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A re-examination of the mechanism and human impact of catastrophic mass flows originating on Nevado Huascarán, Cordillera Blanca, Peru in 1962 and 1970

Stephen G. Evans [a,*], Nicholas F. Bishop [a], Lionel Fidel Smoll [b], Patricio Valderrama Murillo [b], Keith B. Delaney [a], Anthony Oliver-Smith [c]

[a] Landslide Research Programme, Department of Earth and Environmental Sciences, University of Waterloo, Waterloo, Ontario, Canada N2L 3G1
[b] INGEMMET, Av. Canada No. 1470, San Borja, Lima 41, Peru
[c] Department of Anthropology, University of Florida, Gainesville, Florida, USA

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ABSTRACT

The 1962 and 1970 Huascarán mass movements, originated as rock/ice falls from the mountain's North Peak, transformed into higher-volume high-velocity mud-rich debris flows by incorporation of snow from the surface of a glacier below Huascarán and the substantial entrainment of morainic and colluvial material from slopes below the glacier terminus. Water for fluidization of the entrained material originated in the melting of incorporated snow and the liberation of soil moisture contained within the entrained materials. Eyewitness reports indicate very high mean velocities for the events; 17–35 m/s (1962) and 50–85 m/s (1970). The runout distances and velocity profiles of both events were simulated using DAN/W. Both mass movements continued downstream in the Rio Santa as debris floods (aluviones) that in 1970 reached the Pacific at a distance of 180 km. In strong contrast to publications in the geosciences literature, 1961 Peru Census data indicates that the death toll of the 1970 event is ca. 6000 and that total life loss in the two events did not exceed 7000 people.

1. Introduction

1.1. Preamble

On May 31 1970, a complex catastrophic mass movement occurred in the Rio Santa valley, Cordillera Blanca, Peru (Fig. 1; Ghiglino Antunez, 1971; Clapperton and Hamilton, 1971; Browning, 1973; Plafker and Ericksen, 1978; Patzelt (Editor, 1983), Chang and Alva, 1991; Evans et al., 2007). The event was triggered by a complex offshore subduction zone earthquake (M_s ~ 7.8; Lomnitz, 1971; Abe, 1972) at an epicentral distance of 150 km (Ericksen et al., 1970; Plafker et al., 1971; Plafker and Ericksen, 1978). The movement originated on the steep glacier-capped rock slope forming the west face of the North Peak of Nevado Huascarán (6654 m a.s.l.) as a fall consisting of rock and glacial ice, which in the process of traveling very rapidly downslope entrained a considerable volume of snow and morainic material from the slopes beneath Huascarán (Ghiglino Antunez, 1971; Evans et al. 2007). In doing so, the mass movement transformed into a rapidly moving mud-rich debris flow which traveled down the valley of the Rio Ranrahirca (Shacsha)[1], a tributary of the Rio Santa. Part of the debris surmounted a steep valley side of the Rio Ranrahirca (Shacsha) and swept down upon the town of Yungay burying the townsite and most of its inhabitants (Fig. 1). The main debris mass flowed over the Ranrahirca fan (Fig. 1) where most of the material was deposited. Some debris continued its movement after entering the Rio Santa valley (el. 2400 m a.s.l.), turning north (Fig. 1) and traveling downstream in the Rio Santa as a debris flood (aluvión)[2], reaching the Pacific Ocean about 180 km from Ranrahirca. With the exception of the Yungay lobe, the 1970 mass movement ran over a path that had been subject to a similar, but smaller, event in 1962 which destroyed part of the village of Ranrahirca and several smaller hamlets (Fig. 1).

The 1962 and 1970 mass movements have been documented in a number of papers in Spanish, French, English, and German (see references); the broad outlines of the events are well known in the landslide and geohazard literature largely due to the work of Plafker

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* Corresponding author. Tel.: +1 519 888 4567x33232; fax: +1 519 746 7484.
E-mail address: sgevans@uwaterloo.ca (S.G. Evans).

[1] In this paper geographical names for physical features in the Huascaran-Rio Santa area are those currently in use on an official 100,000 scale topographic map published by the Government of Peru (Instituto Geografico Nacional Map Sheet 1352, 19-h (Carhuas, Peru), Edition 2-IGN, 1:100,000).

[2] "Aluvión" is a Peruvian word used to describe a large-scale sudden mass flow of liquid mud and boulders that originates in the glacial environment.

