Chapter 3
Criteria of the Prehistoric Rock Avalanches Identification and Discrimination

Alexander Strom

Abstract Rock avalanches (dry granular flows) are one of the most disastrous types of landslides. They could be distinguished from other types of slope processes based on the specific combination of morphological and sedimentological characteristics. Such combination allows their recognition both on the space images and in the field and distinguishing them from the deposits left by glaciers, rock glaciers, and extreme debris flows that can occur in the presence of the "intermediate" agent of water or ice. Morphological identification of rock avalanches becomes more problematic for older features significantly reworked by erosion. Their correct identification and differentiation is critically important for both landslide and seismic hazard assessment since rock avalanches, unlike other phenomena listed above, often occur being triggered by large earthquakes. The proposed chapter describes the basic criteria allowing well–grounded identification of the prehistoric rock avalanches and distinguishing their deposits from moraines and debris flow fans. They are exemplified by case studies from Central Asia and the Himalayas.

Keywords Rock Avalanche · Morphology · Grain size composition · Central Asia · Himalaya

3.1 Introduction

Rock avalanches, defined as "extremely rapid, massive, the flow-like motion of fragmented rock from a large rock slide or rockfall" (Hungr et al. 2014) are the most disastrous type of landslides in mountainous regions due to their extreme runout and the possibility of rivers' damming. The extreme destructiveness of such events makes the correct assessment of associated hazards and risks to be one of the most important tasks of landslide studies in high mountains. Such review requires, in particular, good knowledge of similar phenomena that had occurred in the study region in the past. Considering that rock avalanches occur rather rarely, "in the past" means

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the historical period and the entire Holocene and even Late Pleistocene. The rock avalanche inventories compiled for such an extended period provide, besides input data for susceptibility analysis, statistical data allowing a better understanding of the regularities of these hazardous natural phenomena. Quite often, well-grounded identification of such objects can be made just by visual interpretation of space images, especially allowing 3D visualization (either stereoscopic or combined with more or less detailed digital elevation models). Their characteristic features are: (1) the concave headscarp on the slope, (2) debris accumulation at its base, and sometimes, (3) evidence of the existing, infilled, or breached dammed lake. Examples of such easily identifiable rock avalanche dams are shown in Fig. 3.1, which demonstrates the rock avalanches in Fergana Range (Tien Shan), about 25 Mm^3 in volume for the northern one that dammed a small valley. It has distinct headscarp below elevation mark 2,080 m a.s.l., partially eroded dam more than 150 m high, and completely silted dammed lake upstream. Debris of the southern rock avalanche, about 40 Mm^3 in volume, moved up to elevation mark 1,430 nm a.s.l. Also, Fig. 3.2 demonstrates the Panjai-Mard rock avalanche, about 100 Mm^3 in volume at in Afghan Badakhshan. Headscarp is marked by red arrows, rock avalanche front by yellow arrows. The rock avalanche dammed a small river valley, and this dammed lake was silted completely, while a small water body in the dammed creek mouth still exists.

However, such univocal interpretation may not be so obvious in many other cases. In the next sections, several complicated cases, mainly from the Central Asian region and the Indian Himalayas, will be discussed briefly. In addition, much more of the Central Asian examples could be found in Strom and Abdrakhmatov (2018).

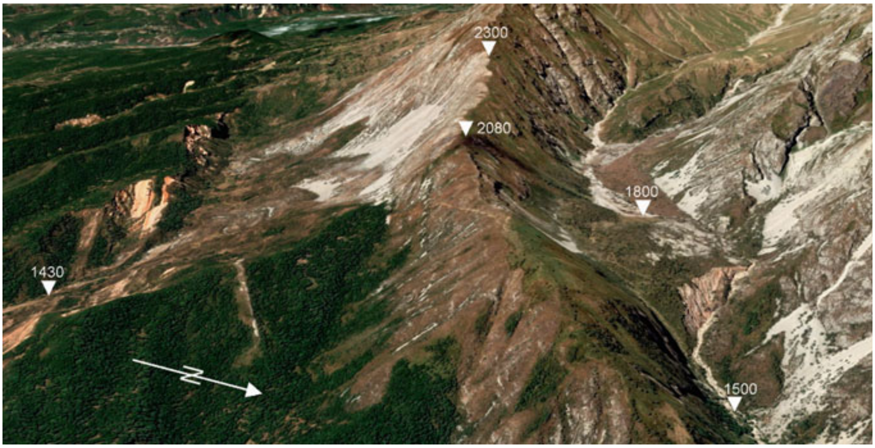

Fig. 3.1 Two rock avalanches from both sides of the watershed in the Fergana Range, Tien Shan (41.394° N, 73.03° E)

