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A catastrophic landslide near Rampac Grande in the Cordillera Negra, northern Peru

Abstract This paper provides a detailed account of the landslide that took place between 09:00 and 10:00 AM on April 25, 2009, near the village of Rampac Grande in northern Peru (department of Ancash). Lives were lost and property destroyed during the event. Archive information, remotely sensed data, and detailed field investigations including sampling were applied to describe the events. Historically, landslides have been a common problem in this region with recorded events dating as far back as the 1800s. The landslide is considered as a deep-seated composite rotational–translational earth slide–earth flow. The local community suspected that a mining company had triggered the landslide as it prospected for precious metals. No evidence was found to suggest that anthropogenic activity caused the landslide. Instead, it was likely caused by the considerable amount of cumulative precipitation during the annual rainy season. Several possible sources of future landslide reactivation have been identified. Finally, a poster has been produced for the local community providing basic information about the event and how to manage the potential future landslide hazard. It is hoped that this simple method of knowledge dissemination will provide a fundamental bridge between the efforts of research scientists and the needs of the local community.

Keywords Landslide · Precipitation · Evapotranspiration · Capacity building · Cordillera Negra · Peru

Introduction

Between 09:00 and 10:00 AM local time on the 25th April 2009, a landslide occurred near the village of Rampac Grande, Carhuaz Province, Ancash Department, northern Peru (Fig. 1). This landslide was located on the northeasterly facing slopes of the Cordillera Negra, the westernmost range of the Western Cordillera in the Peruvian Andes. Within the Cordillera Negra, the nearby mountain of Cotocancha reaches elevation of 4,100 m above sea level (asl). The area affected by the landslide (Fig. 2) lies at an elevation between 2,840 and 3,370 m asl, and it belongs to the Santa River basin, which is limited on the west side by the Cordillera Negra and on the east side by the Cordillera Blanca.

The later mountain range is object of scientific research aimed on glacier recession, moraine lakes, stability of their dams, and use of their water for electricity production and agriculture. On the other hand, apart from the presence of several large mines, the Cordillera Negra is left behind the scientific interests. The presented landslide brought wide attention of the Peruvian officials, journalists, and experts to this region. It was because of the casualties and also the "unexpected" occurrence of the landslide due to absence of the public awareness about this problem. Three months after the event, the local community still missed answers to the basic questions related to the landslide. It was also handling the increasing fear from the "unknown" situation. Therefore, we decided to collect maximum information about the event and present it to the local community and officials to support them in their effort towards landslide mitigation and risk reduction.

The main aim of the presented paper is to describe the landslide, its morphology, movement mechanism, and triggering conditions. To achieve this, the following objectives are to be addressed. Review of the archive sources about historical landslide occurrences including satellite images. Detailed field mapping along sampling and their laboratory analyses are conducted to correctly describe the event. Seismic and climatic data are interrogated to constrain the possible causes of the landslide. Attempt is made to summarize the findings for the use of local community and present it in form of poster.

Background

Geology

The landslide occurred in an area characterized by basement rocks of Mesozoic age. More specifically, the basement comprises folded metasedimentary rocks of Middle–Upper Cretaceous age (Fig. 3). These rocks of siliclastic and carbonate compositions are collectively termed the Goyllarisquizga Group (INGEMMET 1995; Weston 2008). The group contains limestone, shale, mudstone, claystone, sandstone, and conglomerate. These are further divided into the Parihuanca and Carhuaz Formations. The basement rocks are conformably overlain by various igneous rocks of Cenozoic age. More specifically, the rocks comprise the flat-lying intermediate to felsic tuffs and flows of the Calipuy Group (Weston 2008). These rocks are intruded in places by stocks of Neogene age, which are likely to be genetically related to the contemporaneous granodiorite batholith of the Cordillera Blanca. The sequence is also locally overlain by tuffs of Pliocene age, termed the Yungay Formation (Weston 2008). However, this formation is not present in the vicinity of the study area. Fault axes of disharmonic anticlines and synclines in both the metasedimentary basement and overlying igneous rocks generally follow the northwestern Andean trend. In addition, distinct west trending lineaments were identified to the south of the landslide (Fig. 3).

Seismic activity

Based on a study of historical earthquakes from 1900 to 2000, it is seen that the area is subject to high levels of seismicity (Bernal et al. 2002). The majority of the recorded earthquakes are superficial (<60 km) with most of the hypocenters located between the offshore ocean Peru–Chile trench and the coast as a result of the subduction of the Pacific Plate. The largest recorded earthquakes reached a magnitude of 6.4 mb with an intensity of VIII MM. These occurred in both 1966 and 1970 (Bernal et al. 2002) resulting in serious devastation within the region. However, the majority of the recorded earthquakes have an intensity of III or IV MM. Within Peru, the offshore area around the Ancash coast has one of the greatest probability of an earthquake with a magnitude of >7.2 Ms (Heras and Tavera 2002).

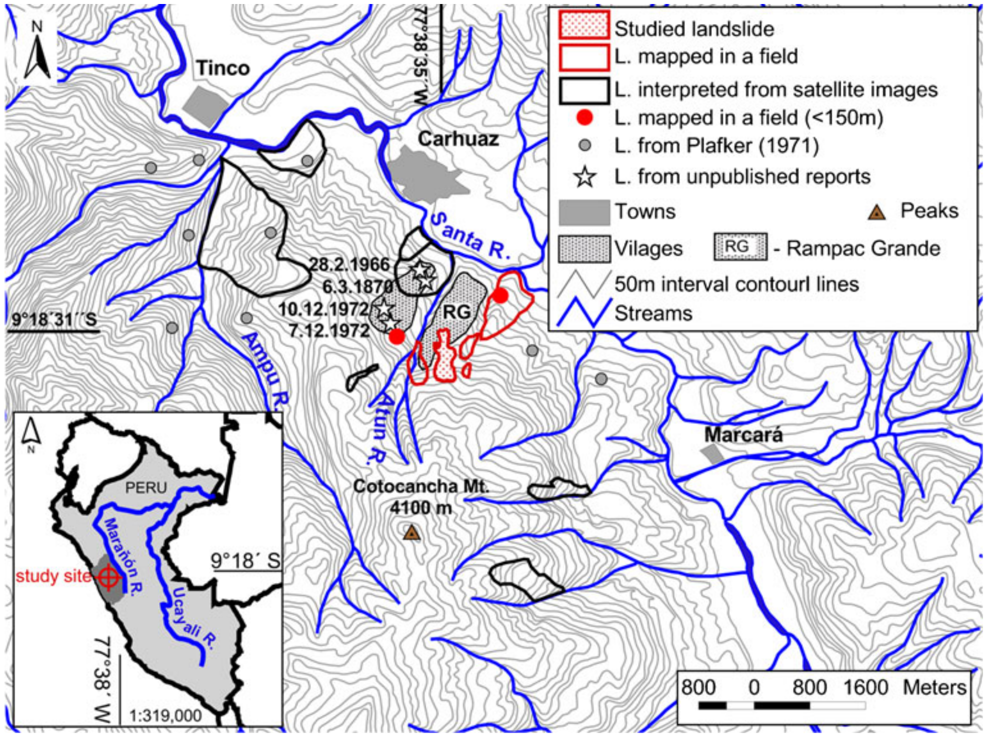


Fig. 1 Location and landslide inventory map of Rampac Grande village and its surrounding (*L.* landslide)

Climate

The village of Rampac Grande is characterized by the mild climate typical of tropical mountains. The annual average temperature varies between 11°C and 16°C depending mainly on altitude. The precipitation pattern is affected by seasonal shifts of the Intertropical Convergence Zone (Kasser et al. 1990). Annual precipitation ranges between 500 and 1,000 mm with significant seasonality. The dry period lasts from May to August whereas the rainy season lasts from October to April.