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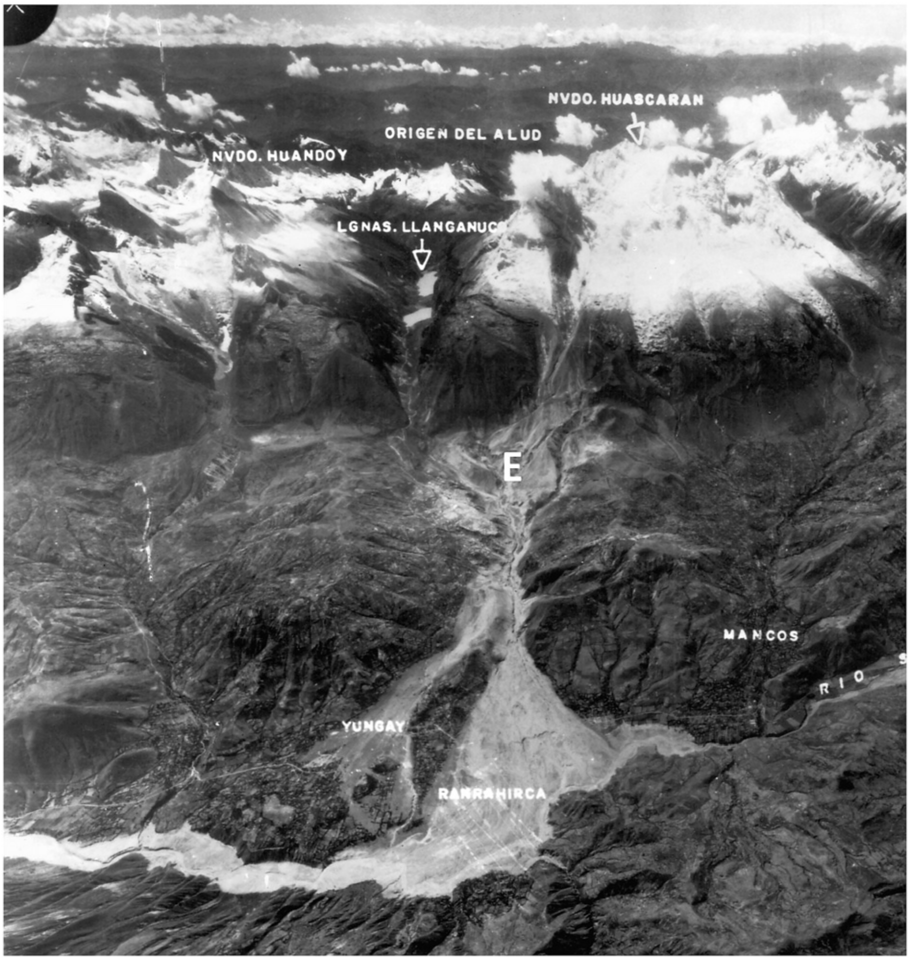

Fig. 1. Oblique aerial view to the east of the May 31, 1970 Huascarán event showing source, path, devastation of Yungay and the Ranrahirca fan, and beginning of downstream distal debris flow/debris flood following the Rio Santa off to the left. The extensive area of entrainment is seen below the terminal moraine system of Glacier 511 (E). Also visible is the peak of Huandoy, the source of an ice/rock fall triggered by the 1725 earthquake which generated a debris flow that led to the destruction of the town of Ancash. (Photograph and annotation; Servicío Aerofotografíco Nacional de Perú; June 13, 1970).

and Ericksen (1978). However, as the most recent discussion of the Huascarán events by Evans et al. (2007) suggests, important details about the events remain unclear, including the precise mechanism of the mass movements, their evolution and velocity, and the source, composition and volumes of materials involved. Moreover, the 1970 event is still considered to be a "rock avalanche" in some recent literature (e.g., Crozier, 2004; Evans, 2006; Sosio et al., 2008) implying that most of the debris involved originated from the North Peak of Huascarán and that the debris that engulfed Yungay and Ranrahirca consisted mainly of rock.

Uncertainty has also emerged about the number of human casualties in both events. For example, some estimates of the death toll in the 1970 Huascarán event alone are as high as 25,000 people (Keefer and Larsen, 2007), which if correct, represents one of the most destructive landslide disasters in history (Evans, 2006; Schuster and Highland, 2007). The 1962 event has been reported to have caused 4000 deaths, which also represents a major global landslide disaster (Schuster and Highland, 2007). However, with reference to the impact of the 1970 event, work in the social science literature based on census data, consistently states that the death toll in Yungay alone was in the order of 5000 people (e.g., Oliver-Smith, 1986) less than 1/3 of the estimates in the geological and geohazard literature.

The need for a critical re-examination of the mechanism and human impacts of the events, in order to characterize hazard and risk in the Yungay–Ranrahirca area, is highlighted by re-occupation of the 1970 debris by the local population and on-going construction of infrastructure, including a new school, on the surface of the 1970 debris.

1.2. Objectives

The present paper substantially expands and radically modifies an initial re-examination of the Huascarán events by Evans et al. (2007). Our objectives are six-fold; 1) to examine the geological and geomorphological characteristics of the area affected by the Huascarán mass movements, 2) to review and re-examine the characteristics of the 1962 and 1970 events, particularly with respect to the content of the well-known report by Plafker and Ericksen (1978), 3) to reconstruct and compare the initiation and evolution of the 1962 and 1970 events, 4) to present a first-order two-dimensional dynamic analysis of the two events based on 3), 5) to review the socio-economic impacts of the 1962 and 1970 events, including a critical examination of the reported death tolls, and 6) to examine the implications for landslide hazard and risk assessment in the Yungay–Ranrahirca area.

1.3. Data sources

Our data sources include a comprehensive review of the available literature on the events, an analysis of a digital elevation model prepared by digitizing the 1:25,000 map of the 1970 event produced by Welsch (1983), field observations in the Huascarán area and the Rio

Santa valley in 2004, 2007 and 2008, examination of aerial photographs flown by NASA (Johnson Space Center) in July 1970, examination of pre-1970 vertical and oblique aerial photographs in the archives of Servicío Aerofotografíco Nacional de Perú, Lima, and the tabulation of the 1961 Peru Census for the Department of Ancash (Republica del Perú, 1968).