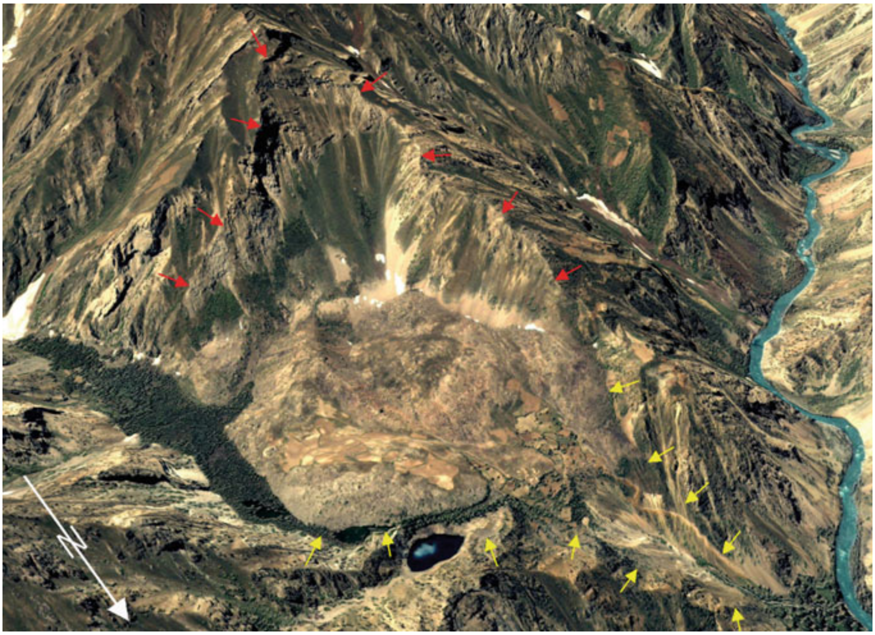

Fig. 3.2 Rock avalanche in the Panjai Mard valley, Afghan Badakhshan (37.87° N, 71.16° E)

3.2 Questionable Case Studies That Required Special Analysis

Rockslides and rock avalanches misinterpretation and their mixing with deposits left by such processes as glaciation, formation of rock glaciers, and extreme debris flows that can occur in the presence of the "intermediate" agent—water or ice, might be caused by several reasons. Among them are the significant reworking of the rockslide landforms by erosion, the large distance between the source zone and deposition zone, and a large amount of moraine material in rock avalanche deposits. Correct identification of the nature of such debris accumulations and discrimination of the prehistoric rock slope failures from landforms created by glaciers or powerful debris flows is important for both landslide and seismic hazard assessment in mountainous regions since rock avalanches, unlike moraines, rock glaciers, and debris flow fans are often, though not always, triggered by large earthquakes. Thus, such prehistoric features can be considered as evidence of strong past seismic events. Considering the contemporary climate changes and glaciers' retreat, modern glaciation cannot produce large-scale damming of the major rivers. On the contrary, rock avalanches can originate regardless of climatic conditions, and nothing prevents their occurrence in the near future if conditions would be favorable.

3.2.1 *Identification of the Real Nature of The Strongly Eroded Debris Accumulations*

Many early Holocene and Late Pleistocene rock avalanches underwent very strong erosion that affected both their source zones and the deposits, reshaping them in such a way that one could hardly identify these landforms as rockslide-related features. Such reworking can be demonstrated by example of the Displaced Peneplain rock avalanche in the Kokomeren River valley in Central Tien Shan (41.9° N, 74.25° E), about 400 Mm^3 in volume (Strom and Abdrakhmatov 2018). It had collapsed from the slope more than 500 m high. Rock avalanche body is composed of fragmented Precambrian dark-red gneiss with schist and some amount of igneous mafic rocks. The rock avalanche had dammed the pre-Kokomeren River valley, and the stream had to erode a new bypass valley through its left bank rock massif composed of light-red granite. Due to significant reworking, this giant feature could hardly be identified visually, both in the field (Fig. 3.3) and on space images (Fig. 3.4).

