition of maximum dispergated samples indicates absence of clayey minerals and, therefore, allow to eliminate possibility of rockslide debris fragmentation due to its subsequent *in-situ* weathering.

2.2. THE AKSU ROCKSLIDE

One more giant prehistoric rockslide about 10^9 m^3 in volume is located in the Aksu River valley on the northern slope of the Kyrgyz Range, 60-km Southwest from the Bishkek City (Figure 1, No 2; 42.54º N, 74.00º E). Its 1.5km-high and 2km-wide scar exposes Palaeozoic granites in its lower and central parts and Ordovician terrigenous deposits in its upper part (Figure 3). The rockslide formed a dam, which highest part is about 450 m above present-day riverbed, with well-pronounced transverse levees on its surface indicating, as we hypothesise, successive overthrusting of moving portions of debris. Rockslide dam has been completely dissected at its proximal part. It gives an excellent opportunity to study its internal structure, and to compare mutual position and extent of comminution of debris formed from granites and from sedimentary rocks.

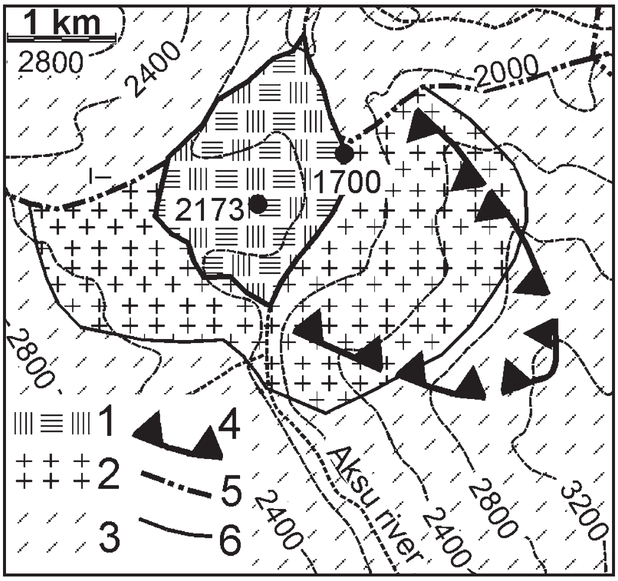

Figure 3. Geological sketch of the Aksu rockslide. Key to legend: 1 – rockslide deposits; 2 – Palaeozoic granites; 3 – Ordovician terrigenous rocks; 4 – rockslide scar; 5 – faults; 6 – geological boundaries (according to 1:200 000 state geological maps [5, 26]); dark circles – points on top and near the base of the deposit with elevations.

2.3. THE DJASHILKUL ROCKSLIDE

Natural dam 150-200 million m^3 in volume and up to 200 m high, blocked the Chon-Kemin River valley and its right tributary where the small Djashilkul Lake still exists (Figure 1, No 3; 42.79º N, 76.37º E). It is similar in shape to the Aksu rockslide, though not so large. Blockage was almost completely dissected by Chon Kemin River at the foot of the scar, just in the same way as in the Aksu case (Figure 4). Since very limited amount of the lacustrain deposits (no more than 5-8 m) presents upstream, the dam seems to have been breached rather soon after its formation. Rockslide descended from the right bank of the Chon-Kemin valley where the bedrock is Middle Riphean green-schist (R_2 in figure 4). Its debris differs significantly from the Palaeozoic red granite that forms the right bank of the valley. Large angular boulders cover rockslide surface while intensively crushed rock debris, similar to what was described at the Kokomeren blockage, forms its internal part. Two other large-scale rockslides are located few kilometres north and south from the Djashilkul blockage. This area lies within the epicentral zone of the 1911 Kemin (M8.2) earthquake [4, 9] and we can expect that all these pre-historic collapses were caused by one or by several preceding strong earthquakes.

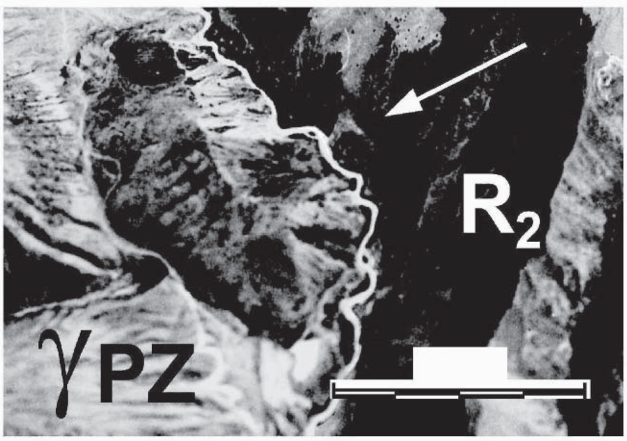

Figure 4. The Djashilkul rockslide dam in the Chon-Kemin River valley. Fragment of high-resolution space photograph. Arrow indicates direction of slope failure. γPZ – Paleozoic granite, R_2 – Riphean metasediments.

2.4. THE BASHI-DJAYA ROCKSLIDE

One more deeply dissected rockslide fell from the right slope of the Chon-Kemin valley near the mouth of the Bashi-Djaya River (Figure 1, No 4; 42.87º N, 76.66º E) composed of amphibolite. Internal structure of the main part of the dam can be observed in the river gorge, and it is clearly seen that high extent of comminution is typical of debris which originated from the hard rock.

