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ORIGINAL PAPER

Implications of geomorphological research for recent and prehistoric avalanches and related hazards at Huascaran, Peru

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Abstract Detailed research of superficial deposits below the northern peak of Huascaran (Cordillera Blanca) provides new information on the limits of a paleo-avalanche originating from this mountain. Geomorphological mapping of the sediments identified glacial deposits, deposits from historical rock-debris avalanches and huge boulders from a paleo-avalanche. Schmidt Hammer rock-hardness tests were used to distinguish between the several generations of rock-debris avalanches, but largely failed to distinguish between the much older moraine and the paleo-avalanche sediments. Thus, only the field geomorphological mapping proved to be reliable for identifying the limits of the paleo-avalanche. The limits identified as granite boulders deposited over volcanic rocks were found to extend 30 m further up the opposite valley slope than previously had been mapped. This larger extent implies a greater volume and/or greater mobility for the prehistoric event.

Keywords Slope movements · Natural hazards · Schmidt Hammer tests · Huascaran · Cordillera Blanca · Peru

1 Introduction

The Cordillera Blanca in Peru is part of the highly tectonically active Andean mountain chain formed by collision of the Cocos, Nazca, Antarctic, and South American lithosphere plates. Intense endogenic processes form suitable conditions for highly active and dangerous geomorphic processes. The Cordillera Blanca forms the NE boundary of the valley

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of the Santa River (Callejón de Huaylas, Fig. 1), which has been affected by many historical natural disasters (Zapata 2002). They vary by type (landslides, rock falls, rock and ice avalanches, debris-flows, outburst floods, and floods), size (Table 1), as well as triggering factors. Rock/ice falls and landslides are connected mostly with large magnitude earthquakes (Silgado 1978) mobilizing mass movements on wide areas. Landslides can be also triggered by seasonal rain in the period from November to April with peak

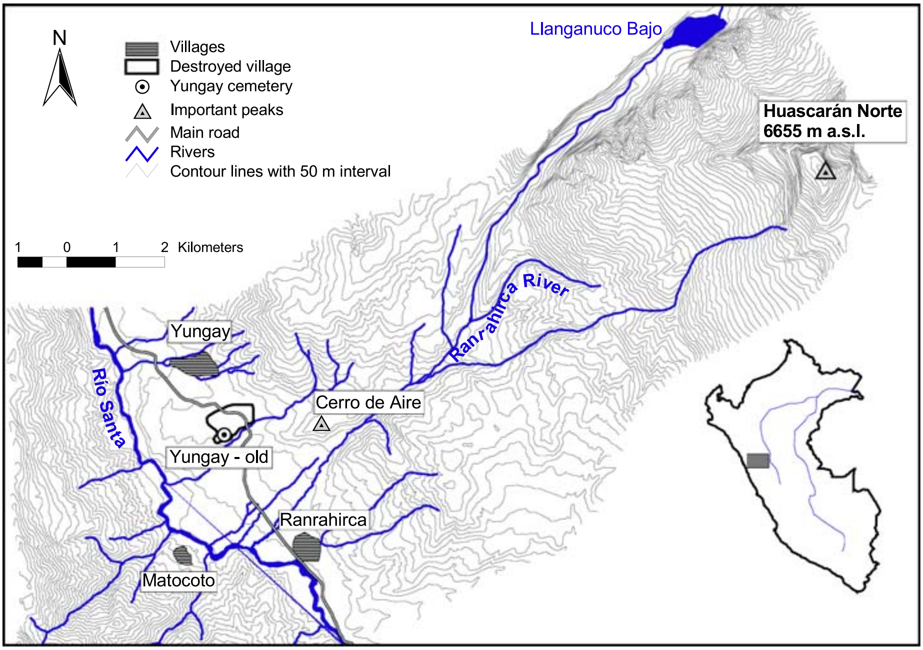

Fig. 1 Location map of the study area

Table 1 Overview of characteristics of recorded rock-debris avalanches from the north peak of Huascaran, western wall (N/A—not ascertained; reported event from 1917 was not included since no detailed data are available—Zapata 2002)

Date	Preparatory condition/ trigger	Volume ($\times 10^6$ m^3)	Speed (km/h)	Run-out distance (km)	Size classification ***	Total area (km^2)	Reference
1962	N/A	13	170	15.5*	8	6*	Bolt et al. 1975
1970	earthquake	50	320	16*	8	25.4**	Bolt et al. 1975
		50–100	280–335	N/A	9		Plafker and Ericksen 1978, Plafker et al. 1971
1987	Precipitations	3.5	N/A	10.5*	7	1.1*	Zapata 2002
1989	Precipitations	N/A	N/A	15	N/A	N/A	Zapata 2002

* Calculated in GIS

** Calculated in GIS, does not include river channel below the hit point filled by the sediments

*** According to Jakob (2005): volume = 10^6 m^3—class 7; volume = 10^7 m^3—class 8; volume = 10^8 m^3—class 9 precipitation in March (Mark 2002), or with precipitation influenced by the El Niño effect (Vilímek et al. 2000). Another frequent dangerous combination of processes are glacial lake outbursts producing floods or debris-flows (Ames 1998; Zapata 2002; Vilímek et al. 2005).