Natural hazards

The problems posed by natural hazards have only been evaluated for the main residential areas in the Santa River Valley, such as for the provincial capital of Carhuaz (Gutierrez et al. 2004). Outside of these areas, potentially dangerous processes have only been described in a very general manner. However, the Cordillera Negra is highly prone to a variety of landslide types due to its lithology, steep terrain, sparse vegetation, intense precipitation, and strong seismicity. It is also populated by mostly small, dispersed settlements, which rely on agricultural production to sustain the local economy.

Methods

Documentary evidence and GIS analyses

Several methods were used to describe the landslide, to identify its passive and active parts, and to reveal the possible triggering factor. The past landslide occurrence near the studied landslide was compiled from archive literature sources, including unpublished reports. In some cases, the landslide location is rather indicative. The 2003 SPOT image was used to provide some general information regarding the main relief forms and related morphological processes operating on the northeastern slopes of the Cordillera Negra. GoogleEarth imagery and a digital elevation model of the study area constructed from a topographic map with a contour interval of 50 m have been used as a basis with which to characterize the slope conditions prior to the landslide and to describe landslide kinematics. The distances of displaced material were measured in a GIS. These values have been derived using the available topographic data and should only be used as an illustrative guide. Samples of material were taken from different parts of the landslide.

Fig. 2 General view of the transport (*f* in Fig. 4) and accumulation (*l*, *k* in Fig. 4) part of the landslide. Approximately in the middle of the figure, distinct break in the slope can be seen. Below the accumulation zone, one of the endangered houses can be seen

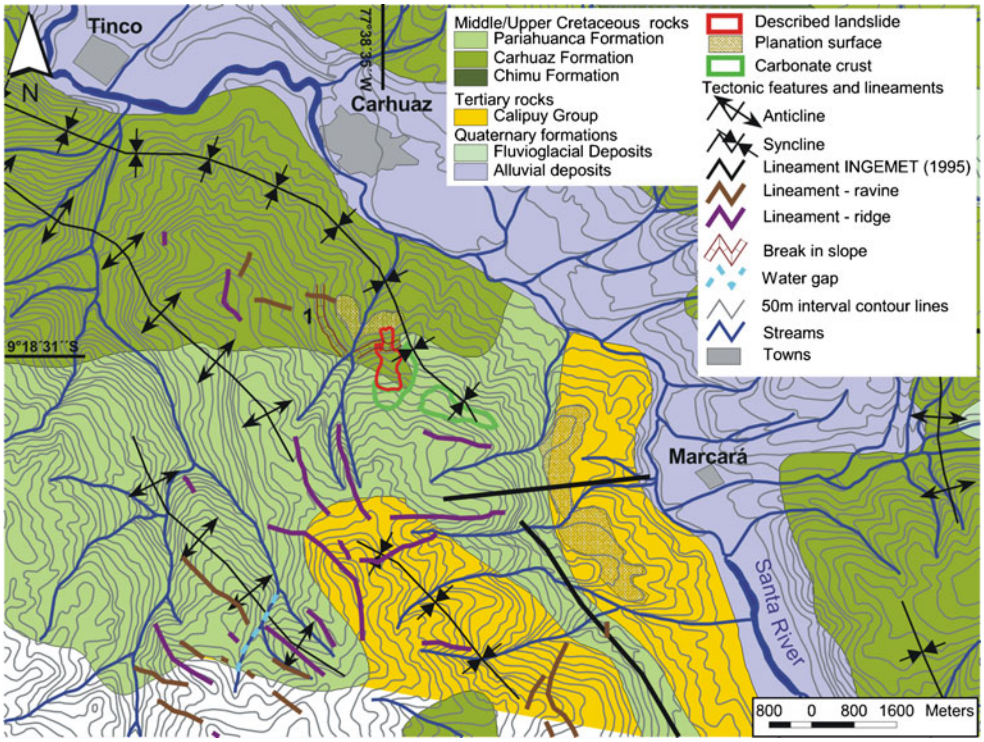


Fig. 3 Geological and geomorphological map of the study area. This map has been constructed from INGEMMET (1995), SPOT image interpretation, and field mapping

Fieldwork

Field geomorphological research done in July 2009 enabled us to describe the main landslide forms and hydrological features. They are shown on a "photomap" based on the panoramic view of the studied landslide from the main square of the Carhuaz town. Interview of the local inhabitants enabled us to describe the landslide event itself. Longitudinal and transversal topographic profiles of the landslide were constructed using a LaserAce inclinometer device. Seven samples of the landslide material were taken from its surface for later granulometric and clay mineral analysis. Two samples are derived from the scarp (sample nos. 3 and 6), three from the transported zone (samples nos. 1, 4, and 5), and two from the accumulation zone (samples nos. 7 and 8; Fig. 4).

Precipitation analyses

Precipitation and temperature data were taken from the meteorological station of Huaráz, located in the Santa River Valley between the Cordillera Negra and the Cordillera Blanca. The station is located at an elevation of 3,080 m asl, some 25 km southeast of the study site. This is the closest station with detailed meteorological data. It has recorded precipitation data on a daily basis from 1998 to 2009 and has monthly totals for the period 1955–2009. The precipitation data were analyzed using several methods. These included calculating the 10, 15, 20, 30, 50, 60, and 70 days moving averages for the period 1998–2009 and difference between long-term average precipitation totals for rainy seasons (October–April) and actual rainy season precipitation totals. The