Frontal part of the dam rises about 160 m above the riverbed and in a road cut it is clearly seen how debris overlies the terminal Q_{III} moraine (Figure 5, 6). Previously moraine was erroneously considered as more recent in respect of rockslide [8]. ^{14}C AMS date of a paleosol developed on the moraine and buried by the Bashi-Djaya rock-slide debris gave an age of 7000-7950 BP [9] (6400-4600 BC with 95.4 % probability according to [7]. Distal part of rockslide outcropping here is composed of angular fragments about 1-3 cm in size on an average at its base and of coarser fragments up to 20-30 cm few meters higher. It should be noted that it is rather rare case when buried soil can be observed under rockslide debris. Its study helps to understand how moving debris affect underlying surface. In this case, in particular, blocks of dark brown organic-rich soil are overthrusted by blocks of the subsoil loam (see figure 6) and all the succession is cut off by rockslide debris. Such involvement of soil in the motion of the rockslide distal part indicates that friction along the basal surface of rockslide was higher than shear strength of soil. It seems that debris 'pulled' underlying soil creating such micro-thrusts and simultaneously cut off forming soil protrusions. Of course, we can not exclude that landslide also pushed soil layer somewhere left from the outcrop shown on figure 5, but in any case soil was partially involved in rockslide motion.

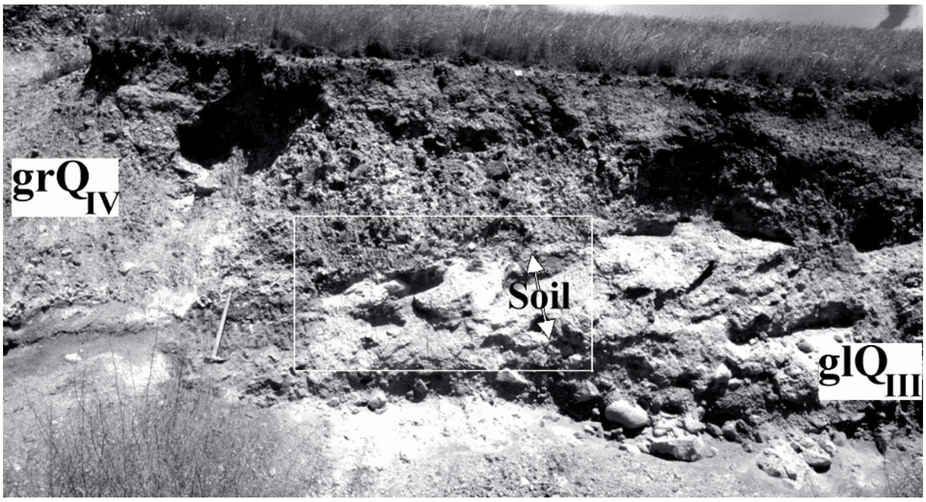

Figure 5. Bashi-Djaya rockslide debris overlaying paleosol developed on the moraine deposits. White rectangular marks the area shown on figure 6. Debris moved generally from left to right. See hammer for scale. grQ_{IV} – the Holocene rockslide debris; glQ_{III} – the Upper Pleistocene moraine.

2.5. THE 1911 ANANIEVO ROCKSLIDE

More complex interaction of moving debris and underlying loose material was found out at the Ananievo rockslide (Figure 1, No 5; 42.8º N, 77.62º E) triggered by the 1911 M8.2 Kemin earthquake [4]. Light-coloured granites outcrop in its triangular scar, 250m-high and more than 600m-wide at its base. Failure took place just above a thrust, gently dipping towards the north-east, ruptured in this earthquake [9, 15]. The landslide body about 40×10^6 m^3 in volume is up to 100 m thick and covers an area 800 m long and 600 m wide. Its southern front is high and steep, indicating an abrupt halt without impact against any visible obstacle. The rockslide deposit is of crushed granite, with huge blocks just below the scar and in the uppermost part of the body. In front of the granite debris at its southern limit there is a shelf 7 to 10 m high composed of a loamy material from loose deposits resting at the slope foot (Figure 7).

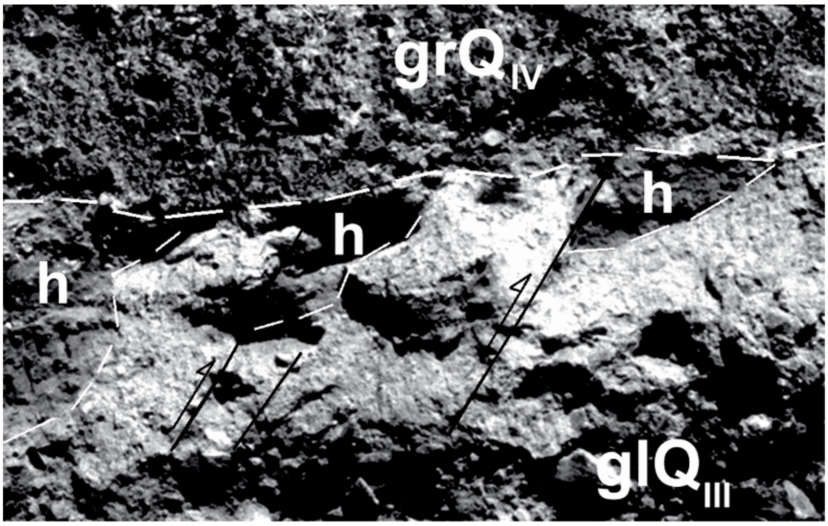

Figure 6. Minor reverse faults in the soil layer below Bashi-Djaya rockslide debris base. **h** – humus-rich blocks have more dark colour while subsoil loam – light colour. For position and indexes see figure 5.

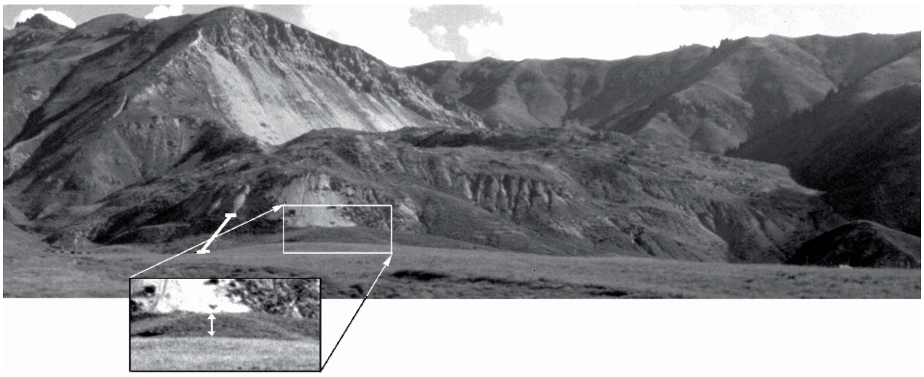

Figure 7. The Ananievo rockslide. View from south. Loamy shelf at the foot of rockslide body is marked by arrow on the inset. White bold line corresponds to the profile shown on figure 8-a.