2. Geomorphological and geological characteristics of the area affected by the Huascarán mass movements

The area affected by the Huascarán mass movements lies on the east side of the Rio Santa valley at the foot of the Cordillera Blanca (Figs. 2 and 3). The Rio Santa flows north and enters the Pacific Ocean at Santa, about 180 km from Ranrahirca. Nevados Huascarán is the highest peak in the Peruvian Andes and consists of a North (6654 m a.s.l.) and South Peak (6746 m a.s.l.).

2.1. The source area of the 1962 and 1970 mass movements

The 1962 and 1970 mass movements originated on the steep west face of the North Peak (Pico Norte) (Fig. 4) of Nevados Huascarán (6654 m a.s.l.), occurring in geologically young terrain in a very active tectonic and geomorphologic environment (e.g., McNulty and Farber, 2002). The Huascarán massif is mainly intrusive rocks of the Miocene/Pliocene Cordillera Blanca batholith (Cobbing et al., 1981) consisting of massive tonalite and granodiorite. The intrusive body has steep almost vertical sides, and, based on exposures in the South Peak of Huascarán, is evidently flatroofed (Cobbing et al., 1981; Petford and Atherton, 1992). The batholith's western margin is formed by the Cordillera Blanca Fault, a major tectonic structure that marks the western limit of the Cordillera Blanca (Fig. 2). The 210-km long Cordillera Blanca Fault is a west-dipping normal fault with repeated displacements in the late Pleistocene and Holocene (Schwartz, 1988). The Huascarán massif is thus in the footwall block of the fault. The batholith rocks have a prominent SW dipping (30–50+ALA) joint fabric that parallels the foliation; both joints and foliation increase in intensity toward the Cordillera Blanca Fault (Petford and Atherton, 1992).

We can infer that the rock masses involved in the initial 1962 and 1970 movements from Huascarán involved granodiorite from very near the roof contact of the Cordillera Blanca batholith and from the footwall block of the Cordillera Blanca Fault. In addition, it appears that that the rock mass was dominated by SW-dipping discontinuities (joints and foliation) which daylight in the steep west face of the North Peak which slopes at about 65° towards the west.

The North Peak has a glacier ice cap which was estimated to have been 30 m thick (Fig. 4; Plafker and Ericksen, 1978) in 1970. The ice cap shrank dramatically during the twentieth century (Broggi, 1943). The sheer west face (Fig. 4) has an average slope of 75° between 6400 m down to 5600 m a.s.l., a vertical distance of 800 m.

The North Peak had withstood severe shaking in the January 6th, 1725 Cordillera Blanca earthquake which triggered a fall from Nevado Huandoy (6342 m), 9 km north west of Huascarán's North Peak. This fall resulted in the failure of a moraine-dammed lake and the generation of a large-scale debris flow. The debris flow overwhelmed the ancient village of Ancash, which was located about 2 km north of present-day Yungay, causing 1500 deaths (Lliboutry et al., 1977; Silgado, 1978; Oliver-Smith, 1986). The North Peak also withstood severe shaking in the M7.3 1946 Ancash Earthquake at an epicentral distance of about 100 km (Silgado, 1951, 1978) without reported failure occurring.

The 1970 earthquake was a complex event, consisting of closely-spaced shocks at different depths, with different magnitudes over a period of 20 s (Lomnitz, 1971). The main shock, at 3:23:31 p.m. local time with an epicentre 150 km from Huascarán, is estimated to have had a magnitude of between 7.8 and 7.9 (Lomnitz, 1971; Abe, 1972).

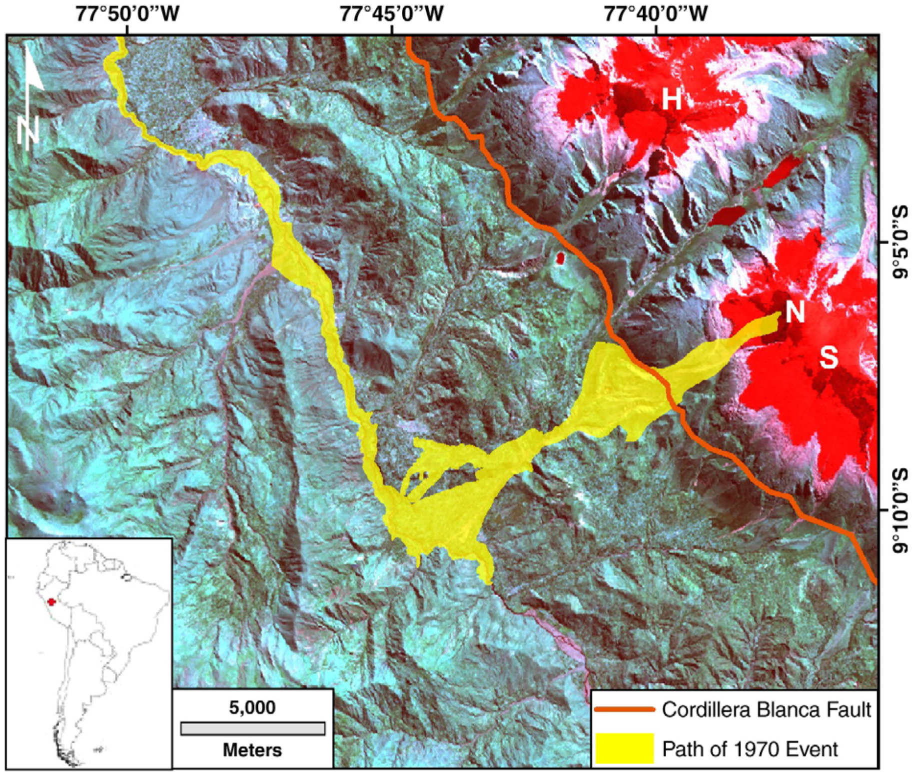

Fig. 2. LANDSAT 5 TM false colour image obtained May 31, 1987 showing the Rio Santa valley, the sharply defined steep mountain front of the Cordillera Blanca, the North (N) and South (S) peaks of Huascarán, the trace of Cordillera Blanca Fault, and path of 1970 event. Peak of Nevado Huandoy is labeled at H. Location map (inset) shows location of Cordillera Blanca in Peru.