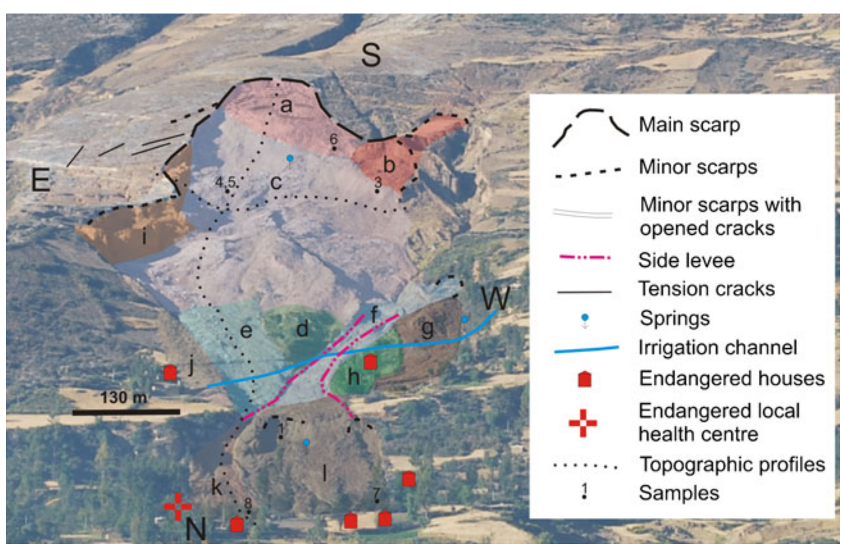


Fig. 4 Oblique photo of the studied landslide with the main landslide features. *Letters* indicating different parts of the landslide are described in detail in the text

difference between the monthly potential evapotranspiration and monthly total precipitation was also calculated using Hargreaves Formula in the software DyilyET.

Results

Historical slope activity

A number of types of landslide have been observed on the slopes of the Cordillera Negra (Fig. 1) near the study site. However, the majority of these have not been described or studied from a scientific perspective reflecting the fact that until now little research has been undertaken in the Cordillera Negra. During recent decades, two significant landslide events have affected the Cordillera Negra. The first followed the major earthquake of 1970 (Plafker et al. 1971) while the second was associated with the major El Niño event of 1997–1998 (Rein 2007). Following the major earthquake of 1970, a considerable number of landslides occurred in both the Cordillera Negra and the Cordillera Blanca. The majority of scientific interest focused on the ice and rock avalanche at Huascaran Mt., whereas little information is available regarding the far more common but smaller landslides that occurred in the Cordillera Negra. For example, Enkeboll (1971) made only a passing reference to the "...numerous scars of local slides on the mountainside west from Caras". Plafker et al. (1971) presented a landslide inventory map mainly compiled from aerial photographs. It shows more than 1,000 single landslides. From the map, it is apparent that several landslides occurred around Rampac Grande. Following the major El Niño event of 1997–1998, at least 93 slope movements, from which some caused casualties, occurred in the Callejón de Huaylas (Santa River Valley) in early 1998. In February 1998, the main road was blocked in four places between the cities of Huaráz and Yungay as a result of debris flows from the Cordillera Negra (Vilímek et al. 2000). Unfortunately, none of the available literature sources specifies the total number of landslides that occurred in the Cordillera Negra.

Further historical slope deformations have described in Rampac Chico. This village is located on the left bank of Atun Stream, at an elevation of 2,850 m asl (e.g., Barrón 1972). Early in the morning of the 6th March 1870, a large landslide hit the village causing 99 houses to be destroyed and the death of about 400 inhabitants. It has been suggested that this figure may actually have been closer to 600 (Gutierrez et al. 2004). As certain difficulties are associated with determining death tolls from archive information and such discrepancies are typical. Evans et al. (2009), working on the ice and rock avalanche at Huascaran Mt., demonstrated that these calculations may be prone to overestimating the number of deaths. The slope deformation is described as "aluvion" in the historical records, the local name for debris flow like movement. According to Zapata (2002), the event was likely to have been triggered by the seepage of water from a lake situated on a slope above the village into which discharged small streams from the Cordillera Negra. It is not clear, from this description, if the lake was natural or an artificial construction used for irrigation purposes. The latter appears more likely. Artificial lake appears only 50 m from the described landslide (Fig. 5). The description of the event is too vague to be certain of the underlying cause. It may be a debris flow caused by a lake dam outburst or by the reactivation of an older landslide and the pond developed at the toe of the main scarp as a result of its previous activity.

On 28th February 1966, an event took place in the vicinity of the village of Rampac Chico. This destroyed 25 houses. The landslide has a total length of 425 m and a width of displace mass of 250 m. Zamora (1966) suggested that a high amount of subsurface water had collected in the vicinity of the landslide. This was evidenced by the abundant water sources, including numerous springs and the permanent flow in Atun Stream. It was suggested that these water sources collected underground. The presence of a small lake also contributed to infiltration. The notion of an elevated amount of surface water hereabouts remains highly speculative. However, based on our field observations, it cannot be disregarded completely. The small lake may play a similar role to that described for the landslide on the 6th March 1870. It may have formed as a result of past landslide and its contribution, in terms of water infiltration, to the new event is likely to be negligible. Zamora (1966) also mentions observations made by local people, who reported open trenches in the upper part of the slope that evolved before the main movement phase. This suggests that the catastrophic phase of landslide was preceded by slower movement during the preparatory phase. It is particularly useful as it can be used as diagnostic evidence of forthcoming landslide activity.

Two other landslides are reported as having destroyed houses in Rampac Chico (Zapata 1972). The first occurred at 6 am on the 7th December 1972. This destroyed four houses and killed one woman. The second occurred 3 days later on the 10th December 1972. This destroyed two houses. In both cases, evidence was found for the reactivation of older landslides. Zapata (1972) suggests that both were caused by the saturation of highly weathered and loosened permeable slope sediments lying over largely impermeable rock layers. Nevertheless, such geological settings were not proved by the presented research.

Geomorphological and geological conditions of the landslide

The geomorphological conditions prior to the landslide have been examined using existing topographic maps and GoogleEarth imagery (Fig. 5). The imagery clearly shows the material stored in the source area that was mobilized during the landslide. The slope has been interrogated using a digital elevation model with a horizontal resolution of 30 m. The average slope angle is 26° with a standard deviation of 6°. The maximum slope angle is 43°, and the minimum is 10°. The eastern boundary of the landslide is terminated by a steep ravine (no. 2 on Fig. 5). This ravine forms an important local tributary for the Atun Stream. During the landslide, it served as a conduit channel for the displaced material. The material partly filled the ravine and accumulated on both sides (no. 3 on Fig. 5). The buried ravine still has a surface expression in form of 2 m deep "V" shaped gully, which divides the accumulation into two distinct lobes. A second ravine cuts through the source area of the landslide (no. 4 on Fig. 5). This merges with the first ravine on the lower part of the slope that was destroyed by the landslide. This second ravine changes its direction sharply twice within its length of 350 m. It follows the general northwesterly trend of the local fault and lineament systems. This suggests there may be an underlying structural influence in the vicinity of the study site. The western boundary of the landslide lies close to another gully. Again, the sides of the gully were remodeled by the landslide.