In contrast to other described case studies this rockslide is not dissected by erosion but we made several trenches through the lower part of its southern slope, that allow to observe debris-soil relationships (Figure 8). It is clearly seen that moving debris scraped loose weak material and pushed it in front of rockslide body as a bulldozer (trench B on figure 8). On the other hand, large fragments of buried soil and loamy subsoil sand overlain by crushed granite were found above this accumulation of underlying material (trench A on figure 8). Thus at the rockslide front thrusting occurred above the basal sliding surface so that the overall geometry of the front can be described as a duplexlike structure [15]. At the immediate front of landslide mixture of humus-rich soil and subsoil loamy sand rests above continuous soil layer that was not affected by rockslide (trench C on figure 8). We hypothesise that it was just such "bulldozing" effect that reduced runout of this rockslide.

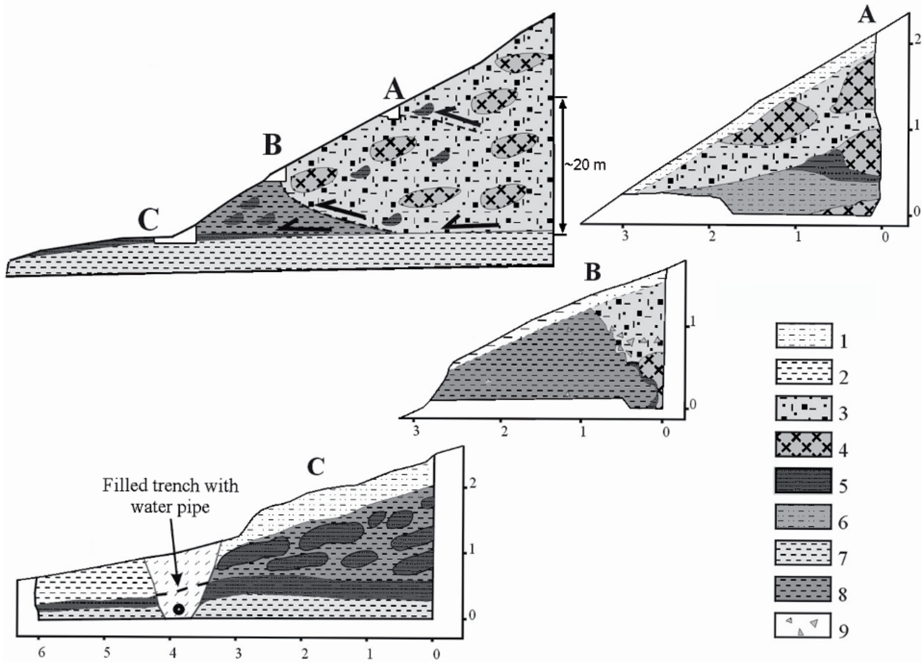

Figure 8. Structure of the southern foot of the Ananievo rockslide. Top left - schematic cross-section with location of trenches A, B, C, which logs are shown in details. Key to legend: 1 – modern scree, 2 – white compact loam, 3 – crushed gray granite - arenites, 4 – blocks and boulders of pink granite, 5 – buried soil, 6 – brown subsoil loamy sand, 7 – white subsoil loam (*in situ*), 8 – light brown loam, 9 – small granite fragments.

2.6. THE DJUZUMDY-BULAK ROCKS AVALANCHES

One more deeply eroded rockslide dam is located in the Naryn River valley, at the mouth of the Djuzumdy-Bulak creek, 10 km to the east from the bridge across the Naryn River on the Bishkek-Osh highway (Figure 1, No 6; 41.78º N, 73.40º E). Here large-scale failures occurred twice, presumably in the Late Pleistocene and in the Holocene. Older avalanche deposits rest on terraces 60-110 m high and it seems that moving debris 'climbed' from terrace to terrace as on giant footsteps. Contrary, younger rock avalanche forms more compact dam 80-100 m high that filled river valley at the foot of the scar (Figure 9). Modern valley was cut through this body at its proximal part and its internal structure can be observed in the gorge. Both times failure occurred from the slope where folded Neogen sandstone and conglomerate are clamped between two blocks of Palaeozoic basement. Neogene is separated from Paleozoic units by large neotectonic faults with wide zones of cataclastic rocks. There are clear evidences of the Late Holocene rupturing along these faults. We assume that last rupturing event about

50 BC – 140 AD caused the formation of younger Djuzumdy-Bulak rock avalanche [3]. Recently, during 1992 Suusamyr earthquake, smaller landslide from the same scar also dammed the Naryn River for a short time.

Both Djusumdy-Bulak rock avalanches are composed mainly of cataclastic rocks of the above mentioned wide fault zones and, partially, of Neogene deposits. Evidently material of fault zones have been intensively shattered *in situ* long ago before collapse. It significantly differs these slope failures from most of other rockslides described above and hereafter. Deposits of both older and younger rock avalanches are composed of rather fine material practically for all their thickness. Large blocks of cataclastic rocks that could present on the surface of the older avalanche were strongly weathered and practically can not be recognised at present. Contrary, in the river cut where it dissects the younger dam we can see clear 'stratification' of debris. Several 'layers' of coarse material could be selected in the upper part and on top of this sequence (Figure 10, unit A), while in its lower part debris is very intensively shattered and looks as if it 'flowed' (Figure 10, unit B).