The greatest known historical disaster in the Santa River Valley was the 1970 earthquake (M_L 7.7) and subsequent rock-debris avalanches from the north peak of Nevado Huascaran (6,655 m). These events followed a smaller avalanche in 1962. In addition, some authors (Cluff 1971; Plafker and Ericksen 1978) note occurrences of an unknown number of large paleo-avalanches in the same area. They describe event of great magnitude with estimated deposition area of 30 km^2, terminal velocity of 140 km/h and deposit thickness on the west bank of the Santa River of about 45 m. The evidence of long-term instability of the northern summit of Huascaran along with an increasing population density in the area raises questions about the frequency and magnitude of potential future events and their risk to the local people.

To better understand the paleo-avalanches, the known events were examined, and in situ relative dating Schmidt Hammer (SH) tests, geomorphological mapping, and sedimentological analyses were conducted. The primary aim was to better delineate the paleo-avalanche first outlined in Plafker and Ericksen (1978).

The catastrophic slope failures occurring on the northern summit of Huascaran combine several different processes which affect their classification. Some authors classify them as avalanches (Bolt et al. 1975) or debris-flows (Lomnitz 1971), and some others use the term rock slides (Browning 1973). Havenith et al. (2003) used the term “rock-debris avalanche” which we think describes best the nature of the events and therefore adopt in this article.

2 Methodology

Numerous (120) in situ Schmidt Hammer (SH) tests were performed and statistically analyzed to reveal relative ages of the different rock-debris avalanche deposits. To validate and interpret the results, several other field and laboratory methods were applied. These included field geomorphologic mapping; satellite-imaging and air-photo interpretation; and rock and sediment sampling and analyses. Thus, much information about the landform types and their activity over the last 40 years were collected to form good base for better understanding the future landscape development.

2.1 Schmidt Hammer tests

Probably the most frequent use of the Schmidt Hammer in geomorphological research is in relative dating of rocky landforms (Evans et al. 1999; Mentlík 2005; Shakesby et al. 2006; Engel and Traczyk 2008). The obtained rebound-values (R) can be interpreted in terms of mechanical strength, which for a given rock type decreases with duration of weathering, so that lower R-values correspond to more weathered surfaces (Mentlík 2005).

We have used an N-type Schmidt Hammer for relative dating of mixed moraine and gravitational deposits originating through glacial processes and rock-debris avalanches.

The SH-test followed the methodological procedure of Goudie (2006) and Mentlík (2005). We divided the measured boulders into three groups based on the type and chronology of the depositional processes identified through field investigations, geomorphologic mapping, and satellite-image interpretation. The first group of measured boulders consisted of moraine material containing boulders with the longest inferred weathering

Fig. 2 Top of the lateral moraine ridge below the north peak of Huascaran with example of boulders tested by the Schmidt Hammer

history (Fig. 2); the second group was formed by boulders most likely deposited in the paleo-avalanche. The last group contained boulders transported during the 1962 and 1970 rock-debris avalanches. For each measured boulder, we acquired its size, volume, location, and basic petrologic description.

2.2 Statistical analysis of SH-test results

We used a linear mixed model to estimate the mean and standard deviation of *R*-value measurements of boulders in the genetically defined groups. This model enabled us to account for varying numbers of measurements on different boulders and to test for possible differences in means and standard deviations across the groups.

We tried several methods of classification analyses to see whether we could discriminate among the genetically defined groups of boulders based on the means and standard deviations of *R*-values, and boulder volumes. Balancing the simplicity of the classification rules and the overall performance, we chose simple classification trees which used only mean *R*-values. In the classification analyses, we established a rule based on acquired data which could be applied to assign new measured boulders into the different genetic groups. This rule was tested only on the same data as were used for rule calculation, which may bias the overall classification results toward more optimistic ones.

Similarly, we performed an automatic cluster analysis to see whether the unsupervised learning process (with no prior knowledge of classes) formed classes similar to the original classes, or at least whether the results of the classification analyses could be reproduced. From the various methods of cluster analysis, we decided to choose the simple methods of K-means with the means of *R*-values as the only variable.

All the statistical analyses were performed using the R computation environment (http://www.r-project.org).

2.3 Geomorphological mapping and grain-size analyses

Landform mapping and description were undertaken during field work as well as through interpretation of 2006 and 1984 SPOT satellite images and 1970 infra-red aerial photographs (scale 1:42,000). These investigations focused on identifying and describing the main landforms and their contained materials to explain the origins of the boulders tested by the SH device.

Recent glaciations and ice-scoured bedrock were delineated from the satellite images where these areas appear as white and light grey polygons, whereas the adjacent moraines have darker tones of grey and brown and usually form clearly visible ridges. Possible confusion among these forms may be due to the shadows below sub-vertical slopes and continuous transitions among the color tones. Identification of these landforms was checked with photographs taken during field work. Moraines in the Santa River Valley were identified mainly during field mapping.

Recent processes (e.g., mass movements, water erosion) and resulting forms are not shown on the map.

Basic grain-size distributions were obtained for eight sediment samples taken from the matrix of moraine, paleo- and 1970 rock-debris avalanche deposits. Samples were taken near the surface (maximum depth of 0.4 m) and analyzed in the laboratory to characterize fine-grained matrix of the deposits and their possible differences. Matrix composition is important for describing rock-debris avalanche flow characteristics.