A distinct limestone crust covers the eastern margin of the source of the landslide. This extends over an area of 0.2 km^2. A

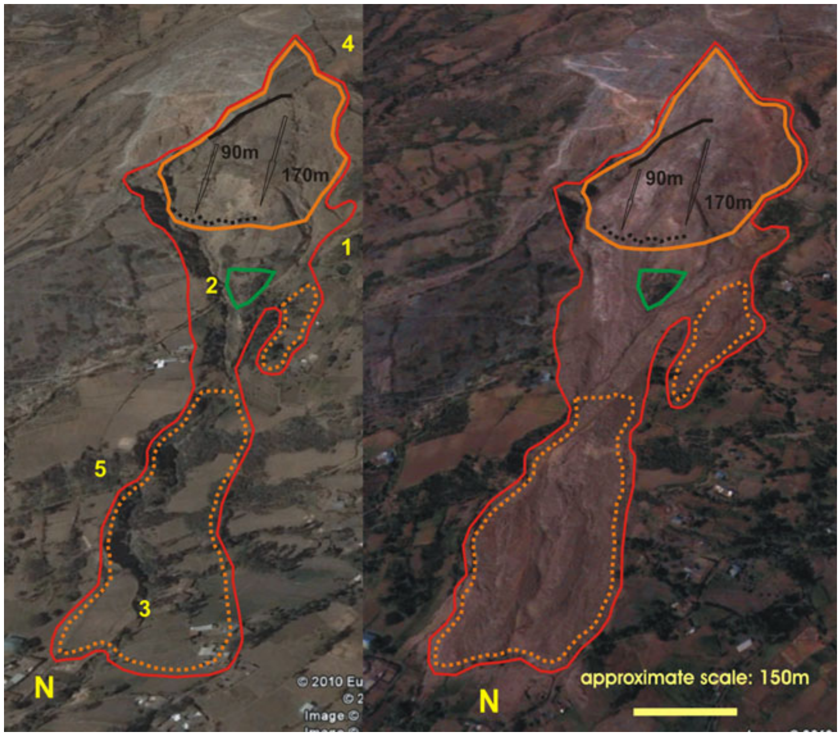


Fig. 5 Comparison of GoogleEarth satellite image before the landslide event (*left*) and after the event (*right*). *Orange solid line* zone of depletion; *orange dashed line* zone of accumulation; *black solid* and *dashed lines* displacement of the upper part of landslide; *numbers* indicating horizontal displacement; *green solid line* area with least displacement; *1* artificial lake; *2* and *4* ravines; *3* accumulation area along the ravine; *5* distinct break in the slope

distinct break in the slope is marked by green vegetation (no. 5 on Fig. 5). This break is also seen on the geomorphological map (Fig. 3). It maintains an elevation of between 2,990 and 3,090 m asl and runs for a length of 1.7 km. The break is interpreted to be the morphological expression of contrasting lithologies.

The geomorphological features that characterize the wider area around the landslide are shown in Fig. 3. Particularly notable are lineaments represented by ridges and ravines. The ridges are defined as clearly visible tracts of locally high elevations usually affected by stream erosion in their proximal parts. Those ravines, whose followed general slope dip, were not included among the lineaments. The majority of the lineaments strike in a N–S or NW–SE directions following regional fault trends, although some strike in a W–E direction. One of the tributaries of the Ampu River forms water gap cutting through stripes of more resistant rocks forming distinct anticline ridge. Distinct, albeit small, platforms were identified on the slopes surrounding the study site. The mean slope angle of these platforms is only about 12° with a standard deviation of 7°. They have a mean elevation of 2,955 m asl and cover a total area of some 1.6 km^2. The platforms may represent planed denudation surfaces or the remnants of previous sliding, as is most likely the case in the area around Rampac Grande. Other traces of such a landslide are not visible in the field any more. We suggest that the recent landslide mobilized only small part of the area previously affected by one or series of slides dated before the written records are available. The mapping of inactive landslides was based primarily on the interpretation of SPOT imagery. Therefore, only features that could be clearly identified as landslides were included. Such features would need to be characterized by clear scarps with bodies interrupting regular topography pattern of slope. Possible landslides with less distinct morphological features were omitted in order to maintain database homogeneity. There may well be cases where a landslide was subsequently affected by more prominent ravine erosion. If this occurs, it is not possible to determine the original landslide topography.

The landslide material comprises a mixture of highly weathered argillite rocks and tuffs of various colors and mineral composition with a significant portion of secondary carbonates (Table 1). The samples contain a dominant component of clay particles with only a minor component of sand grains, and they are classified as fine gravelly very coarse slit sediments (Fig. 6). It should be noted that sample 5 has very distinct granulometric characteristics as it comprises more than 50% sand (classified as fine, gravelly, very coarse slit sediments). Mineralogical analysis shows significant differences in the composition of the samples (Table 1). This particularly relates to the smectite and quartz contents. For example, the largest proportion of smectite was found in sample nos. 5 and 6 (29% and 10%, respectively) while some traces were also found in sample nos. 1, 7, and 8 (4% each). Surprisingly, sample 4, taken just 3 m from sample 5, does not record any smectite minerals. However, the colors of these two samples are markedly different—sample 5 is ochre while sample 4 is red. This suggests that there was considerable mixing of materials from different source areas within the landslide.

The only outcrop of solid bedrock lies to the west of the landslide at the bottom of a ravine. It comprises sandstone interbedded by claystone shale. The fissure planes are commonly covered or filled by calcium. The dip orientations and dips of (1)

Table 1 The mineral composition of the individual samples

No	Color	Sm (%)	Ch (%)	I (%)	K (%)	Q (%)	Pf (%)	Plg (%)	Amf (%)	$CaCO_3$ (%)
1	Ochre	4	0	19	14	56	6	1	0	20
3	Red	0	0	11	4	85	0	0	0	26
4	Red	0	0	16	1	83	0	0	0	57
5	Ochre	29	0	16	3	43	0	8	1	31
6	Gray–white	10	0	7	5	74	0	4	0	37
7	Reddish	4	0	11	3	82	0	0	0	36
8	Reddish	4	0	6	3	87	0	0	0	37

The carbonate content has been calculated in relation to the total sample whereas the content for all other minerals have been calculated in relation to the insoluble part of the sample

(*Sm* smectite, *Ch* chlorite, *I* illite, *K* kaolinite, *Q* quartz, *Pf* Potassium feldspar, *Plg* plagioclase, *Amf* amphibole)

the bedding planes and (2) the main fissures are 243°/18° and 164°/72°, respectively. Both structural elements dip to in accord with the slope. All other rocks within the vicinity of the landslide are highly weathered with partly preserved stratification gently dipping towards the slope.

Landslide description

The Rampac Grande landslide was classified as composite earth slide–earth flow where sliding occurs along compound shear planes mostly in its upper part, and it bears signs of flow movement in its lower part. The altitudinal difference between the highest and lowest points is 383 m, and its total length and width of displaced mass are 863 and 450 m.