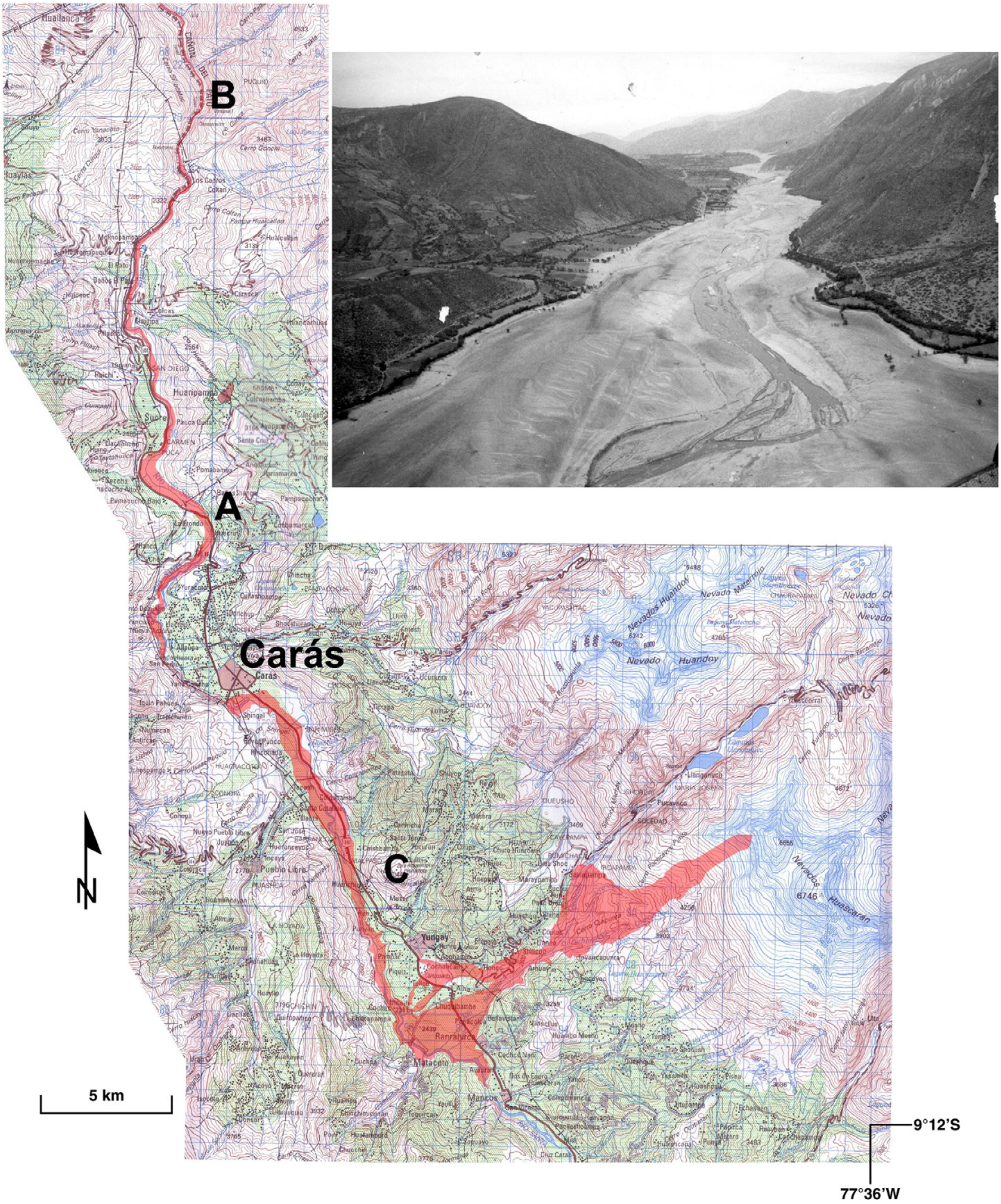

Fig. 3. Map showing path of 1962 and 1970 Huascarán mass movements and distal flows in the Rio Santa river valley. Debris outline of 1970 event obtained from 1:25,000 Department of Ancash topographic maps based on 1970 aerial photography. A = Chaquecocha Bridge, B = Cañon del Pato Dam on Rio Santa. Both structures were destroyed by 1970 distal debris flood (aluvión). Inset photograph shows path of 1970 aluvión in the Rio Santa valley upstream of Carás. View is upstream to the south. (oblique aerial photograph by G. Plafker, United States Geological Survey). Hill in top left quadrant of photograph shown as C on map. Base map reproduced from 1:100,000 scale maps 1352 (18-h and 19-h) published by Instituto Geográfico Nacional, Lima, Peru.