3 Results

3.1 Historical rock-debris avalanches from the northern summit of Huascaran

The first recorded catastrophic rock-debris avalanche from the northern summit of Huascaran (western wall) destroyed the village of Ranrahirca and several smaller settlements, killing about 4,000 people on the January 10, 1962 (Plafker and Ericksen 1978). Záruba and Mencl (1982) stated that the rock-debris avalanche was triggered by an earthquake, but none of the recorded seismic shakings preceded the event (Plafker and Ericksen 1978); thus, its causes remain largely unknown. It is also difficult to quantify the ice and water content of the 1962 rock-debris avalanche, but according to the eyewitnesses it was quite high (Plafker and Ericksen 1978).

On the May 31, 1970 at 15:23 local time, a shallow earthquake with epicenter situated 25 km west of the coastal town of Chimbote, Peru with local magnitude of 7.7 occurred. Its hypocenter was situated at a depth of about 50 km. Nearly all of the towns in the Santa River Valley were destroyed in this event and about 1 million people (800,000 according to Bolt et al. 1975) lost their homes.

In the Huascaran region, the first seismic shock (according to eyewitnesses, Voight 1978) triggered a rock-debris avalanche on the western wall of the northern summit of Huascaran killing, perhaps, 18,000 people (Plafker et al. 1971) in the towns of Yungay and Ranrahirca. It apparently started as a fall of giant rock blocks which dragged down ice and snow from the summit and glacier below the western wall. The total volume of transported material was estimated by Bolt et al. (1975) as 50 million m^3, while Plafker et al. (1971) estimate 50–100 million m^3 (Table 1). The avalanche run-out distance was 16 km, over a vertical height of 4,000 m. Other avalanche properties and their comparison with other events occurring in the Ranrahirca River basin are listed in Table 1. High mobility of the

1970 rock-debris avalanche apparently was caused by the high water content. According to Plafker and Ericksen (1978) the water originated only partly from the ice, because non-melted ice blocks were found in the accumulation in the Santa River Valley and even in the Matocoto village on the opposite Cordillera Negra slopes (M. Z. Luyo, oral communication). They assumed that the water came mainly from water courses and from a damaged irrigation system with additional contribution from underground water. On the other hand, Huggel et al. (2005) attributed the high mobility of the avalanche to fluidization effects at the base of the moving ice/debris mass with high pore pressures and a continuous supply of water due to frictional melting of ice. Ice and snow as the main source of water in the avalanche is also supported by the fact that it occurred at the end of the humid period with possibly a large snow accumulation. The minor importance for the quantity of water in the rock-debris avalanche could also have the fact that the earthquake occurred in the afternoon during the best conditions for snow melt.

The 1962 and 1970 avalanches differed considerably in the volumes of mobilized material and also in their aerial extent (Fig. 3). Most notably, the side lobe of the 1970 rock-debris avalanche overtopped the ridge Cerro de Aire and buried almost the entire town of Yungay (Fig. 4). The huge volume and energy of the transported material, and the centrifugal effect of a bend in the river channel are, along with local topography, responsible for the split in the avalanche trajectory. Significant elements in the local topography include the lower NW side of Ranrahiraca Valley (which is of 130 m lower than SE bank) and an important narrowing of the valley just above the place where the overtopping took place, which caused accumulation of material behind it (confirmed by eyewitnesses). The 1970 rock-debris avalanche crossed the Santa River and climbed up to

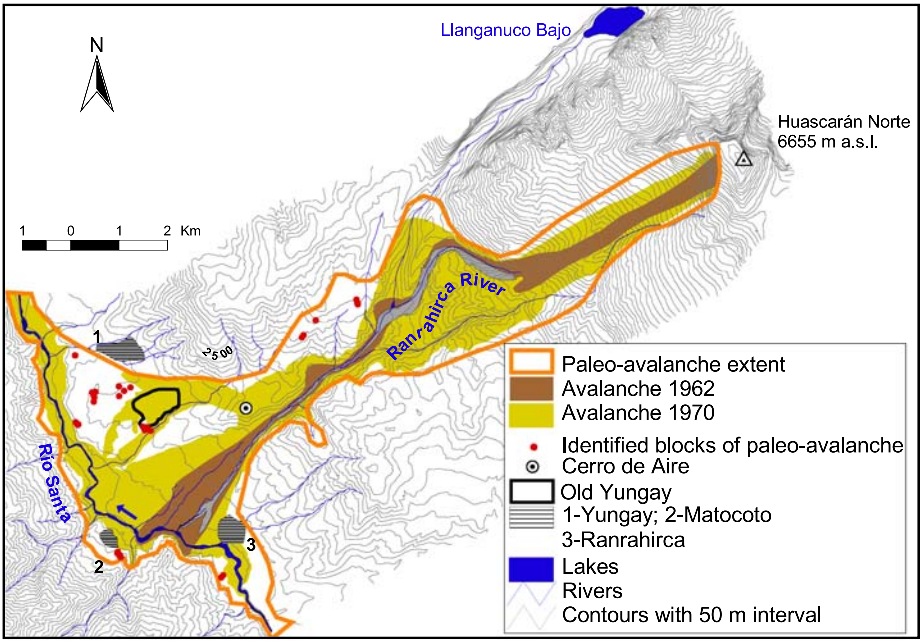

Fig. 3 Extent of the 1962 and 1970 rock-debris avalanches, 1987 debris-flow, and possible extent of paleo-avalanche from Huascaran based on satellite images and aerial photograph interpretation, geomorphological evidence, and field mapping of large granite boulders