The main scarp is about 5.5 m high followed by number of minor scarps with opened transverse cracks in some places 0.5-m wide (Fig. 7). The cracks separate blocks of loosened rock material (including block of hard rock–argillite shale and carbonate rocks). Block surfaces are slightly back-tilled with rather well-preserved original surfaces with vegetation (Fig. 4a). Mainly vertical movement with minor horizontal displacement occurred there. The northwestern lower end of the main scarp area is pushing to the block of reddish argillite rocks with 9 m high main scarp (Fig. 8) and estimated volume of 35,000 m^3 (Fig. 4b). It bears evidence of previous sliding activity as there are old scarps and filled tension cracks on its margins. The stress caused by pushing the material under the main scarp against the rock block, along with unloading of its toe, contributed to the reactivation of this part of the landslide scarp. Sliding continued further down slope for some 280 m below the main scarp (Fig. 4c). A large majority of the landslide material was mobilized from this zone of depletion. Less deep sliding with rather short run-out was observed in the lower part of the zone of depletion bordering with the part *d* of the landslide (Fig. 4). This landslide part is largely free from the sliding material. Field observations as well as examination of the pre-landslide conditions on the satellite images suggest that this area underwent just a minor movement, if any.

Transport part (Fig. 4e, f) of the landslide starts below the zone of depletion showing signs of high mobility of the material and also, in some parts, of its flowing rather than sliding (Fig. 4f). It is indicated by the empty source area shown on Fig. 4 as minor scarp and presence of a levee along its channelized transport path with a height of up to 1 m. High mobility of the landslide material

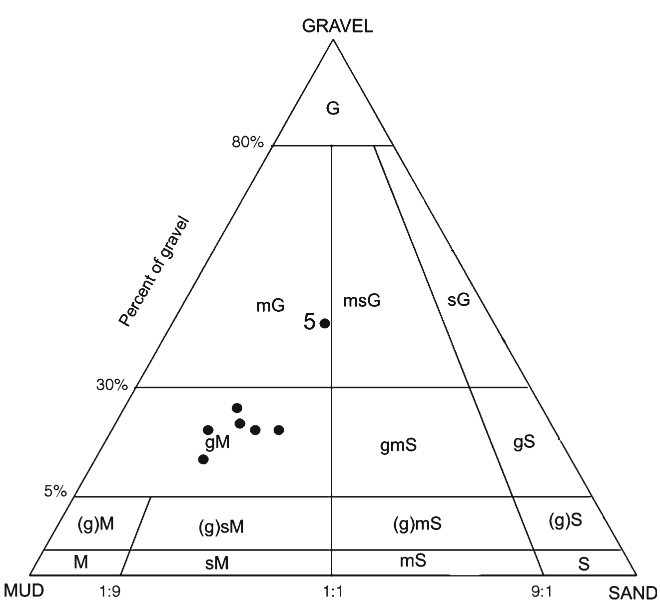


Fig. 6 Granulometric analysis of the samples (5 indicates sample no. 5)

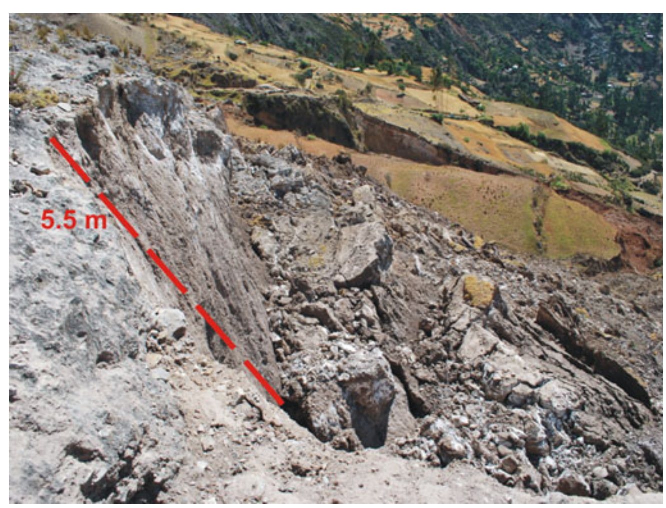


Fig. 7 Main scarp of the complex landslide (*a* in Fig. 4) with well visible minor scarps with opened cracks and rock blocks with slightly back-tilled surfaces

Fig. 8 General view of the main scarp and depletion zone of the landslide (*a*, *b*, and *c* in Fig. 4) from east to west

Fig. 10 Farm house destroyed by stones transported aerially (*h* in Fig. 4). Accumulation with depth up to 1.8 m (*g* in Fig. 4) can be seen *left* from the house

is evidenced by the fact that part of the material was transported aerially on top of the stable ground (Fig 9, Fig. 4g). The maximum measured length of earth flow material transported through the air is 56 m with a vertical exaggeration of 26 m. It is pertinent to note that a house located outside the landslide area (Fig. 4 description h) was badly damaged by stones which fell on top of it, destroying mainly its roof (Fig. 10). Around the house, splashes of mud and "exotic" stones with diameters of up to 0.4 m were found on otherwise undisturbed ground and vegetation. Furthermore, tree branches were broken up to 3 m above the surface of the landslide (Fig. 11). Distinct side scarps 7 m high detached rock blocks (Fig. 4i) which formed part of the east landslide limit. The largest rock block has estimated volume of 27.000 m^3. The toes of these blocks are partly covered by transported material, so the original depth of the ravine on which side the slide blocks evolved could be only estimated to 11 m.

Part of the transported material was accumulated along its way down slope. On the northeast side (Fig. 4j), the material was deposited on the area of about 1,100 m^2 in the place where it overtopped side of the ravine forming the eastern landslide limit. Thickness of this accumulation is 0.4 m, and it stopped just next the limits of the closest house. Another accumulation was deposited on the opposite side of the landslide (Fig. 4g), covering an area of about 7,200 m^2 and reaching the thickness of 1.8 m. The main accumulation area (Fig. 12, Fig. 4k, l) has thickness ranging from 0.5 to 7 m. It destroyed one house and stopped 25 m from another house and 36 m from the local health center. It formed two distinct lobes separated with up to 2 m deep ravine. Its material was washed out on its sites as well as along its toe covering areas previously free of the landslide material. Deposition of material up to 0.3 m develops in this way. Before reaching

Fig. 9 Splashes of landslide material on stable ground (*g* in Fig. 4) indicate that the material came from *left to* the *right* of the photo

Fig. 11 Note scars on the trunk and broken branch of the tree caused by landslide material. It is located just on the border between parts *f* (assumed earth flow) and *h* in Fig. 4

Fig. 12 Accumulation area of the landslide with two distinct lobes (*l* and *k* in Fig. 4). This part of landslide caused largest damage

the accumulation area, the material overcame the distinct break in the slope (with slope angle of 40°) where two small (about 10 m high) slides with well visible shearing planes developed.