Fig. 4. Pre-1962 oblique aerial photograph of the North Peak of Huascarán. View is to the east. Both the 1962 and 1970 mass movements originated as falls from the steep west face (A). Bedrock is massively jointed granodiorite. Note the summit glacier ice-cap (B). In both events, the fragmenting mass traveled over the steeply sloping surface of Glacier 511 (C) and was channeled by the Little Ice Age terminal moraine complex (D). We hypothesise that the steep west face is the scarp of the massive pre-Columbian rock avalanche, the deposits of which cover the slopes below Huascarán and fill the Rio Santa valley. (photograph: Servicío Aerofotografíco Nacional de Perú 11371; August 16, 1948).

2.2. Glacier 511

Below the steep north face a second ice mass exists (Fig. 4), known as Glacier 511, which in 1970 extended from el. 5300–5400 m to el. 4200 m a.s.l. The mean surface slope of Glacier 511 is about 20°. The glacier links to the steep west face through an intermediate 36+ALA slope. The vertical drop from the top of the west face of the North Peak of Huascarán to distal limit of the terminal moraine complex is about 2300 m (approximately 58% of the total drop to the Rio Santa) over a horizontal distance of only 3.75 km.

The cirque glacier has also experienced dramatic ice loss since the Little Ice Age maximum, a process which has left a well defined terminal moraine complex between elevations 4100 m and 4500 m a.s.l. (Fig. 4). Between 1920 and 1970 the snout of Glacier 511 retreated over 500 m (Kaser and Ames, 1996).

2.3. Moraines and surficial cover of slopes from Glacier 511 to the Rio Santa

The slopes between Glacier 511 and the Rio Santa (Fig. 2) are mantled with morainic material but the Quaternary geology has not been examined in detail. Broad features of the morphology, and relative and absolute age of moraines in the Huaraz–Yungay area of the Cordillera Blanca have been reported (e.g., Clapperton, 1972, 1981; Rodbell, 1993). End moraines associated with late-Wisconsin (Late Glacial) limits of major mountain glaciers that occupied E–W running glacial troughs through the Cordillera Blanca extend only small distances beyond the mountain front (Clapperton, 1972, 1981, 1983). For example, the moraine associated with the Wisconsinan limit of the Llanganuco Glacier is well marked at a point 7.2 km upstream of the confluence with the Rio Santa at el. 3025 m.a.s.l (Fig. 2). Beyond this limit, and down to the Rio Santa, moraine which blankets the landscape is from a more extensive glaciation and is thought to be of Illinoisan age (ca. 128,000 yr BP) (Clapperton, 1972, 1981). Cosmogenic age dating of moraines in the Huaraz area confirms this outline chronology (Farber et al., 2005), with the youngest date obtained from the stratigraphically oldest moraines being 120 ka. Some large-scale moraine-like features found downslope from the Wisconsinan limits are inferred to be from this older and more widespread glaciation. Surface blocks of granodiorite on these old moraines and older till surfaces are highly weathered (Clapperton, 1981; Rodbell, 1993; Farber et al., 2005). Clapperton (1981) also notes extensive weathering of this older moraine surface, which in places, penetrates to 5 m below the surface resulting in a red oxidized zone. This was seen by the present authors in several locations in the Rio Ranrahirca (Shacsha) and suggests a very old surface. The moraine typically consists of large blocks of granodiorite set in a finer till matrix, a texture quite similar to that of rock avalanche deposits.

We conclude that exposed glacial materials on the east side of the Rio Santa within the general area of the Huascarán mass movements below el. 3025 m a.s.l. are older than ca. 100,000 years. We also infer that any deposit of moraine-like materials containing large blocks of granodiorite set in a finer till-like matrix found below el. 3025 m a.s.l. which dates younger than this age are most likely to be a rock avalanche deposit with its source in the Cordillera Blanca.

2.4. The Pre-Columbian rock avalanche

Plafker and Ericksen (1978) noted the existence of a massive rock avalanche deposit consisting of large granodiorite boulders set in a pulverized matrix of unknown age which they considered to be Pre-Columbian in age. This deposit extends down the lower slopes of the valley side below Huascarán and forms a thick hummocky deposit of debris that fills the Rio Santa valley (Fig. 5). Cemetery Hill is one of the hillocks on the debris surface (Fig. 5). Exposures are seen along the sides of the Rio Ranrahirca (Shacsha) valley and in road cuts through the debris on the fan such as those directly beneath the western side of Cemetery Hill (Stadelmann, 1983; Fig. 6). The source appears to be the granodiorite forming the west face of North Peak of Huascarán (Fig. 2) and the scar thought to be created by this massive detachment (Fig. 4) was the source for the initial falls in 1962 and 1970 discussed below. Yungay and Ranrahirca were located on this prehistoric rock avalanche debris.

Cosmogenic dating of one of the granodiorite boulders on the surface of the Pre-Columbian rock avalanche deposit was carried out (Valderrama et al., 2008). A date of 47.8 ka was obtained (CNEF-1666). This Pleistocene age is somewhat older than anticipated but is consistent with the glacial chronology and geomorphic history outlined above.

The deposit covers ca. 17 km^2 in the lower Ranrahirca and main Rio Santa valleys; its volume is estimated to be in the order of several hundreds of millions of cubic metres. The existence of the "Pre-Columbian" rock avalanche event provides important context for twentieth century mass movement events from Huascarán.