Fig. 4 Boulder transported over the Cerro de Aire by the 1970 rock-debris avalanche depositing near the Old Yungay cemetery

123 m (Plafker and Ericksen 1978) above the river-bed close to the Matocoto village. Near this village, the accumulation also reached a river terrace 75 m above the river (Fig. 3).

The thickness of the deposits of the 1970 avalanche in the Yuangay area, although not the same everywhere, is estimated by Browning (1973) to reach up to 33 m (after the melting of the ice). This was confirmed in our field mapping which compared differences along the original and new road segments constructed on the surface of the deposits. The height difference reached on one margin of the avalanche deposit was about 35 m, on the other one, about 10–25 m. The thickness of the 1962 avalanche at the Santa River Valley bottom was estimated to be 15 m (Plafker et al. 1971).

3.2 Geomorphologic mapping

The presented map combines basic landforms with material characteristics so it also describes their basic formative processes (Fig. 5).

Talus deposits and debris-flow fans fringe steep rock slopes in the Llanganuco Valley and were mostly identified during the field work. They are susceptible to mass movements, mainly rock falls and debris-flows, which are active in this area. Genetically slightly different, is the complex alluvial fan identified in the Santa River Valley formed along the lower course of the Ranragirca River (Fig. 6). It is a compound landform of several individual forms including the recent Ranrahirca River fan (Fig. 7), remnants of previous, older fans, and platforms formed on polygenetic sediments. The most active part of the complex fan is the Ranrahirca River fan which is subject to deposition during repeated debris-flows and rock-debris avalanches (1962, 1970 and, 1987). At the NNW end, it is detached from the elevated platforms (around old and new Yungay towns, Fig. 6) by steep slopes ranging from 10 to 65 m in relief. All these platforms between Cerro de Aire and Santa River (Fig. 6) are planed surfaces on the older (presumably prehistoric) alluvial fan

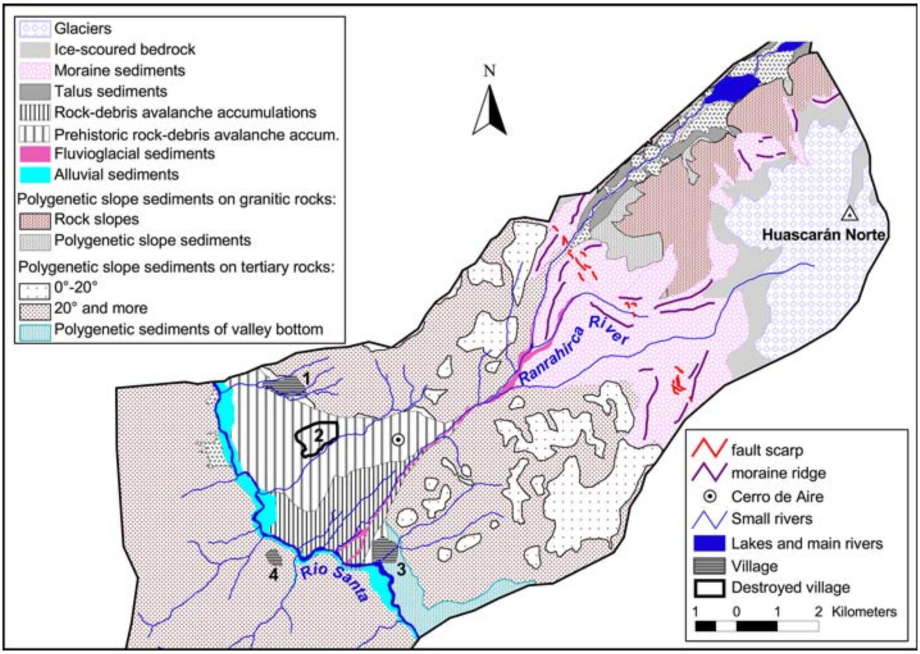

Fig. 5 Geomorphological map of the area (1—Yungay, 2—old Yungay, 3—Ranrahirca, 4—Matocoto)