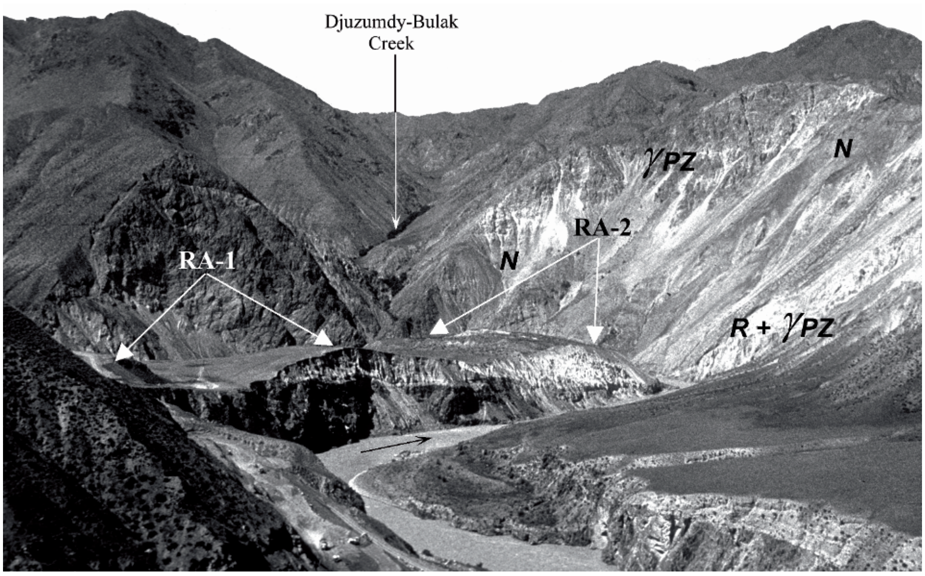

Figure 9. Successive rock avalanches (RA-1 and RA-2) in the Naryn River valley at the mouth of the Djusumdy-Bulak Creek. Dark-grey zone with smooth micro-relief that crosses the scar is composed of Neogene deposits (*N*), while more rugged parts correspond to the tectonically comminuted Palaeozoic granite (*γPZ*) and Riphean metasediments (*R*).

2.7. THE KARAKUL ROCKSLIDE

Three large rockslides descended from the high and steep north-western slope of the Eastern Karasu River valley (Figure 11). Remnants of older rockslide deposits marked as D-1 (41.66º N, 72.70º E) and D-2 (41.65º N, 72.66º E) on figure 11, could be seen 350-500 m above present-day valley bottom. These failures occurred from the slope composed of the more or less uniform lithology - Devonian limestone. The most recent Karakul rockslide (Figure 1, No 7, 41.63º N, 72.63º E, D-3 on figure 11) formed a 300m-high dam exactly at the mouth of the Eastern Karasu [24]. It blocked Eastern Karasu and, partially, Naryn River valley 3 km downstream of the present-day Toktogul dam site. While the powerful Naryn River cut the blockages slope to expose a good section through the rockslide deposit, the much smaller Karasu River found its new way around the blockage. Thus, the dammed lake was filled with alluvial and lacustrine deposits more than 100 m thick on which Karakul town was built. Hypothetically frontal parts of older rockslides (No 1 and 2 on figure 11) are buried under this lake fill [24].

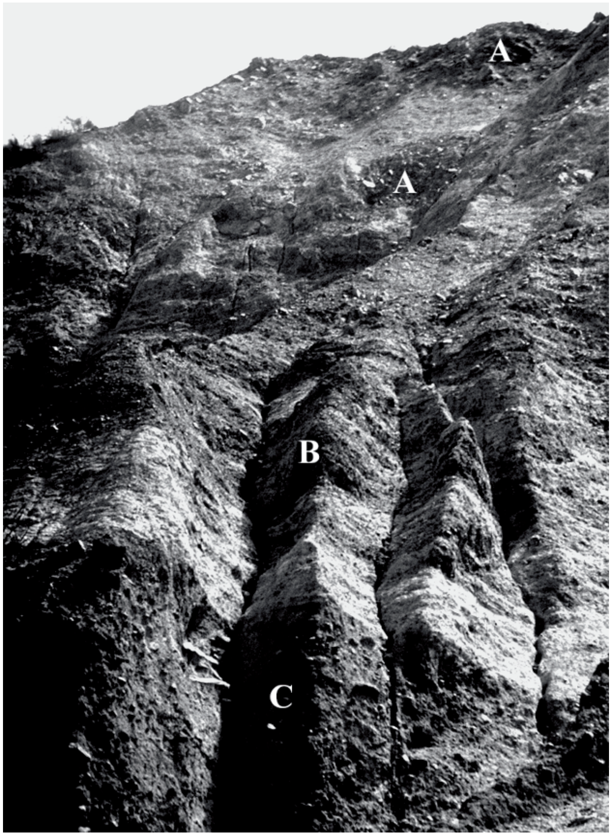

Figure 10. Succession of "strata" in the younger Djusumdy-Bulak rock avalanche debris in the Naryn River gorge (this outcrop is about 30 m high). Take note of comminuted layered debris of the lower part of the deposits (B) and of its mainly blocky upper part (A) with interbeds of comminuted material. The lowermost part of the outcrop (C) probably is composed of the pre-rockslide debris-flow deposits.

Visible part of the Karakul rockslide scar is composed of light (white and yellowish) Devonian limestone that form 400m high cliff above hilly surface of rockslide. But this failure also involved Permian red sandstone, siltstone and conglomerate that form the slope's foot and the base on which rockslide deposits rest. These units are divided by the Karasu reverse fault dipping 50-70 degrees to the north-west. Since rocks involved in a slope failure have different colours, it will be easy to study mutual position of corresponding debris units and to reconstruct displacement mechanism. According to Matveev's interpretation [24] based on the fact that rockslide debris overlaid different levels of pre-rockslide topography, failure at this site occurred several times during Quaternary period. However, we think that such debris distribution could be produced by a single-event rockslide that filled the deep gorge of Karasu River and splashed over its left bank similar to the Avalanche Lake rock avalanche in the Mackenzie Mountains [11] or Lettopalena rock avalanche in the Apennines [27].