Freshly opened tension cracks were identified beyond the upper eastern part of the landslide. These cracks have widths of between 2 and 7 cm while some also record vertical displacements of up to 5 cm. The cracks have developed due to unloading acting tangential to their strike. In the same area, older generations of cracks have filled with weathered material. Local inhabitants have confirmed the periodic development of these features without relation to obvious landslide movement.

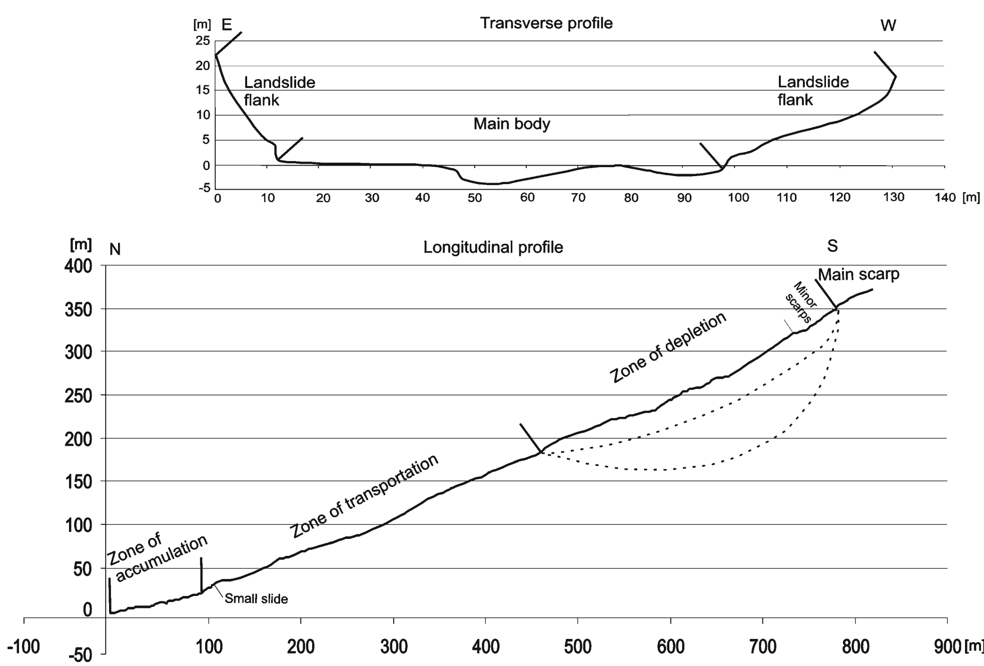
Estimated depth of the main surface of rupture is between 50 and 100 m in the place of the topographic profile (Fig. 13). Their depths and shape were determined uniquely interpreting the profile data, landslide morphology (identification of the toe of surface of rupture), and basic assumption that the landslide moved along mostly planar shear plane. It is probably rotational near the main scarp (Fig. 13). Further downslope, no evidences of rotational shape of the shear plane were found. The 50-m depth of the surface of rupture may, at least in some parts of the landslide, overestimate the actual landslide depth. Thus, the deeper estimate (100 m) is rather a scenario for the case that the surface of rupture would be rotational, which we think is less probable. The longitudinal profile also shows that the zone of depletion is disrupted by local ridges and depressions which are usually conform to the landslide longer axis.

Triggering conditions

A number of local people, including officials from the municipality of Carhuaz, were interviewed for their opinions regarding the possible causes of the landslide. All were convinced that the event was caused by the prospecting efforts of an unspecified mining company. The company was thought to be using explosives in order to find precious metals. The main supporting argument for this was that no earthquake or rainfall events occurred before the landslide. However, no evidence exists to suggest a blast actually occurred, and no other evidence for anthropogenic activity was found within the vicinity of the landslide during our fieldwork. Therefore, we decided to examine the earthquake and rainfall records more closely. The USGS National Earthquake Information Centre has only one record at the time of the landslide. At 18.51 UTC, an earthquake occurred with a magnitude of 4.2 nbGS. The hypocenter was located some 758 km SSE from the study site at a depth of 85 km. The low intensity of the earthquake and its considerable distance from the study site allow us to rule out any seismic trigger for the landslide.

The climatic data from the meteorological station of Huaráz were then examined more closely. It was clear that the recent precipitation record confirmed the observations of the local people. No precipitation was recorded in the 7 days prior to the event, and the total amount of precipitation for the 10 days preceding the event was 13.4 mm. In fact, a significant water deficit (−30 mm) was calculated for this period once the daily total potential evapotranspiration had been set against the total amount of precipitation. Calculating the 10, 15, 20, 30, 50, 60, and

Fig. 13 Longitudinal and transverse topographic profile of the landslide. Note the main landslide parts and suggested surface of rupture. The profiles are not elevated. Their location is shown in Fig. 4



70 days moving averages largely failed to provide any explanation for the landslide. In every case, the landslide occurred during an overall decrease in mean precipitation, which showed a distinct peak 7–14 days before the event. The 30 days moving average curve shows minor peak for 24.–25.4. In addition, much larger values of the moving average occurred in February 2009 when compared with the data for April 2009 (Fig. 14). However, the difference between the monthly potential evapotranspiration and monthly total precipitation was also calculated (Fig. 15). These data show a large precipitation surplus of 100 mm for March 2009 that changes to a precipitation deficit of 17 mm for April 2009. This implies that the landslide could have resulted from the accumulation of excess water during March 2009 if a lag of about 25 days between rainfall and landslide is assumed. Nevertheless, we cannot rule out the possibility that the landslide movement started during the peak precipitation in April and accelerated into the sudden event after several days (10–14) of preparatory phase. Unfortunately, no witnesses about possible movement initiation in the crown area are available.

The changes in total precipitation during each rainy season (October–March) in relation to the long-term average have also been examined (Fig. 16). There is a clear increase in the total amount of rainy season rainfall from 1982 to 1983. This is particularly pronounced from 1997 to 1998. The total amount of rainy season rainfall peaked at 975.6 mm in 2008–2009, the same year as the landslide. This is despite the fact that two strong El Niño events, characterized by enhanced precipitation, occurred during this time (Kane 2000). During the first event in 1982–1983, the rainy season precipitation total attained 880.8 mm whereas during the second event in 1997–1998, the rainy season precipitation total attained 912.9 mm. Moreover, the monthly rainfall of 229.6 mm recorded during March 2009 was the second highest monthly total recorded after March 2006 (252.6 mm). If the amount of precipitation is the major triggering factor for the studied landslide, its initiation relates more closely to longer-term trends rather than short intense rainfall events. Therefore, long-term soil saturation may be decisive in dictating the occurrence of landslides. The extreme rainy season of 2008–2009 is likely to have caused saturation and build-up of pore water pressure in the deeper parts of the slope, lowering its stability and resulting in the sliding and subsequent flow processes.