3. Characteristics of the 1962 and 1970 events

In the following sections we attempt to reconstruct the occurrence, mechanisms, types and volumes of materials involved, and the material budgets of the 1962 and 1970 events. Four materials are involved in the movements; 1) glacial ice from the summit ice cap, 2) granodiorite from the steep rock face of Huascarán's North Peak, 3) snow and possibly firn from the surface of Glacier 511, and 4) surficial material from the terminal moraine complex and the slopes below the snout of Glacier 511. Based on an examination of post-event aerial photography, we consider it unlikely that any significant volume of ice was entrained from the surface of Glacier 511 in either event.

In the reconstruction of the 1962 and 1970 events that follow it is important to point out that times, distances, volumes, and velocities are reported as accurately as possible with minimal rounding of numerical values. We have converted velocities reported in km/h to m/s. In doing so we report the conversion result to the nearest digit. Our estimates of volumes are necessarily speculative but in reporting water equivalent of snow, for example, we report the conversion result in Mm^3 to one

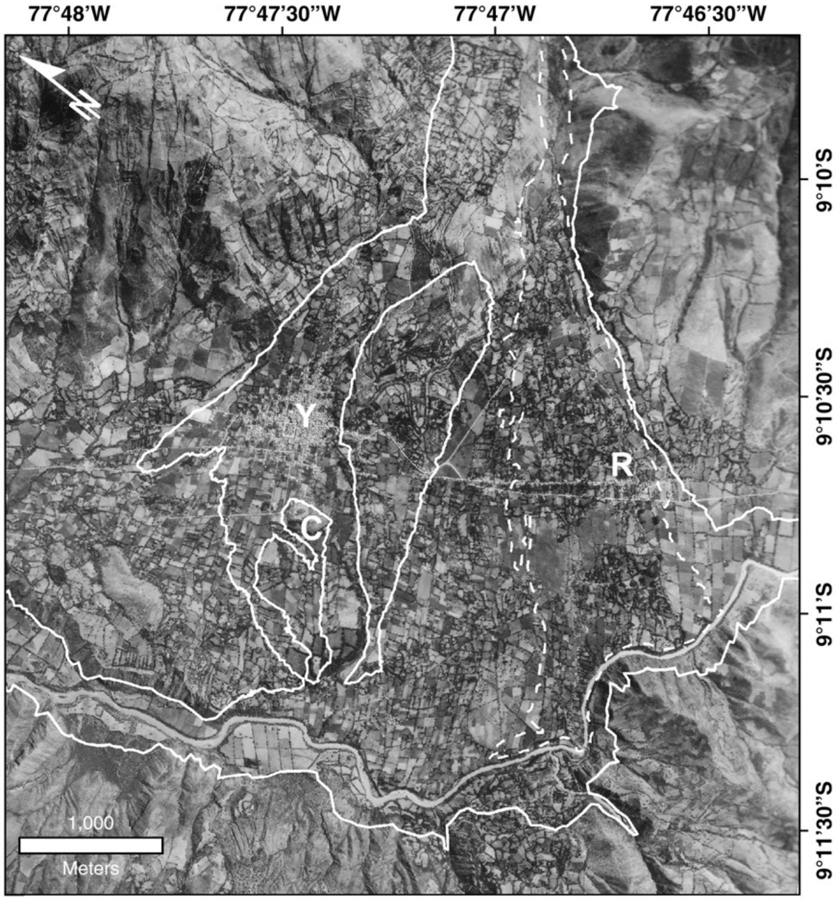

Fig. 5. Pre-event aerial photograph taken the day before the 1962 mass movement, showing outline of 1962 (dashed white line) and 1970 mass flows (solid white line) in the area of Ranrahirca and Yungay. Note location of Ranrahirca (R), Yungay (Y) and Cemetery Hill (C). Roadcut in Fig. 6 is located on the west side of Cemetery Hill. Compare to Figs. 10 and 15. (photograph: Servicío Aerofotografíco Nacional de Perú #3502; January 9, 1962).

decimal place. Distance measurements are considered to be quite accurate. However, we recognise that recall of event sequence and times reported by eyewitnesses (so-called "flashbulb" memories) can be subject to considerable bias (e.g. Wright, 1993; Pezdek, 2003).

Three sources of uncertainty arise in attempting to quantify the volumes of material involved in the mass movements. They concern; 1) the fact that both events contained significant volumes of snow and ice which melted during or soon after the event 2) uncertainties in the depths of deposits on the Ranrahirca fan (in 1962 and 1970) and in the Yungay lobe (in 1970), and 3) the volume of material transported in the downstream debris flows in the Rio Santa both in 1962 and 1970. The greatest uncertainty concerns the source volumes of both events and the proportion of ice and rock in the initial failure mass.

Fig. 6. Deposits of the Pre-Columbian rock avalanche exposed in a road-cut directly beneath the western edge of Cemetery Hill. Large angular boulders of granodiorite are set in a pulverized matrix. Note person for scale. The exposure is located in Fig. 5.

3.1. The mass movement of January 10th, 1962

3.1.1. Process, volume estimates, and entrainment

The more devastating 1970 event was presaged to a remarkable degree by the 1962 rock/ice fall-debris flow (Figs. 3 and 7) which was initiated shortly after 6:00 p.m. local time on January 10th, 1962. Some uncertainty exists about the precise time of the initial fall. Dollfus and Penaherrera (1962) state that the initial fall occurred a "little after 6" on January 10th. Morales Arnao (1966, p.312) reports that an eyewitness observed the initiation of the movement at "about" 6 p.m. whilst Morales Arnao (1962) and McDowell and Fletcher (1962), quoting eyewitnesses, are precise about the initial fall occurring at 6:13 p.m. No trigger was apparent for the 1962 fall.