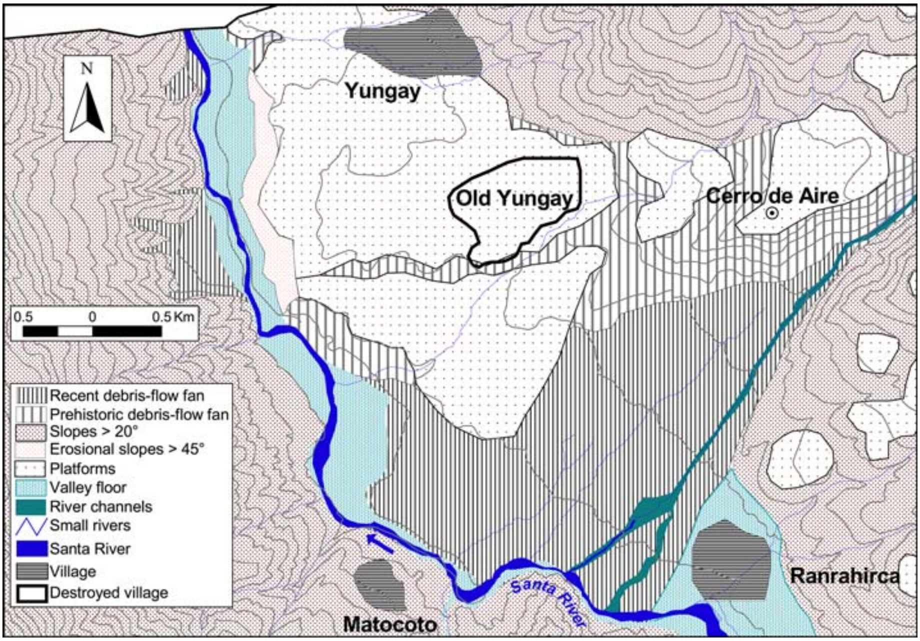

Fig. 6 Detailed geomorphologic map of the Ranrahirca dejection cone

Fig. 7 View of the Ranrahirca River fan (in the center) from the opposite slopes of the Santa River Valley. The north peak of Huascaran is covered by clouds on the right rear part of the image

formed by one or series of prehistoric rock-debris avalanches. This assumption was further strengthened by the 1970 rock-debris avalanche depositing part of its material in the area of old Yungay already located on the prehistoric fan. It suggests that the prehistoric rock-debris avalanches could be responsible for depositing the material over the similar area and also it shows that the prehistoric fan is still active. The evidence enabling the detection of this feature includes morphology, a deviation in the Santa River course (it is pushed against the Cordillera Negra slopes of the valley) and large number of paleo-avalanche boulders found on the prehistoric fan (Fig. 3).

The large accumulation event(s) forming the prehistoric fan also initiated intense down cutting of the Santa River, to form erosional slopes up to 100-m high (Fig. 6). The uppermost limit of recent headward erosion has reached some 2,200 m downstream from the mouth of the Ranrahirca River, which roughly corresponds to the limit of the 1970 avalanche deposit. This shows the important influence of the recent rock-debris avalanches on the river-course development.

Fluvial sediments include river-bed and flood-plain sediments as well as two stages of river terraces, which were mapped only along the Santa River and are shown as “Alluvial sediments” on the geomorphological map (Fig. 5). Fluvioglacial sediments were identified during the field work forming mostly narrow bands in the channels of the Ranrahirca River and its tributaries.

The Santa River Valley between the foot of the Cordillera Blanca and the river is underlain by Tertiary rocks producing colluvium covered in some areas by glacial till and rock-debris avalanche deposits further transformed by water erosion. This heterogeneous material was classified depending on the slope as polygenetic slope sediments evolved on Tertiary rocks on slopes below and above 20°. Slopes under 20° form planar surfaces with average dips of 7° which are bordered by steeper slopes or gullies.

3.3 Grain-size distributions

Granulometric analyses of fine-grained sediments (matrix) taken from the moraines as well as the different debris-rock avalanche deposits did not prove to be able to distinguish between the different types of sedimentation events, largely because of their overlapping grain-size distributions (Fig. 8).

3.4 Statistical analysis of *R*-values

3.4.1 Descriptive statistics

Basic characteristics of the genetically defined boulder groups based on the *R*-values from the Schmidt Hammer tests are summarized in the Table 2 and shown on Fig. 9. Boulders deposited during the 1970 event have the highest mean *R*-values whereas moraine boulders have the lowest mean *R*-values. The variability of *R*-values measured between boulders is the lowest for the 1970 event, whereas the other two groups are quite similar for this indicator.

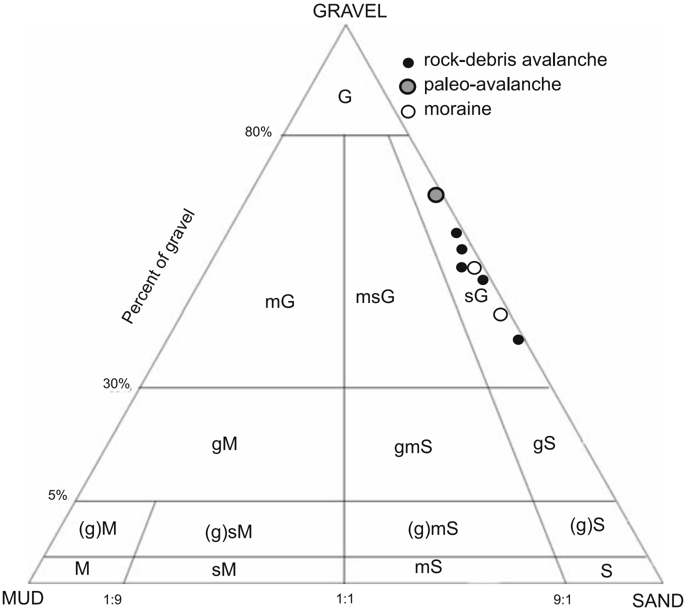

Fig. 8 Grain-size compositions of moraine, paleo-avalanche, and 1970 debris-rock avalanche sediments