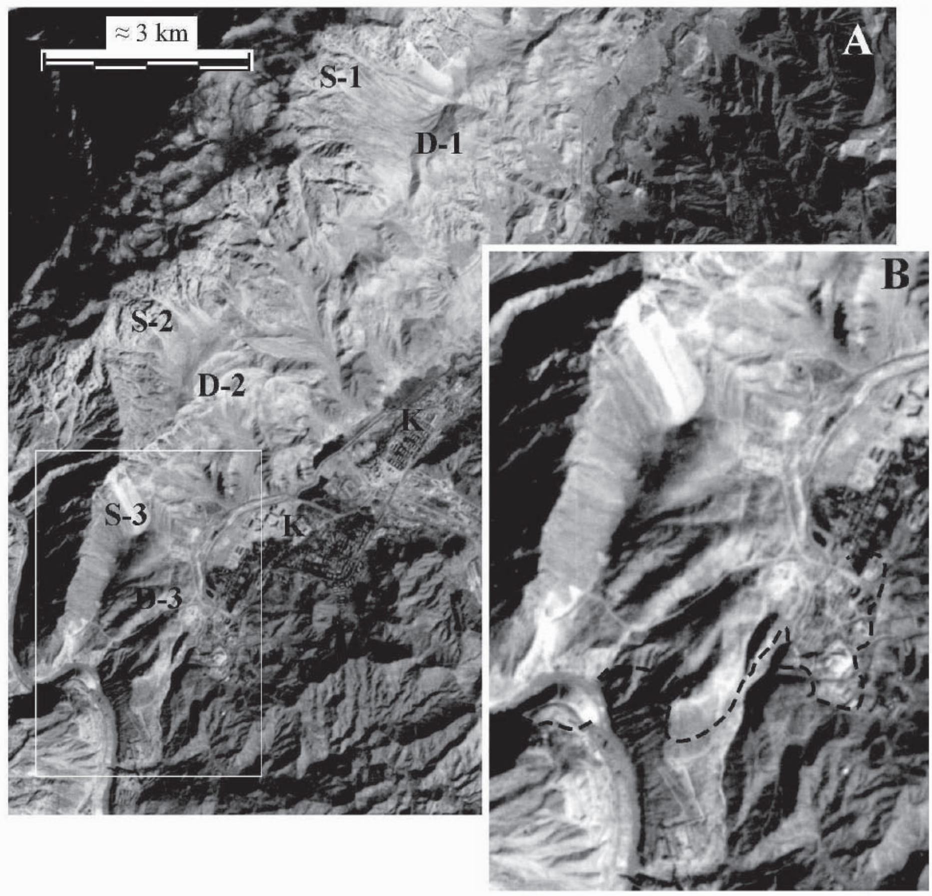

Figure 11. Rockslides near Karakul town (K). A - Part of high-resolution space photograph. B - Enlarged inset showing the morphology of the Karakul rockslide corresponds to the area bounded by white rectangular. S – rockslide scars; D – rockslide deposits. Dotted line on the inset – approximate front of the rockslide debris.

2.8. THE INILCHEK ROCKSLIDE

The Inylchek rockslide (42.17º N, 79.45º E) about 50×10^6 m^3 in volume in the eastern part of Kyrgyzstan (Figure 1, No 8, Figure 12) is a classical example of a stratified rock avalanche [28, 29]. Its deposits up to 70m-thick consist of layers of fragments of the rocks that outcrop in its scar, preserving the same succession from top to bottom – black limestone, black schist and red granite (Figure 13). An 'interlayer' of granite fragments lies between the 'layers' of limestone and schist fragments (2* on figure 13) and the same granite vein was recognised in the scar (Figure 14). Predominant part of debris is rubble-size diamicton, while the uppermost part of the upper unit composed of black limestone debris include large amount of angular boulders of bigger size. Rockslide scar is crossed by several surface ruptures of the Inylchek active fault zone that support the assumption of its seismic origin. The age of this failure can be estimated as Holocene since rock avalanche deposits overlay frontal part of the older Atdjailau rock avalanche (42.15º N, 79.45º E) that fell from the opposite slope of the Inylchek valley (see figure 13) and, in its turn, rests on the recent flood plain. Between the deposits of the Atdjailau and the Inylchek rock avalanches there is about 8 meters of alluvial pebbles with loess-like loam interbed transformed into large 'spherulites' more than 1 m in diameter, composed of compressed, cracked loam (Figure 15). It looks as the Inylchek rockslide debris struck the alluvium, compressed and deformed it. The same unit is seen on figure13 beneath red granite debris in the incision in the Atdjailau rock avalanche deposits. We must note that origin of these alluvial deposits is questionable. It can be hypothesised that they were accumulated due to complete blocking of the Inylchek River by Atdjailau rock avalanche which front could reach opposite (right) bank of the valley. Now this part is covered by the Inylchek rock avalanche debris.

In contrast to the Inylchek rock avalanche, the Atdjailau rock avalanche descended from the slope composed basically of the limestone of Palaeozoic age and, very locally, of black shale underlying limestone layer. This rock avalanche is of the 'spread' type [30] with proximal part about 100 m thick accumulated at the scar’s foot and 10-20 m thick ‘pancake-shape’ apron about 1200 m in a radius. Its large portion is now eroded and in the cliffs we can see mixture of limestone and, rarely, shale angular boulders and debris in the pulverised limestone matrix. It is the rare case without distinct evidences of more intensive comminution of the basal portion of debris – practically whole outcrops are composed of angular boulders with rather small amount of matrix. We hypothesise that it could be due to specific mechanism typical of 'spread' rock avalanches which frontal part is crushed by following portion of the descending rock mass and squeezed out.