Most of its headscarp (Fig. 3.5) looks like a high talus slope, while its section visible at the left part of this figure is the huge block that had subsided for several hundred meters but did not fail completely. Each part of this giant feature does not allow a sound conclusion on its origin, but their complex analysis combined with the study of the deposits' lithology and grain-size composition allows its univocal interpretation as the prehistoric rock avalanche. A closer look at the deposits composing the hilly area marked in Fig. 3.4 by the dashed white line shows that rock avalanche body is composed of fragmented rocks outcropping at the source slope that do not exist on the slopes west from the deep gulley passing at the foot of the above-mentioned talus slope. Thus, the latter is the only source zone for this material. Besides, evidence of the inverse grading were found that is characteristic of rock avalanche deposits (Heim 1932; Erismann 1979; Hewitt 1988, 1999, 2006; Strom 1994, 2006, 2021; Davies and McSaveney 1999; Wassmer et al. 2002; Abdrakhmatov

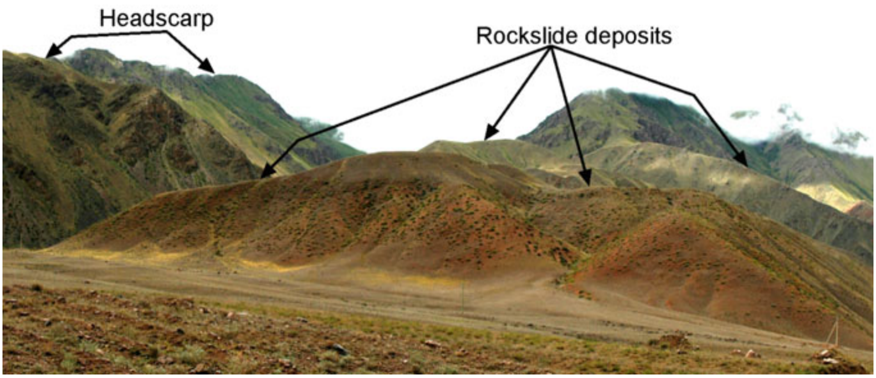

Fig. 3.3 General view of the Displaced Peneplain rock avalanche (light-red slope in the foreground at the right part of the panorama—bedrock granite)

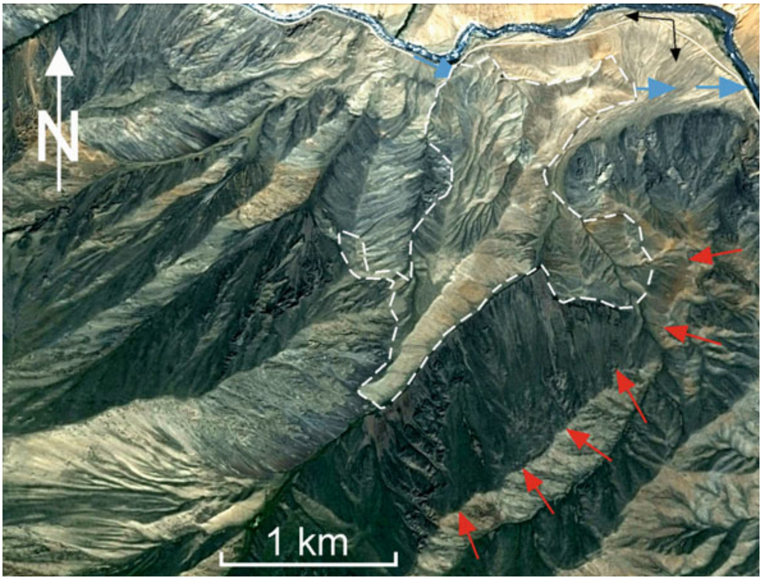

Fig. 3.4 Space image of the Displaced Peneplain rock avalanche. The headscarp is marked by red arrows; the remaining part of the deposits is outlined by white dashed line; the assumed oroginal position of the pre-rockslide Kokomeren River is shown by blue arrows; the panorama shown in Fig. 3.3 was made from the point marked by small black arrows (after Strom and Abdrakhmatov 2018, Reprinted with permission of Elsevier)

Fig. 3.5 Headscarp of the Displaced Peneplain rock avalanche

and Strom 2006; McSaveney and Davies 2006; Dufresne et al. 2009, 2016; Dufresne and Dunning 2017). Such a combination of the lithology of crushed debris that clearly show from where it could originate, and a very specific grain-size composition proves the rock avalanche origin of the deposits in question.

Fig. 3.6 Rounded boulders (stream alluvium) resting at the "entrance" of the abandoned river valley blocked by the Displaced Peneplain rock avalanche deposits. They are visible behind students at the right part of the photograph

Besides sedimentological evidence, the additional piece of the puzzle that proves the rock avalanche origin of this feature is the existance of the abandoned Kokomeren River valley on the present-day right bank of the stream (Figs. 3.4 and 3.6). This old channel is filled with large well-rounded granite boulders that could be transported by the powerful stream only since no granite outcrops exist on the right bank of the Kokomeren River close to this site. It should be pointed out also that the good roundness of the boulders shows that the river transported them for a long distance. All these indicate that river had passed originally south of its present-day course and had to erode a new gorge when this original way had been blocked.

This example demonstrates that even strongly reworked and reshaped rock avalanches could be identified univocally through the combined analysis of sedimentological and morphological data and careful study of the evolution of the local drainage network.