Table 2 Basic statistical characteristics of the *R*-values of genetically defined boulder groups

Group of rock blocks	Mean ($\bar{x}$)	Standard deviation (*SD*)	Coefficient of variation[a]
Moraine	41.18	5.78	14
Paleo-avalanche	45.9	7.44	16.2
1970-avalanche	55.75	2.85	5.1

[a] $SD/\bar{x}$

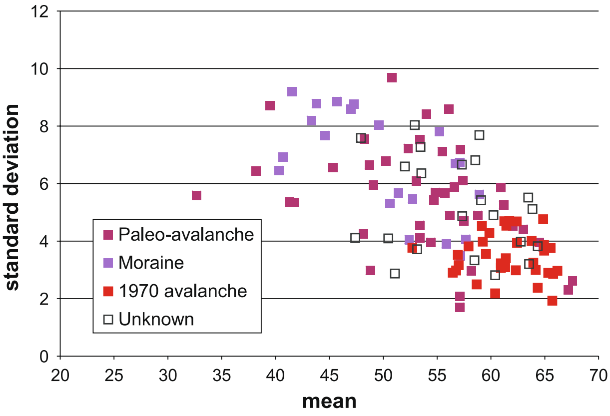

Fig. 9 Plot of means and standard deviations of *R*-values for each measured boulder grouped into four groups. Unknown boulders represent those for which origins could not be determined during the field work

Table 3 Statistical significance of differences between means and standard deviations of the studied boulder groups based on the *p*-values resulting from a mixed linear model (*SD*–standard deviation)

	p-values for difference in means	*p*-values for difference in *SD*
Moraine versus paleo-avalanche	0.025	0.453
1970 avalanche versus moraine	*<0.001*	0.013
1970 avalanche versus paleo-avalanche	*<0.001*	*0.001*

The quite distinct properties of the 1970-event boulders were also demonstrated in a linear mixed model. We used the model to provide a formal statistical test for differences observed in Table 2. The *p*-value differences for a pair wise comparison of the estimated means and standard deviations are shown in Table 3. By taking into account possible multiple testing problems, we demonstrated that the observed difference in the mean *R*-values for the 1970-event boulders and the other two groups were strongly statistically significant. Also the difference in standard deviation between the 1970 event and the paleo-avalanche is strongly significant. On the other hand, the difference in the mean values and observed standard deviations between the moraine and paleo-avalanche are near the borderline of statistical significance. This is true also for the difference in the standard deviations of the 1970 avalanche and the moraine boulders.

The distinct properties of the 1970 boulders are also illustrated in Fig. 6 where the mean values are plotted against the standard deviations of individual boulder *R*-values. The figure shows that there is just a very small overlap of the 1970 rock-debris avalanche boulders with moraine boulders, proving distinct *R*-value properties of these two groups. On the other hand the striking overlap is with the paleo-avalanche and moraine boulders.

3.4.2 Classification and cluster analyses

We used only the mean *R*-values for the classification analyses because the standard deviations of *R*-values and boulder volumes did not add any substantial new information. The classification analyses of the individual boulders (Table 4) successfully distinguished 72% of all boulders, although the capacity to correctly classify paleo-avalanche and moraine groups of boulders was only slightly higher than 50% (for moraine boulders it is only 52%). The moraine boulders are confused (in 48% cases) with paleo-avalanche

Table 4 Results of classification analyses of mean *R*-values of studied boulders

	Moraine	Paleo-avalanche	1970-avalanche
Moraine	*11*	8	*0*
Paleo-avalanche	*10*	26	*1*
1970-avalanche	*0*	8	*33*
Successful classification	***52%***	**62%**	***97%***

Table 5 Results of automatic cluster analyses of mean *R*-values of studied boulders

	Moraine	Paleo-avalanche	1970-avalanche	**Successful classification (%)**
Cluster 1	*0*	7	*33*	**83**
Cluster 2	*11*	10	*0*	**52**
Cluster 3	*10*	25	*1*	**69**

boulders, but they were not confused with the 1970-event boulders. The paleo-avalanche boulders were confused in 19% of cases with both moraine and 1970 rock-debris avalanche boulders. The best classification results were obtained for 1970-event boulders, which were correctly classified in 97% of cases. Therefore, the classification model was very successful in identifying boulders deposited during the 1970 event and it may be also helpful in identifying the extent of the paleo-avalanche, because these boulders were correctly classified in 62% of cases.

Second, we compared three classes of boulders defined by the automatic cluster analyses with groups of boulders defined during field work (Table 5). The results were very similar to those gained by the classification analyses, even though the origin of each boulder was not considered before the cluster analysis. Cluster 1 corresponds to 83% of the 1970 rock-debris avalanche group, meaning that the automatic classification procedure performed quite well. Thus, it demonstrates a strong inherent similarity of boulder *R*-values and thus weathering properties within this group. Slightly poorer results were gained by cluster analyses for cluster 3, which corresponds to 69% of the paleo-avalanche group. Moraine boulders proved to have the least similar properties and they were the least well-defined group of studied boulders, with large internal variability. The automatic cluster analyses were able to correctly distinguish only 52% of the boulders.