2.9. THE "ANCIENT" ROCK AVALANCHE

Good example of the completely dissected long-runout rock avalanche with expressive stratification of debris is the "Ancient" Pleistocene event about $20\text{-}40\times10^6$ m^3 in volume (Figure 1, No 9; 41.89º N, 74.25º E). It descended from the slope composed of granites of different types and rests on the right bank of the Kokomeren River approximately 3 km downstream from the Kokomeren rockslide.

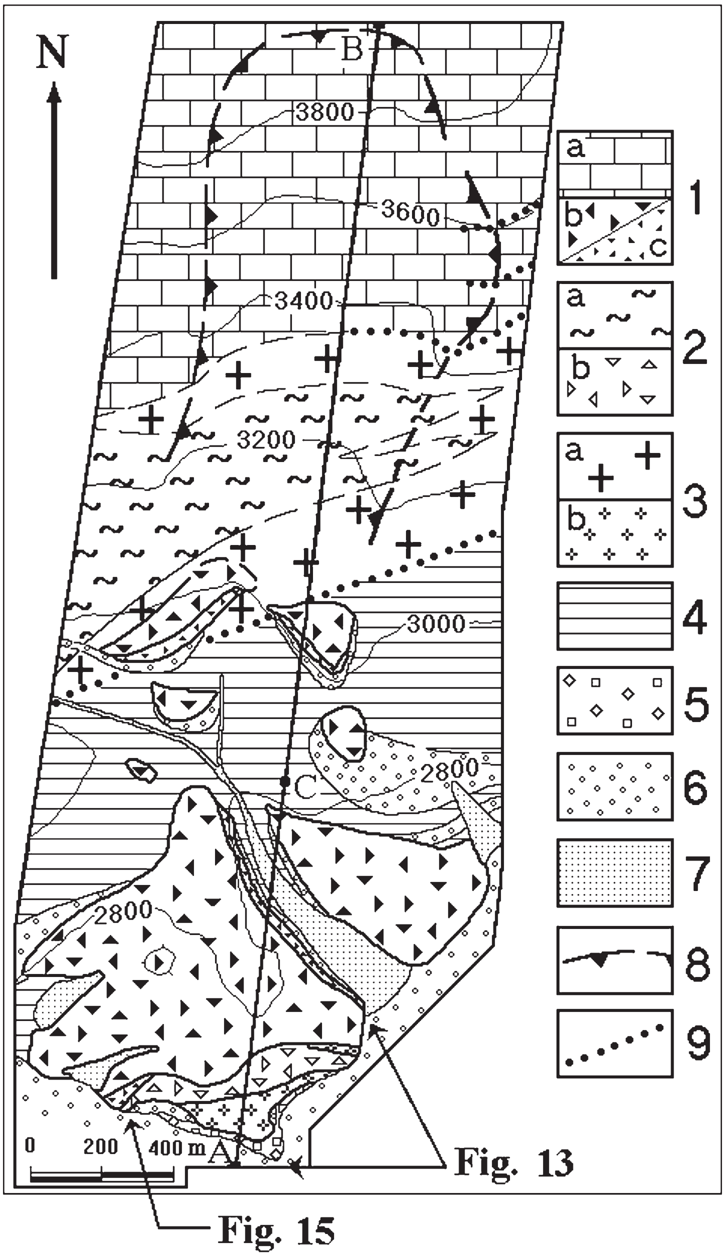

Figure 12. Schematic geological map of the Inylchek rock avalanche. 1a – limestone, 1b, c – limestone debris, crushed into large blocks (b) and into rubble-size fragments (c); 2a – shist, 2b – shist debris; 3a – granite, 3b – granite debris; 4 – sandstone and slate; 5 – older rockslide that originated from the opposite slope of the Inylchek valley; 6 – river flood plane and terraces; 8 – rockslide scar; 9 – surface ruptures.

Figure 13. Deposits of the Inylchek rock avalanche (moved from right – white arrow) overlaying distal part of the Atdjailau rock avalanche (moved from left – black arrow). 1 – white limestone debris (Atdjailau rock avalanche deposits), 2 and 2* – red granite debris, 3 – greenish schist debris, 4 – black limestone debris, a – alluvium.

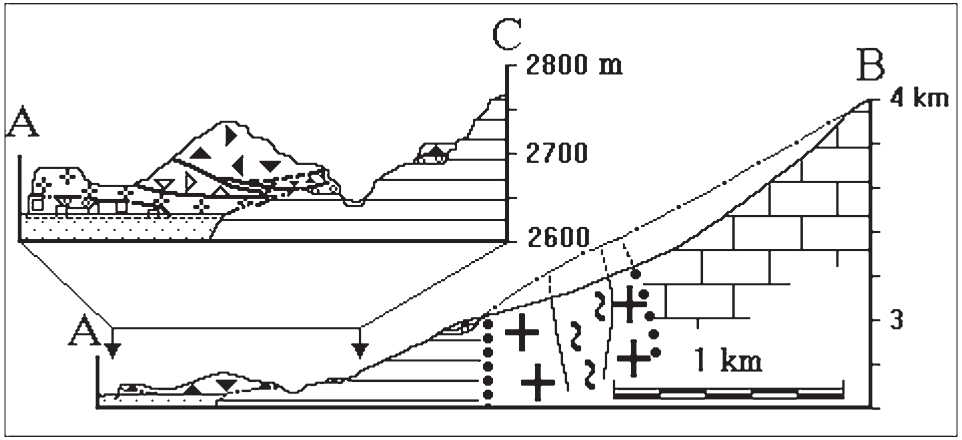

Figure 14. Schematic cross-section of the Inylchek rock avalanche. Position of the profile and key to legend see on figure 12.