Hydrological conditions

Three springs have been observed within or close to the body of the landslide during field mapping in August 2009. The first fissure spring on the northwestern limit of the landslide, in the fractured sandstone outcrop, yielded a flow of 0.07 l/s (4.2 l/min). The water flows out of open cracks of up to 5 mm. However, it is beyond the limit of the landslide in the almost vertical slope of a ravine. The second spring is located at the toe of the secondary slip surface that developed on the break of slope above the main accumulation. A small pond has formed around the spring. It was accompanied by a strong smell of sulfurous gasses at the time of fieldwork. The third spring is located in the scarp area and was only evidenced by wet ground. It is worth noting that these springs were observed during dry period of the year, in accord with the previous observations of Zamora (1966). The superficial drainage of the slope was considerably disrupted by the landslide. Those ravines that acted as drainage channels are now largely infilled by landslide material. Water is starting to now finding its way through those ravines, in particular, the ravine that forms the eastern boundary of landslide accumulation. Finally, there is also an artificial irrigation channel that crosses the landslide.

Discussion

Landslide kinematics

A comparison of the GoogleEarth images with field mapping allows areal extent of the landslide to be seen within its regional context. The area subjected to major displacement is located within the solid orange line in Fig. 5. The total horizontal displacement of this material ranges from 430 to 863 m. It is assumed that the areas indicated by the dashed orange lines in Fig. 5 represents the accumulation areas of the landslide and that the material was moving over predominantly stable ground. Any material incorporated from the stable ground would have been mobilized as a result of plucking by the passing landslide debris.

Clearly, not all material in the landslide underwent the same amount of displacement. For example, the area covered by limestone crust at the apex of the landslide (indicated by the solid black line, Fig. 5) appears to have been subjected to a smaller amount of displacement. This has been estimated to amount to about 170 m in the horizontal component and about 90 m in the

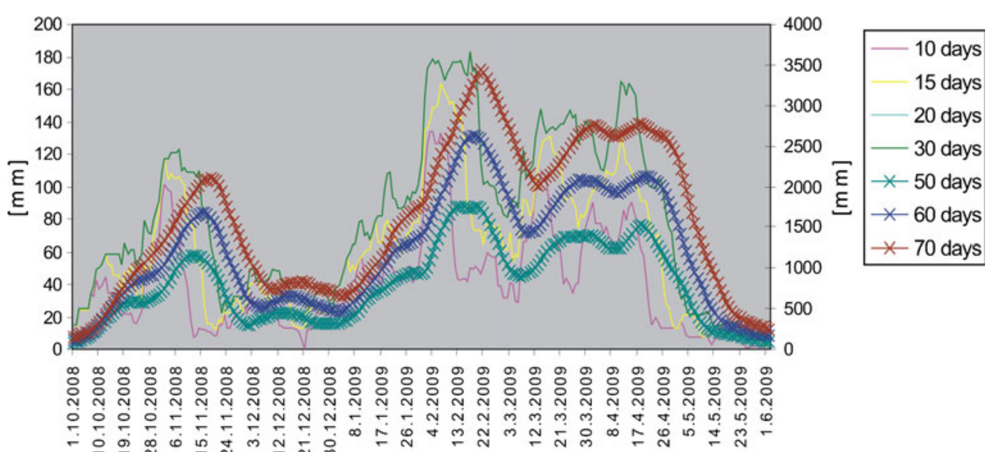


Fig. 14 Ten, 15, 20, 30, 50, 60, and 70 days moving precipitation averages for the Huaráz meteorological station

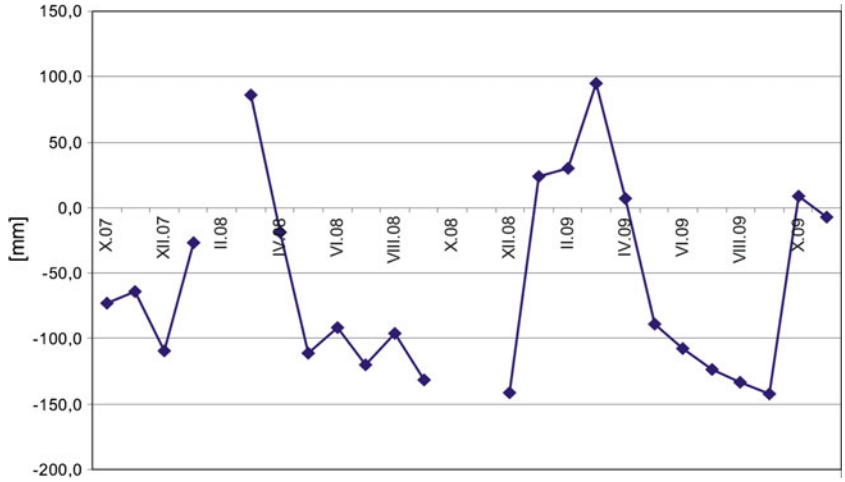


Fig. 15 The calculated difference between the total monthly potential evapotranspiration and the total monthly precipitation (data from SENAMHI)

vertical component. These figures are based on the presence of remnants of the limestone crust found within the body of the landslide.

The area subjected to the least displacement is located within the green limits in Fig. 5. Fieldwork has indicated that this middle sector of the landslide was its least active part and that, only surface material has been moved.

Future landslide scenarios

Despite the fact that the landslide has reached a stable state, a significant hazard remains. This is primarily due to the unstable positions occupied by the rock blocks that were detached by minor scarps. Their toes lack support and also suffer over deepening as a result of the evacuation of the landslide material. In addition, the loosen material beneath the head of the main head scarp has been disturbed as a result of cracks opening. These may be vulnerable to water saturation in the future that may, in turn, induce further sliding. Another source of potential hazard is the open tension cracks identified beyond the upper eastern part of the landslide. These lower the strength of the slope material and therefore make it more susceptible to future movements. However, the presence of older cracks that have healed and filled suggests that this may be a somewhat low hazard. In accord with this are the testimonies of local people, who have witnessed the opening of such cracks without subsequent slope movements. Of course to draw this conclusion may well underestimate the stability change induced by the recent landslide. In effect, the processes and thresholds that previously governed the development of this part of the slope may have changed so much that the past development is no longer possible to use to predict future landslide scenarios. The ravines that existed prior to the landslide, but are now filled by the landslide material, are another possible source of future hazard. The infilled landslide material is much less compact than the original underlying colluvium. This material is susceptible to water accumulation that may, in turn, trigger shallow sliding or earth flow movements. In addition, erosion within the ravines would slowly destabilize their slopes. Repeated stability problems around the adjacent village of Rampac Chico have been recognized in 1870, 1966, and 1972. This suggests that it is only a matter of time before another hazardous situation arises. There is no indication as to whether this is likely to be characterized by a number of smaller movements or one catastrophic event.