Like the 1970 event, the 1962 mass movement originated as a fall from the west face of the North Peak with an original failure mass that consisted of significant volumes of both ice and rock, it incorporated a significant volume of snow in its 3 km travel over Glacier 511, it further entrained a large amount of morainic material in its path as it was transformed into a rapidly moving debris flow below the glacier that reached the Rio Santa, and it continued to travel a long distance downstream in the Rio Santa valley as a distal debris flood/aluvión (Dollfus and Penaherrera 1962; Morales Arnao, 1966; Schneider, 1983) (Fig. 8).

Fig. 7. Oblique view of the path of the 1962 rockfall-debris flow in the Rio Ranrahirca (Shacsa). Note the origin on the west face of Huascarán's North Peak and the run-out on the Ranrahirca fan. Yungay is visible in mid-foreground (Y). (Servicio Aerofotografíco Nacional de Perú O-22224; August 1, 1965).

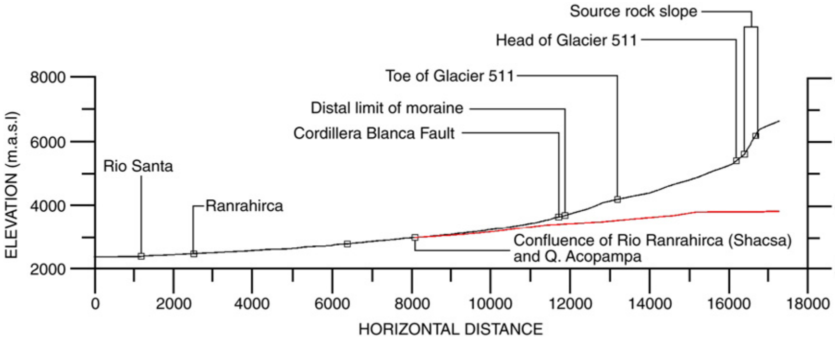

Fig. 8. Topographic profile of 1962 Huascarán event constructed from Department of Ancash 1:25,000 topographic map.

The volume of the initial fall from Huascarán in 1962 has been estimated (Ruegg, 1962; Morales Arnao, 1966; Schneider, 1983) as 2.5–3.0 Mm^3, a volume which includes ice from the glacier ice cap. Some uncertainty surrounds the exact source of the fall and the proportion of ice and rock in the detached mass. Morales Arnao (1966) suggests that the initial fall consisted of ice from the summit ice cap from an elevation of approximately 6300 m which "dragged along a great quantity of granodiorite blocks". The release of the rock mass was apparently facilitated by cracks running parallel to the slope face (Morales Arnao, 1966). The ice content of the initial fall was augmented by that of a second avalanche that occurred minutes after the initial fall from a hanging glacier about 1000 m below the source of the original avalanche. The volume of ice involved was estimated at 200,000–300,000 m^3 (Morales Arnao, 1966, p. 308). It is noted that the volume of this ice avalanche is incorrectly given as 2–3 Mm^3 in Plafker and Ericksen (1978, p. 309).

The fall of ice and rock impacted on the surface of Glacier 511 and travelled over its surface. We estimate the average path width over the glacier to be 220 m. The moving mass is estimated to have entrained 1 Mm^3 of snow in its 3 km travel down the 20° slope of Glacier 511 (Schneider, 1983), suggesting a water equivalent[3] of 0.5 Mm^3, and an entrained snow depth of 1.5 m. Morales Arnao (1966, p. 309) noted that the surface of the glacier looked as though it was "ploughed flat by a bulldozer".

The volume of the immediate solid deposits of the 1962 event (including rock, soil and glacial ice but excluding snow and material lost in the downstream debris flow/aluvión) has been estimated at 13 Mm^3 (Dollfus and Penaherrera, 1962; Morales Arnao, 1966). Morales Arnao (1966) cites the calculation by Ing. Ghiglino who estimated that the initial deposition in the lower path and the Ranrahirca fan, contained 20–25% ice. This amounts to an ice volume of 2.6–3.25 Mm^3, an observation that suggests the volume of rock included in the initial fall could be less than 1 Mm^3. These volume estimates further suggest that at least 10 Mm^3 of moraine was entrained below Glacier 511, indicating a minimum entrainment ratio (Hungr and Evans, 2004) of 3.3 (Table 1). It is noted that Schneider (1983) estimates the volume of solid deposits apparent in the field in 1964 (including rock and soil but excluding the melted ice and the volume lost to the downstream debris flow) to be in the order of 8 Mm^3, an estimate that roughly corresponds to the Ghiglino–Morales estimate noted above.

These estimates suggest that the initial detached mass from Huascarán had a volume of ~3 Mm^3 and consisted of 70% ice (2 Mm^3) and 30% rock (1 Mm^3) as outlined in Table 1. This is in contrast to the

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[3] Assuming that the average density of snow and firn on the glacier surface is 500 kg/m^3.