3.2.2 Distant Position of Rock Avalanche Deposits from Its Source Zone

The extreme mobility of rock avalanches can play a dirty trick on the ability to identify and interpret such features correctly. It complicates establishing natural links between deposits and their assumed source zones, which can be exemplified by the ca. 5 km long Aigyrkul rock avalanche in Southern Tien Shan (38.91° N, 67.93° E). It was identified first as an accumulation of fragmented rock debris covering about 2.3 km of the valley bottom with an area of one square kilometer. It was unclear, however, from where this material could be transported to its present position since no distinct headscarp exist on the surrounding slopes. However, a careful check of the space images revealed the horseshoe-like headscarp at the local watershed, almost 1 km above the valley bottom and about 3 km away from the closest part of the deposits

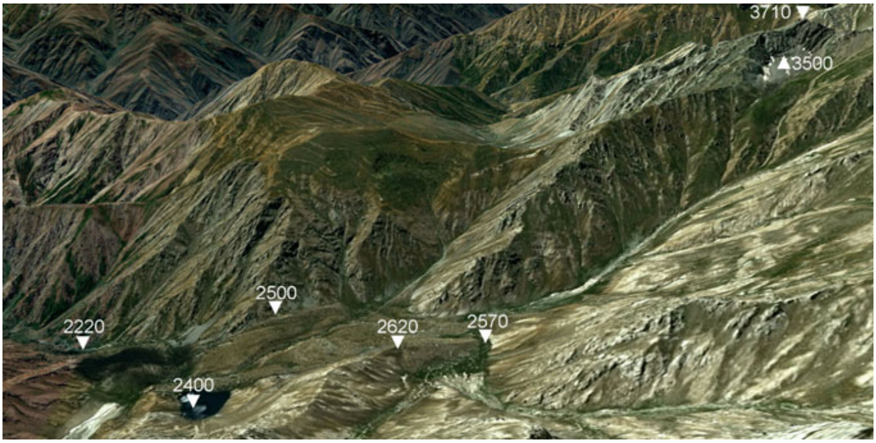

Fig. 3.7 The Aigyrkul rock avalanche in the Tupolangdaria River basin. The source zone is at the top right of the image between elevation marks 3,710 and 3,500 m a.s.l. Rock avalanche deposits stretch from 2,570 to 2,220 m a.s.l. (after Strom and Abdrakhmatov 2018. Reprinted with permission of Elsevier)

(Fig. 3.7). No visible evidence of the clastic material could be found on the way from the headscarp to the rock avalanche body that had split into two parts after collision with a rocky spur at 2,620 m a.s.l. The smaller one turned left and blocked the tributary valley, while the main part flowed ahead up to 2,220 m a.s.l., spreading over the valley bottom and damming a gulley where the small Aigyrkul Lake still exists.

In such cases, it might not be so easy to prove the relationship between the bouldery deposits at the valley bottom and the potential distant source zone. Nevertheless, a thorough analysis of the landforms at the surrounding slopes provides data allowing univocal interpretation of the entire assemblage of the suspicious landforms and deposits.

A similar analysis was performed to specify the origin of the extremely mobile rock avalanches at the northern and eastern boundaries of the Pamir mountains. The Yimake (Yuan et al. 2013; Fig. 3.8), the Komansu (Strom 2014; Robinson et al. 2015; Reznichenko et al. 2017), and the Lenin (Reznichenko et al. 2017) rock avalanches located here had more than 20 km and up to 34 km long runouts.

In all these cases, source zones are located at very high altitudes within the presently glaciated area or very close to it. Glaciation creates negative circus-like landforms similar to most large rockslides' source zones. If niche glaciers form them, their similarity becomes even stronger. Nevertheless, complex analysis allows sound interpretation of all these features as long-runout rock avalanches rather than moraines or landforms of a fluvial origin (Strom and Abdrakhmatov 2018). A correct interpretation of such features is especially important for hazard assessment in the depressions, bounding high mountain ranges. Hazard produced by the gigantic rock avalanches exceeds hazards associated with other mass-waiting phenomena. Glaciers