3.5 Paleo-avalanches from Huascaran

Our geomorphological mapping and mapping of large granite boulders transported to the Santa River Valley confirmed the existence of one or several prehistoric rock-debris avalanches from the northern summit of Huascaran and provided additional information about the extent of the affected area.

The suggested limits of the paleo-avalanche shown in Fig. 2, reflect known events as well as locations of large granite boulders identified as transported by the paleo-avalanche. We also included areas splattered by mud and rocks shown in Plafker and Ericksen (1978) within the paleo-avalanche extent even though we did not find granite boulders there. Nevertheless, if we would consider paleo-avalanche events with larger volumes than the 1970 avalanche, these areas would likely be covered by their deposits.

During the field mapping, we identified large blocks of granite between 150 and 164 m above the Santa River, near the Matocoto Village. This is almost double the run-up height of the 1970 avalanche, and also some 30 m higher than the paleo-avalanche limit identified in Plafker and Ericksen (1978).

4 Discussion

The Schmidt Hammer was originally designed to test the hardness of concrete structures with more or less well-known composition, processing technology, and defined testing conditions (Koca et al. 2006). All these preconditions limit considerably the variability of properties of tested concretes, which greatly contrasts with the highly variable and often unknown properties of natural rocks for which the device has been subsequently used. Despite this, many applications outside the original scope of its intended use (Goudie 2006; Aydin and Basu 2005) show that the SH is a very valuable device for non-destructive testing of a variety of rock material properties. However, some results are unconvincing, e.g., Evans et al. (1999) obtained only a limited success in relative dating of moraines using a SH. He considers glacial reworking of previously deposited material to be the main reason influencing his results. Our work reached a similar conclusion proving that the SH-testing is not a useful method for relative dating of polygenetic landforms containing glacial as well as gravitational sediments that have experienced a long weathering history. This is illustrated by the fact that the moraine and paleo-avalanche boulders are statistically indistinguishable. This can be explained by similarities in their weathering history or by large portions of the moraine boulders being included (reworked) in the paleo-avalanche sediments. These two groups can be distinguished only through field geomorphologic mapping by carefully examining the sedimentological and morphological evidences of glacial deposits and landforms overlain by paleo-avalanche sediments.

On the other hand, statistical analyses of mean *R*-values showed that in situ SH-tests can be used to identify boulders transported by the 1970 rock-debris avalanche, which have quite distinct properties from the other two groups. These boulders generally were correctly identified during the cluster analyses in 83% of cases.

If we interpret the SH-test results in terms of relative ages of the superficial deposits, we would conclude that the paleo-avalanche boulders were closer in age to the moraine deposits (minimum-limiting age estimated by Rodbell 1993 to be 30,000 B·P) than to the boulders of the 1970 rock-debris avalanche event. This result is very imprecise, but supports the assumption about a long rock-debris avalanche history within the region. The similarities between the paleo-avalanche and moraine deposits may also be explained by erosion by the avalanche incorporating substantial volumes of moraine material during its movement. This explanation was questioned by Cluff (1971) when describing the 1970 avalanche. He stated that in most parts of the 1970 avalanche track, its material had overridden and been deposited on top of original surface without causing large morphological changes of the relief. This is supported by close examination of the pre-1946 and post-1970 avalanche aerial photographs, which did not reveal any large morphological changes in the 1970-avalanche track. Also volume calculations of the 1970 avalanche in Plafker and Ericksen (1978) do not require substantial input from the debris other than the rock material mobilized within the source area. The only evidence of erosion by the avalanche are in Plafker and Ericksen (1978), who reported intensive erosion caused by the rock-debris avalanche in the upper course of its track resulting in lowering of the crests of the moraines by 10–20 m and deepening of the original channels. Nevertheless, considering the much larger volumes suggested for the paleo-avalanche, the only significant morphological evidence of it is the debris-flow fan in the Santa River Valley. The upper track of this avalanche, including several steep and rather narrow lateral moraines, does not show any significant alteration or irregularity compared to similar areas elsewhere in the Santa River Valley. Therefore, we suggest that the similar SH-test characteristics reflect rather the similar age and weathering history of the studied sediments.

The major difference between the 1970 and 1962 rock-debris avalanches was the unexpected path of the material that destroyed Yungay in 1970. It was caused by curvature of the channel, the uneven height of its banks (lower height of cut-bank), and sudden drop (narrowing) of the channel transporting capacity. These conditions are quite similar to those responsible for similar debris-flow overflows in Aguas Calientes Village, Cuzco, Peru (Vilímek et al. 2006). Thus, identifying these conditions may be useful in evaluating the debris-flow hazard elsewhere.