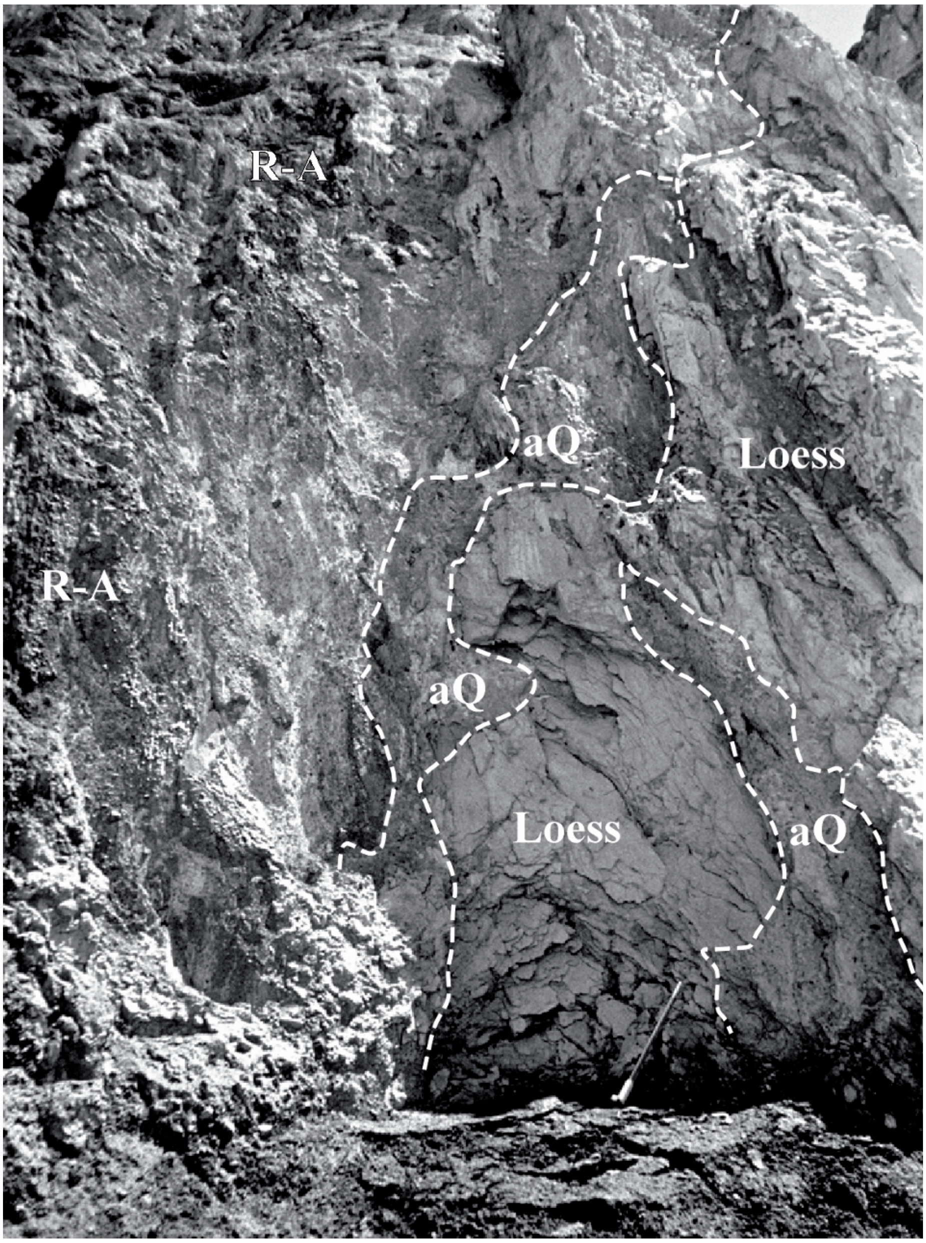

Figure 15. The contact between the Inylchek rock avalanche debris (R-A) and underlying alluvium (aQ) with large 'spherulites' composed of compressed, cracked loess-like loam. Handle of the geological hammer at the lower part of photograph is 60cm-long. Rock avalanche moved generally from left to right. The basal surface of the overlaying rockslide debris is nearly vertical.

Rock avalanche moved at least 2.5 km from the foot of the scar and formed deposits up to 50-100 m thick. Part of rock avalanche that remains after erosion rests on the terrace about 300 m above present-day riverbed of the Kokomeren River and forms a smooth terrace-like surface. Its lower 20-30m unit is composed of intensively crushed macadam-size debris, mainly of grey granite with several "interbeds" of debris of different colour while the upper 30-70 m – of angular boulders of red gneissoid granite up to 1-2 m in size (Figure 16). The abrupt boundary between these layers may be traced for at least 800 m [29].

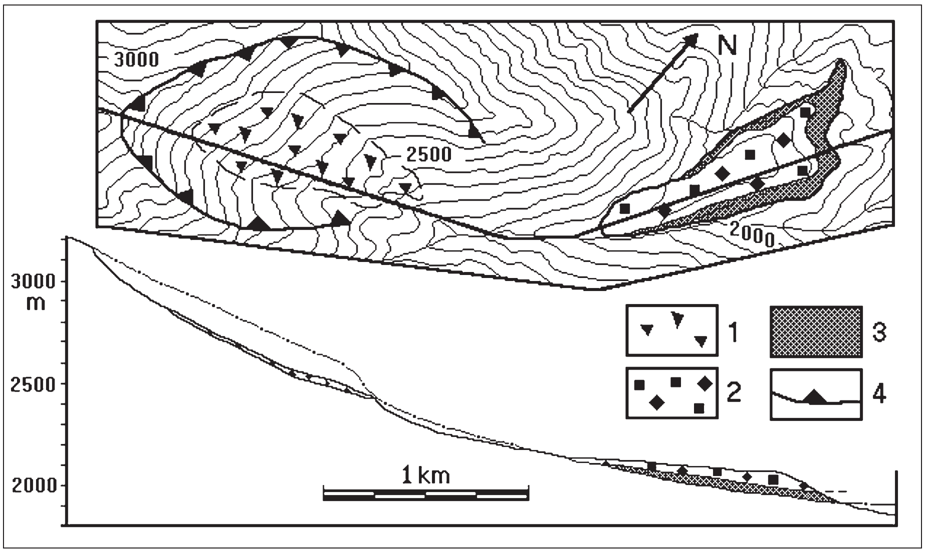

Figure 16. Schematic map and cross-section of the Ancient rock avalanche in the Kokomeren River valley. Key to legend: 1 – debris remaining in the scar, 2 – angular boulders of red gneissoid granite, 3 – crushed grey granite, 4 –scar limits.