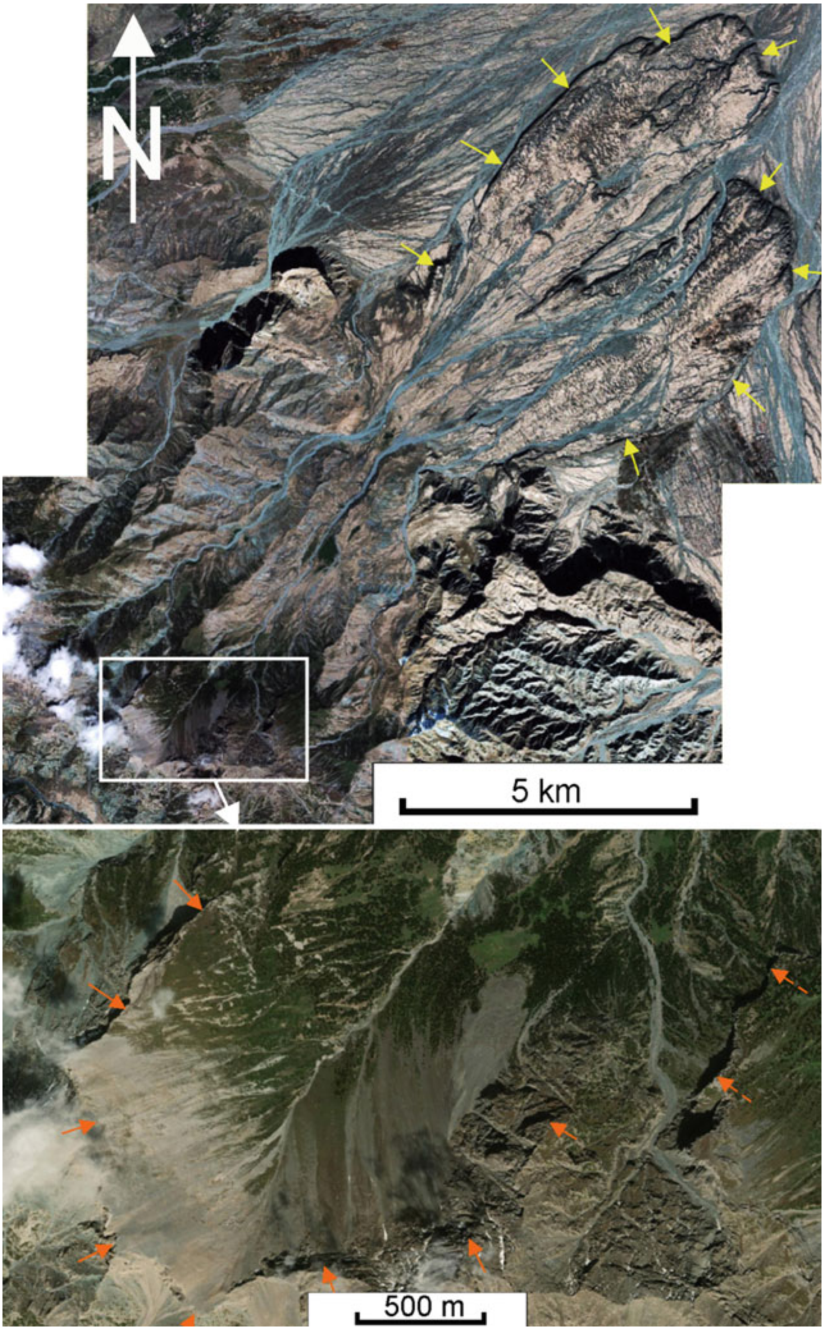

Fig. 3.8 The Yimake rock avalanche at the northeastern foot of the Chinese Pamir (39.2° N, 76.15° E). Yellow arrows show the limits of its' leave-shape body 9 × 5.3 km in size and 15–20 m thick; orange arrows mark the deep headscarp shown in the inset. Dashed orange arrows outline assumed the right part of the source zone

and rock glaciers move not so fast and do not protrude so far towards the plains; most debris flows, excluding those produced by breach of large dams and lahars from major volcanos, lost their destructive power, while spreading over the range foot.

In contrast, rapidly moving dry granular flows millions of cubic meters in volume can destroy almost any affected structure. Besides, rock avalanches produce powerful air blasts reported by eyewitnesses of some catastrophic events, such as the 1949 Khait rock avalanche in Tajikistan (Semionov and Semionova 1958) and some landslides triggered by 2008 Wenchuan earthquake (R. Huang, personal communication 2018). Such effect increases the affected area.

3.2.3 Moraine Material in Rock Avalanche Deposits

The factor that complicates correct discrimination of rock avalanches and glacial deposits at most is the presence of a large amount of glacial material in debris accumulations resting at the slopes' feet. Some researchers consider the presence of sub-rounded boulders in the gravelly-sandy-silty matrix that form part of the deposits as the direct evidence of their glacial origin (Ischuk 2013). However, in high mountains that underwent intensive glaciation in the past, glacial till is widely distributed at the valley's bottoms and on their slopes. That is why large-scale rock slope failures can entrain a large amount of such material that originated as glacial deposits but has been transported to its present position by a purely gravitational process. It can be exemplified by the giant prehistoric Kudara-Pasor rock avalanche of about 1 km^3 in volume (Fig. 3.9) in the Kudara River valley in Central Pamir (38.39° N, 72.58° E), 13 km north of the famous 1911 Usoy rockslide.