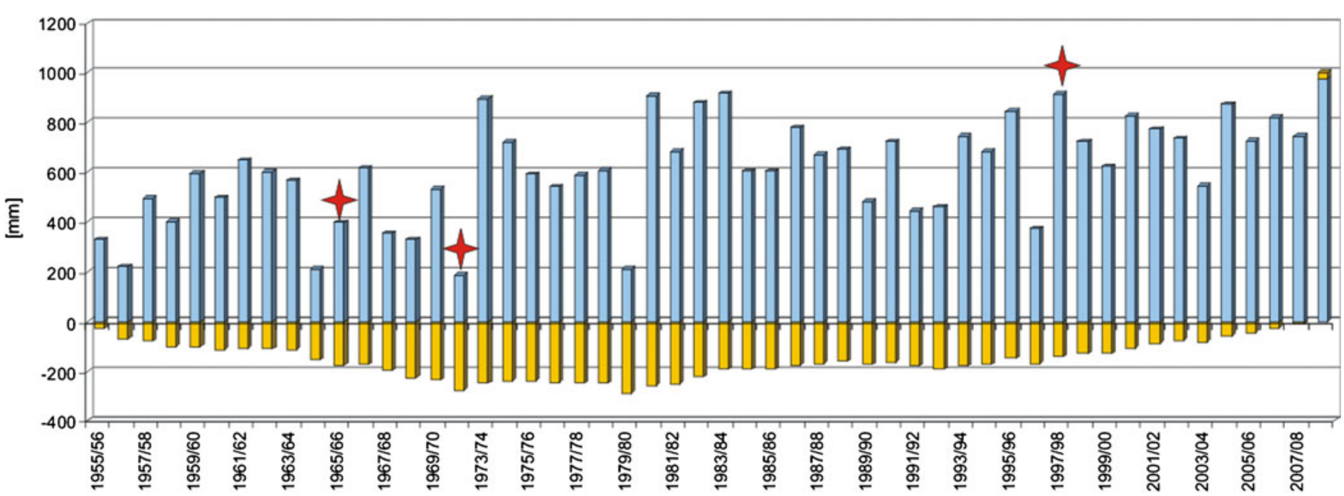


Fig. 16 The total precipitation for each rainy season (October–April) since 1956 (*in blue*) and the accumulative disparity between them and the long-term average (*in yellow*). Based on data recorded at Huaráz, the mean total precipitation during the rainy season is 556 mm for the period 1955–2009 (SENAMHI). *Red stars* mark rainy seasons with reported landslide occurrence (years of 1966, 1970, 1997)

Local community and its response to the catastrophic event

Aside from the casualties and direct loss of property, the local community has also suffered from psychological and social damage caused by the landslide. Its occurrence was particularly difficult for the community to understand as this area has not experienced such an event for 36 years, and there was no obvious triggering event. The community of Rampac Grande was not alerted by the already existing knowledge that several historical landslide events occurred in the neighboring community of Rampac Chico. It suggests how short the time needed to completely suppress information about natural hazards from human memories as well as how social, cultural, and property boundaries could limit spatial understanding of this phenomenon. Based on present knowledge and practice, the local authorities supported the community with the material and technical help required for immediate disaster relief. However, local authorities largely failed to help the community to adapt to the longer-term legacy of the event such as the loss of some of its members, properties, and agricultural terrain. In addition, a new threat is posed by the presence of an unstable landslide body in the middle of their community. These problems are clearly reflected in the opinion of the local people. From our discussions, the main criticisms focused on the absence of information regarding recent and future landslide hazards. No information has been provided on the type of damage posed by the landslide or to help people decide whether they should relocate or abandon their property. A year after the event, the local officials are still concerned about the situation and are assisting the local community in their decision to relocate the community health center situated very close to the landslide accumulation to a different part of the village.

At the time of fieldwork, the local government sent an architect to answer all these questions. Unfortunately, local officials have limited knowledge regarding the existence of expert organizations such as INGEMET (Geological Survey) and the Glaciology Department of the Autoridad Nacional del Agua. These organizations are likely to be able to help given their considerable experience in solving these types of problems. In light of these issues, we have prepared a straightforward poster (Fig. 17) that aims to provide useful and understandable information for the local community. This tries to explain what happened, why it happened, and what the next steps are likely to be. No structural measures were suggested as the poster attempts to provide information that is relevant and useful for all members of the community. The poster is written in Spanish, which partly limits its use as a number of the inhabitants of Rampac Grande speak Quechua. We have tried to use illustrative photos to deliver the most important information as not all the inhabitants are literate. The poster was sent both via email to the responsible authorities and delivered personally to them during a visit to Peru in 2010.

At this point, it is also important to note that the Zapata (1972) suggests relocating all the inhabitants of the neighboring village of Rampac Chico (600 m to the north of the study area)

Fig. 17 The poster produced for the local community. This tries to explain some of their questions about the landslide including what happened, why it happened, and what the next steps are likely to be

and giving the area over entirely to agriculture because of the considerable risk of landsliding posed to the local community. This shows good understanding of the level of risk, although it is unlikely to ever be practical due to the lack of viable alternatives. Problems include but are certainly not limited to ownership issues and the absence of areas free from other natural hazards.

Conclusions

The Rampac Grande landslide has been categorized as a deep-seated, composite earth slide–earth flow. It was caused by the considerable amount of accumulative precipitation during the annual rainy season with possible preparatory phase of 10–14 days. No evidence was found to suggest that anthropogenic activity caused the landslide. Several possible sources of future landslide reactivation have been identified. They include loose rocks below the head of the main scarp, rock blocks detached by minor scarps, material in the transportation zone, and where open tension cracks have developed as a response to stress changes within the rock massif. It is supposed that the area is stable during the dry season. During wet seasons with below average or average accumulative precipitation, only a small amount of material, if any, may be mobilized. However, if the accumulative rainfalls are as high as those recorded during 2008–2009, it is possible that a large portion of the landslide could be remobilized.

The local authorities and affected community have only a limited number of possibilities for managing the landslide hazard and risk. Therefore, the first step must be to recognize the cause of the landslide. The superficial or shallow subsurface drainage of the landslide may only have a limited effect on movement mitigation. The proper drainage of springs beyond the unstable slope would represent a basic step toward its stabilization. An effective way of risk reduction, which is quite difficult to perform, is spatial or temporal reduction of the elements at risk. In this case, it means relocation of directly endangered houses to more safe places or temporal change of their use. Such buildings could be used as agricultural facilities rather than residential houses during the rainy season. More detailed studies should be undertaken to quantify the slope stability of the affected area and to better understand the role of precipitation as the main triggering factor. It is, however, necessary remember that the village is located on a steep slope where mass movements are a common process during landform development.

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