3. Discussion

Even limited observations on the internal structure of the above rockslides and rock avalanches show that most of them are characterised by significant comminution of debris in the lower/internal parts of deposits, in some cases up to grain size composition typical of sand. Contrary, their upper/external parts are composed of angular boulders up to several meters across and, rarely, of fractured blocks extending for hundreds meters in lateral direction. Such grain size distribution is typical both of compact blockages that form high natural dams and of long-runout rock avalanches forming vast thin aprons. The same grain size distribution was described repeatedly in other case studies from different mountainous regions [18, 20, 21].

The comminuted internal parts of high natural dams must form practically impermeable dams' cores. This assumption is supported by data on the Usoi dam – the largest historical blockage more than 500 m high where infiltration takes place only through the uppermost part of the dam and springs appear about 140 m below lake water level [12, 25].

Other feature typical of most of described case studies is the absence of mixing of different lithologic units in the debris that traveled several kilometers before it came to a halt. "Layers" of rock fragments shattered at a different extent, each consisting of a specific lithologic type of rocks could be observed everywhere where different types of rocks have been involved in the failure. Similar “stratification” has been observed by Johnson at the Blackhawk rock avalanche [21] and by Hewitt at numerous Karakoram events [17, 18, 19, 20]. At the Kokomeren, Inylchek and "Ancient" rock avalanches we can clearly see the same succession of lithostratigraphic units in the debris as observed in the scar [28, 29]. It should be pointed out that debris produced from rocks, which rested at the lower part of the slope and formed the frontal part of the displaced massif, have been found not at the distal parts of rockslide/rock avalanche bodies (as it should be in case of real retention of rock type succession), but at their lower parts, being overlaid by the 'layers' of debris, which parent rocks outcrop higher in the scars. Just the same was observed at the Naltar, Nomal and Batkor rock avalanches in Karakoram [19]. Such peculiarities of the internal structure of rockslide deposits indicate that portions of sliding rock mass that had bigger specific potential energy (descended from the higher part of the slope) overrun and overlay those portions that originated from the lower parts of the slope. It is still questionable why such overrunning occur just along lithologic boundaries. One more conclusion that can be made from these observations, supplemented with data on retention of large-scale original structure of rocks (such as have been described by Erismann [10]) is that large portions of debris move like a single unit, undergoing comminution without significant relative displacements of separate rock fragments. As noted by Hewitt [17], millions of cubic metres of fines have been produced in the moving Bualtar rock avalanche within few minutes. The same process should take place in the above Tien Shan cases.

Very interesting results could be obtained from the analysis of basal surfaces of rockslides and of well-pronounced boundaries between different units selected in the rockslide deposits that can be observed in deeply eroded rockslides. Direct observations of these elements allow better understanding of boundary processes. We can directly check reliability of different models proposed to explain high mobility of long runout rock avalanches, which are based on presence of different 'lubricants' such as air [22], melted rock [10] or evaporated water [14] or on 'pure' mechanical processes such as granular flow [2, 6], basal pressure wave [23] or basal shearing [13]. Realisation of any model must result in different structure of the basal layer and of underlying substratum where fingerprints of really acting processes must present.

These studies in Tien Shan are at their starting point. Debris-soil interaction described above at the Bashi-Djaya rockslide indicates partial involvement of underlying soil in rockslide motion and afterward shearing of those parts of soil layer which protrude up in the debris. These observations are, generally, in line with the model, proposed by Grigorian [13], according to which that of two interacting media (debris and substratum) undergo destruction, which shear strength is smaller. We hope it will be also possible to check, if mechanism based on Bagnold's model [2] really take place along the basal sliding surface. On the other hand, as exemplified by the Ananievo case, scrapping of loose material and its accumulation in front of moving rockslide can significantly reduce its mobility.

Presence of 'layers' of intensively shattered and pulverised debris between units composed of coarse diamictons indicate shearing caused by mutual displacements of 'layers' inside moving debris similar to what was described in Karakoram by Hewitt [20].

4. Conclusions

Rockslides and rock avalanches with deeply dissected deposits should be considered as the most interesting cases, which can provide unique information about internal structure, content and mechanical properties of rockslide debris. Of the especial interest are those cases where failure occurred from slopes, composed of different lithologies, such as the Kokomeren rockslide and the Inylchek rock avalanche. The fact that most of the described above case studies, as well as numerous examples in the Alps, Karakoram, New Zealand and other mountainous regions have the same characteristic features – intensively comminuted debris of the lower/internal parts overlaid by blocky facies that blanket it and the absence of mixing of different lithologies in the rockslide debris – allow to consider these peculiarities as universal features, reflecting some basic processes acting during rockslide formation and motion.

Other features peculiar of one or several case studies may reflect processes that underwent in the specific conditions. They can be used as classification criteria and their analysis can shed light on the mechanism of rockslide debris motion.

Large variety of morphological, structural and lithologic patterns of the Tien Shan rockslides and rock avalanches, especially of deeply dissected events, perfect exposure due to arid climate and attainability of sites makes this region an excellent natural laboratory for such investigations.

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