The position of the very distinct lithological units forming rock avalanche deposits clearly indicates that it debris motion was across the river valley, rather than along it. This rock slope failure had affected the shoulder of the right-bank valley slope, including the portion of an old glacial trough filled with moraine material that rests now at the proximal part of the dam body (4 in Fig. 3.9). On the way, this rock mass scraped fluvial and, probably, the youngest glacial deposits from the valley bottom and bulldozed them towards the opposite valley slope (1 in Fig. 3.9).

Another very didactic case study is the Imom rock avalanche, about 15 Mm^3 in volume in the Gunt River valley (37.692° N, 72.327° E) in Central Pamir (Fig. 3.10). Its 1,350 m long and up to 600 m wide body rests on the low river terrace. It affected large Late Holocene alluvial fan formed by the debris flows. Such relationships show that rockslide that caved from the 700 m high slope composed of crystalline rocks is quite young. Crushed debris of such rocks forms the inner part of the rock avalanche body with a hummocky microrelief. In contrast, this body's frontal, 50–100 m wide outer belt is composed of rounded and semi-rounded boulders with sandy matrix—typical moraine (Fig. 3.10).

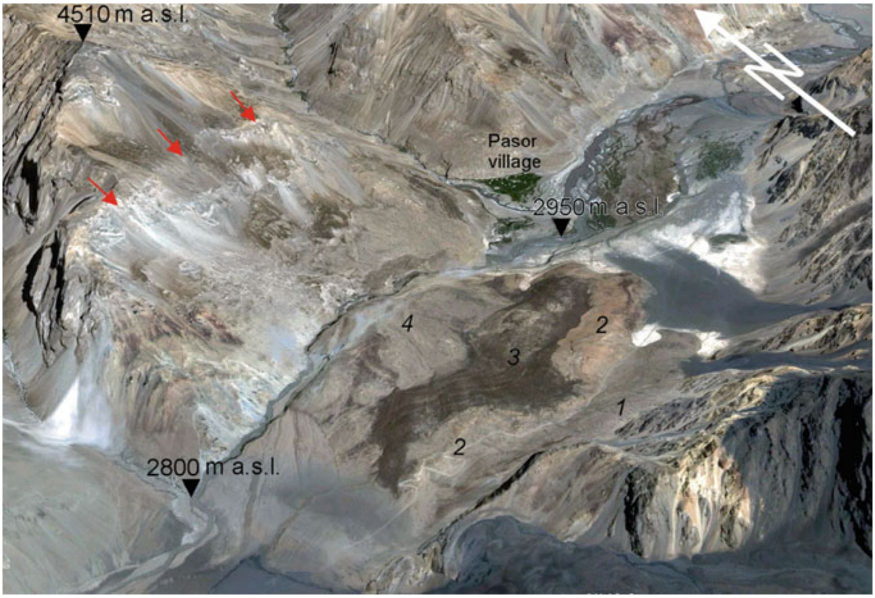

Fig. 3.9 Oblique view of the Kudara-Pasor rock avalanche. 1–4—different lithological units clearly identifiable in the rock avalanche body; red arrows—headscarp crown

3.3 Natural Dams Sourced in the Tributary Valleys

Working in the field, researchers often find huge debris accumulations that block main river valleys being sourced, partially or completely, somewhere in the upper reaches of the tributary valley. Such a feature can be seen, for example, in the Uttarakhand, in the Bhagirathi River valley on the way from Uttarkashi to Gangotri at 30.931° N, 78.681° E (Fig. 3.11). A huge body about 250 m thick came out from the Kanodia-Ghad valley and partially blocked the Bhagirathi River valley. It is composed of intensively fragmented rock debris with distinct varicolored zones corresponding to different lithological units that were transported for a long distance but not mixed, which is typical of rock avalanche deposits. Thorough check of space images confirmed that this body is the distal part of the 5.7 km long rock avalanche that collapsed from the 1,300 m high northern slope of the Kanodia-Ghad valley composed of gneiss, and then turned left and moved more than 3,000 m down the valley (Fig. 3.12). Finally, it blocked the Bhagirathi with a dam that was several dozen meters high.

One more interesting Himalayan case study is in the Himachal Pradesh State, in the Beas River basin, at 32.03° N, 77.127°, opposite the Dhakpo Shedrupling Monastery (N. Singh, personal communication). Here right bank of the Beas River is formed by the fan-shaped body up to 150 m high, stretching for 1.5 km along the river (Fig. 3.13).