It is very difficult to establish a frequency–magnitude relationship for the catastrophic events originating from the northern summit of Huascaran. The reasons are both paucity of recorded historical events and variety of triggering factors responsible for them, including earthquakes (Table 1). Moreover, long-term effects of climate change described by Thompson (2000) and Ramirez et al. (2003) may play an important role in triggering past as well as future rock-debris avalanches. Evaluation of these effects is almost impossible because of the absence of reliable data describing current climatic conditions at the avalanche source area and Huascaran ice cap, and missing link among changes of these conditions and avalanche's triggering processes. Therefore, it is not clear which future climate change scenario would enhance or diminish the rock-debris avalanche hazard. It is obvious that several possible processes responsible for triggering of very large events (reaching size 8 or 9 using the debris-flow classification of Jakob 2005) exist. We suggest using the probability of occurrence of an earthquake with similar or higher magnitude than the one on May 31 1970 as a proxy to define recurrence intervals of similar catastrophic events. It is because this is the only evidence, though weak link between triggering factor and large rock-debris avalanche occurrence. Study by Heras and Tavera (2002) suggests the minimum return period of such earthquakes (with M_L equal to or higher than 7.2) is 50 years for the Huascaran region (District of Ancash). It is not likely that every earthquake of the similar magnitude to the May 1970 will trigger a rock-debris avalanche on Huascaran, but coupling an earthquake of certain magnitude with a catastrophic event of given magnitude can help to define the hazard possibly imposed on the local inhabitants.

To use the paleo-avalanche evidence to assess current and future hazards is even more difficult and speculative because the only approximation of its possible age was drawn from relating the paleo-avalanche age to the moraine sediments based on the SH-test results. Therefore, this approximation is very uncertain. Just how inaccurate such assumptions about the age of large, unrecorded events can be, is illustrated in the results of Bell 2007. This detailed analysis precisely dated the historical occurrence of a large landslide, which was previously considered to be thousands of years old. If we accept the possibility of "reclassifying" the "prehistoric" rock-debris avalanche as a "historic" event, the appeal of Plafker and Ericksen (1978) to use its extent to delineate safe areas for housing gains additional strength and seems to be reasonable.

Unknown triggering mechanism of the 1962 rock-debris avalanche is a source of further uncertainty in assessing future avalanche occurrences. It could be connected with geomorphological processes continuously reducing the stability of the rock mass in the W wall of Huascaran as was witnessed during visual inspection which revealed accumulation of fallen rocks on the glacier below the wall (M. Z. Luyo, oral communication).

Unfortunately, there is no relevant quantitative information allowing evaluation of the effects of climate change on these processes. Furthermore, monitoring, modeling, and predicting of rock-slope stability in the source area of the avalanches are very difficult because of its inaccessibility and the extremely dynamic processes.

The smaller debris-flow (size class of 7 based on Jakob 2005) was triggered by high precipitation and even though it took the same path as the 1970 rock-debris avalanche, its source area lay much lower in the moraine accumulation.

Comparisons between granulometric analyses of recent sediment samples and those taken a few weeks after the 1970 event (Plafker and Ericksen 1978), show interesting changes in the grain-size composition of rock-debris avalanche sediments. Even though interpretation of the sediment composition may be questionable due to the small number of samples (12 in Plafker and Ericksen 1978 and 5 from our recent study), we observed large differences in fine-particle content. The samples from 1970 reach 3.5–24.4% in silt and clay content whereas the recent samples show maximum abundances of 1.5% for this grain-size fraction. On the other hand, gravel-size particles make no less than 39.6% of recent samples whereas they constituted only up to 39.1% of the samples from 1970. We suggest that these differences are not due to limited sampling, but they rather reflect intense wash-out (elutriation) processes gradually changing the sediment composition at least in the near-surface layers from which the samples were taken.

The assumptions about the physical conditions and behavior of the prehistoric rock-debris avalanche presented in Plafker and Ericksen (1978) do not consider the possible influence of varying topography in the studied area which has experienced large changes since then. These include especially sedimentation and erosion processes, which are in general very dynamic in the area under study.

5 Conclusion

The Schmidt Hammer tests proved to be a powerful method for identifying the 1970 rock-debris avalanche deposits, but were not useful in distinguishing the paleo-avalanche sediments from the moraines. The boulders of the 1970 avalanche can be distinguished quite well on the basis of the means of *R*-values. Other characteristics of the boulders included in the statistical analyses (e.g., standard deviation of *R*-values and volume of the boulders) did not improve the test performance.

When interpreting the SH-test results in terms of relative age of superficial deposits, we may conclude that the paleo-avalanche boulders are similar in age to the moraine deposits. This may imply that the paleo-avalanche (or sequence of avalanches) is as old as 30,000 BP, based on the minimum-limiting age of moraines estimated in Rodbell (1993). This conclusion should be further studied and verified, preferably by means of absolute dating.

Our latest field investigations provided evidence that the extraordinary large paleo-avalanche or series of smaller events reached 30 m higher on the counter slope of the Cordillera Negra than had been previously identified.

A future recurrence of an event of the size and nature of 1970 debris-rock avalanche has to be seriously taken into account in land-use planning in the area, because published information shows that preparatory as well as triggering conditions of this type of disasters are either still present in its source area or their probability of occurrence (e.g., earthquakes) is quite high (e.g., 50 years). The presented geomorphological evidences of dangerous rock-debris avalanches from Huascaran may be used for urban development management. Moreover, the study pointed out serious deficit in knowledge about possible rock-debris avalanche triggering mechanisms affected by current climate change. The missing information is fundamental for more reliable hazard assessment of the studied area.

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