Fig. 3.10 Oblique view of the Imom rock avalanche. The inner part of its body is composed of crushed crystalline rocks, while the outer part is by the bulldozed moraine material

It can be just an abnormally large alluvial fan composed of multiple debris flow deposits. However, another possibility cannot be excluded too. Close view of the space images available at Google Earth shows that the tributary valley where this fan-shape body has been sourced is filled by a rockslide (rock avalanche) that caved from the left-bank slope of the valley more than 1 km high and left a distinct headscarp with smooth steep sliding surface. Its downstream face has been eroded significantly, but it can be hypothesized that some part of rock avalanche debris could be ejected through the gulley mouth and accumulate in the Beas River valley forming the fan-shaped body.

Reliability of such mechanism can be seen clearly in the Chinese Tien Shan, in the Muzart River valley at 41.95° N, 80.87° E. The valley here had been blocked at a distance of almost 2 km by the similar, though much larger fan-shape debris accumulation up to 150 m thick and ~250 Mm^3 in volume (Fig. 3.14). First, about 400 Mm^3 of the Proterozoic metasediments and igneous rocks collapsed and formed a dam in the tributary valley. Most likely the secondary rock avalanche was ejected from the downstream side of this dam during the two-stage process (Strom 1996, 2006). It had passed 4.3 km and blocked the Muzart River valley. Moreover, the distal part of this dam was raised on the opposite valley slope for ca. 100 m above the blockage crest. Such runup is typical of rapidly moving dry rock avalanches but not

Fig. 3.11 View on the distal part of the Kanodia-Ghad rock avalanche

of water-rich debris flows. Their viscosity is much less and, thus, debris flow would spread up and downstream the main valley. Morphological similarity of this didactic feature to the case study from the Beas River valley allows the assumption that the same process could create the latter landform. Of course, the site shown in Fig. 3.13 requires a more detailed field study to conclude the real nature of the suspicious landforms.

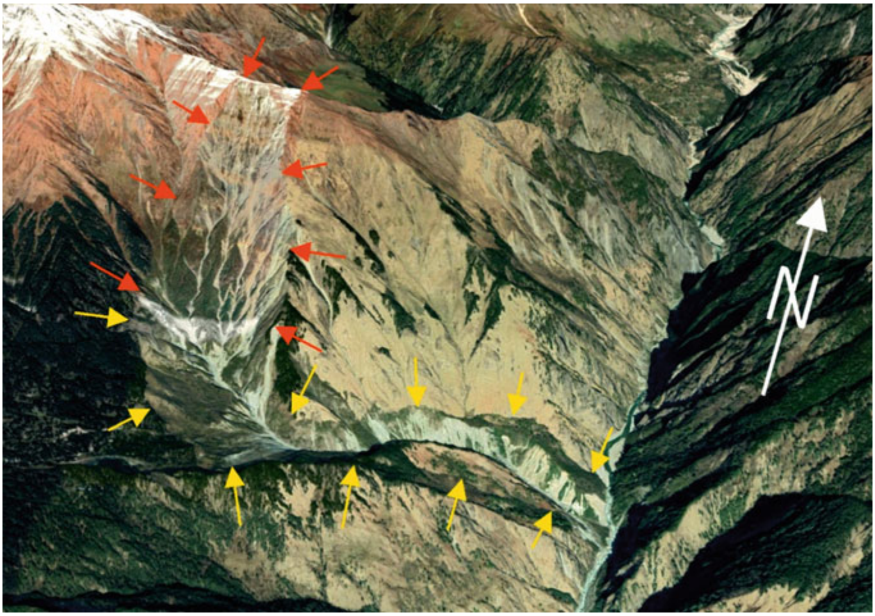

Fig. 3.12 Oblique view of the Kanodia-Ghad rock avalanche site. Red arrows—headscarp: by yellow arrows mark the travel path of rock avalanche

3.4 Conclusions

This chapter has attempted to demonstrate briefly the possibility of rock avalanches' identification and well-grounded discrimination from debris accumulations formed by other mass wasting processes even in controversial cases from Central Asia and the Himalayas. Such justification should be based on the complex analysis of the overall and detailed morphology of the suspicious landforms combined with a thorough analysis of the deposit's grain-size composition and of their internal structure. Rock avalanches are characterized by the absence of mixing of various lithologies that collapse from the slope and by the distinct inverse grading with intensively fragmented body facies and coarse bouldery carapace. It is very important for researchers working in this field to learn about similar features worldwide. It will help to compare the study objects identified in a particular region with possible analogues worldwide, which can be very helpful.

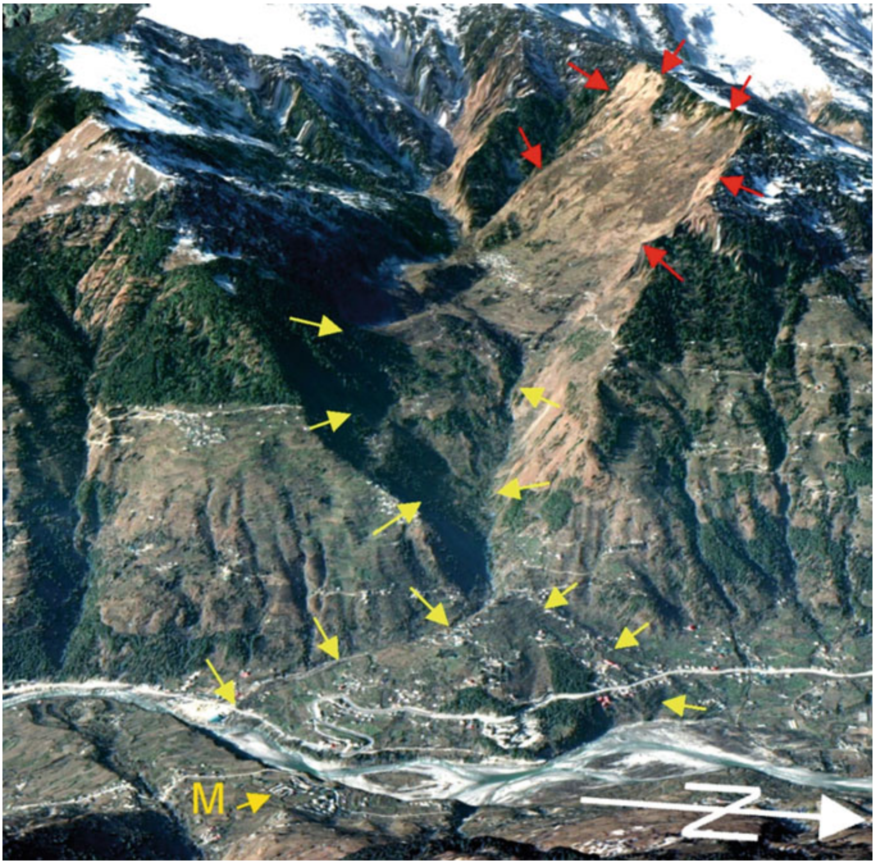

Fig. 3.13 Oblique view of rock avalanche in the right tributary of the Beas River. Headscarp is marked by red arrows, boundaries of the assumed rock avalanche deposits—by yellow arrows; M—the Dhakpo Shedrupling Monastery

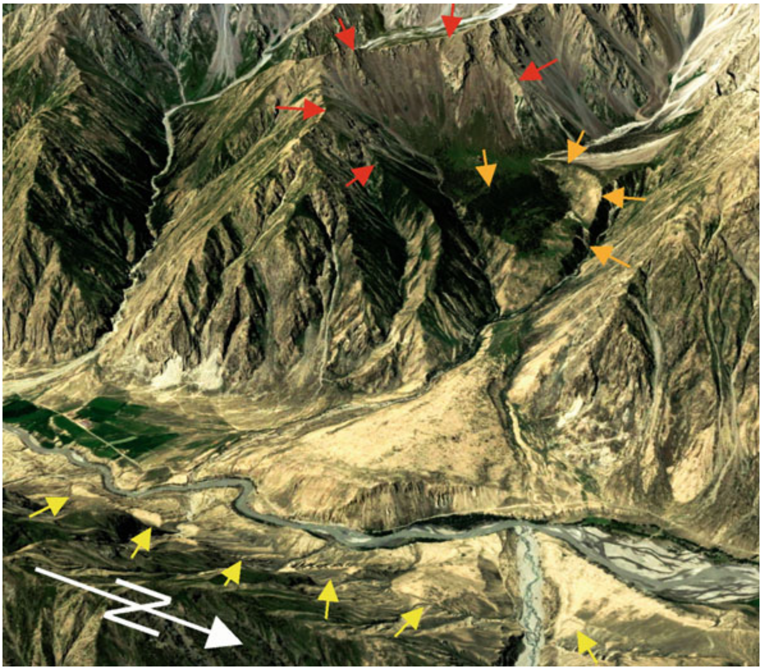

Fig. 3.14 Oblique view of the secondary rock avalanche in the Muzart River valley. Red arrows mark the headscarp crown, orange arrows—the secondary scar (headscarp of the secondary rock avalanche that had blocked the Muzart River), and yellow arrows—rock avalanche front on the left side of the Muzart River valley

Declaration Author has no conflict of interest of any type.

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