Table 1
Best estimates of solid–fluid budget for 1962 and 1970 Huascarán events (These calculations involved the key assumptions that 1) the solid concentrations in the 1962 and 1970 debris flows in the Rio Ranrahirca were 65%, 2) the solid component of the debris flows underwent 20% bulking, and, 3) the entrained material was saturated at the time of the events; see text for discussion on methods used to obtain these values).

	Component of material budget	Units	1962	1970
1	Initial fall-volume of ice from summit glacier	Mm^3	2	1
2	Initial fall-volume of rock from source slope	Mm^3	1	6.5
3	Total volume of initial fall (1+-2)	Mm^3	3	7.5
4	Average depth of entrained snow on glacier 511 (required by 5)	m	3.6	9.0
5	Volume of snow entrained from Glacier 511	Mm^3	3.6	15.6
6	Water equivalent of entrained snow (assuming snow/firn density of 500 kg/m^3)	Mm^3	1.8	7.8
7	Volume of debris deposited on surface of Glacier 511	Mm^3	0	2
8	Volume of entrained material	Mm^3	10	43
9	Total volume of solids in debris flow (including glacier ice)	Mm^3	13	48.5
10	Total volume of solids in debris flow with 20% bulking	Mm^3	15.6	58.2
11	Entrainment ratio (without bulking)		3.3	6.6
12	Volume of water in entrained material	Mm^3	2.3	10
13	Total volume of water in debris flow in Rio Ranrahirca (based on assumption in 14)	Mm^3	4.1	17.8
14	Solids concentration of debris flow in Rio Ranrahirca (assumed)	%	65	65
15	Deposition in Rio Ranrahirca down to Rio Santa	Mm^3	13	48.6
16	Deposition in Yungay lobe	Mm^3	0	3.6
17	Total deposition down to Rio Santa	Mm^3	13	52.2
18	Volume of solids in downstream flow in Rio Santa (including glacier ice)	Mm^3	2.6	6
19	Volume of water in downstream flow	Mm^3	3.0	10.0
20	Solids concentration of downstream flow	%	46	37

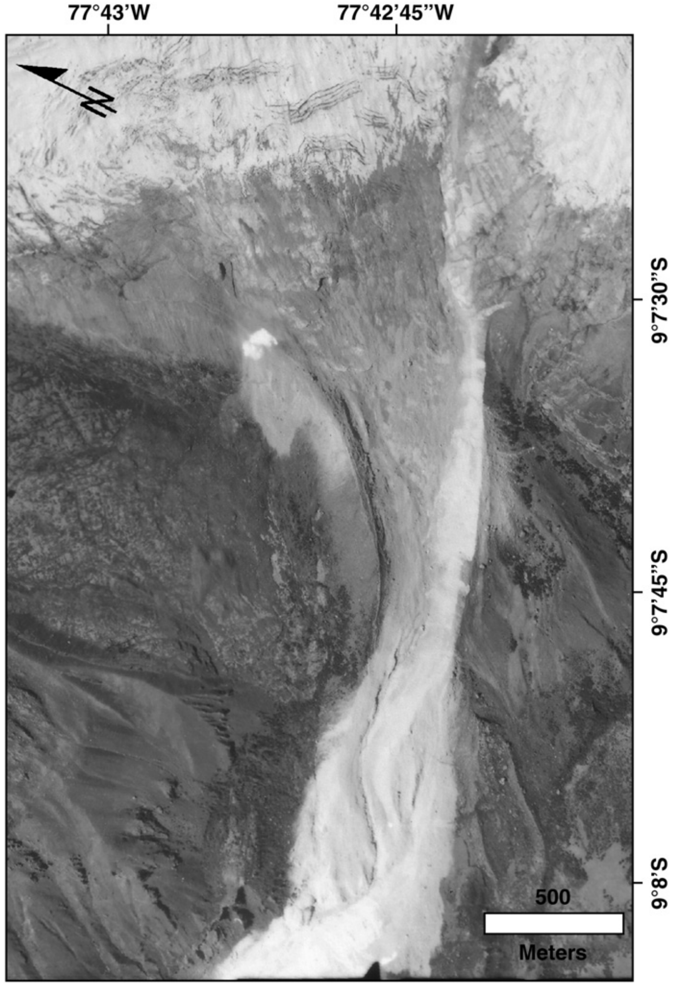

Fig. 9. Vertical aerial photograph of terminal moraine system of Glacier 511 after being overrun by the 1962 ice/rock avalanche. Note channeling effect of moraine and entrainment area immediately downstream of moraine system towards the bottom of the image. (Servicío Aerofotografíco Nacional de Perú, 16729; June 19, 1962).

estimate by Plafker and Ericksen (1978) who suggest that the fall contained more rock than ice and who also assumed that the entire volume of the deposited debris (ca. 13 Mm^3) fell from Huascarán in the initial fall (Plafker and Ericksen, 1978, p. 308).

The moving mass of rock, ice and snow (some of which had melted to water) was constricted by the terminal moraine complex of Glacier 511 (Morales Arnao, 1966; Fig. 9) and eroded a considerable volume of material from the surface of the moraine (Morales Arnao, 1966). Below Glacier 511, the 1962 debris entered the headwaters of Quebrada Armapampa and was extremely fluid (Fig. 7). This was due to two factors; i) the pulverization of some of the glacier ice incorporated into the movement (as in 1970 this generated a rain of ice shards in the air that, according to a local farmer, made it difficult to breath near certain parts of the upper path), ii) the incorporation of snow from the surface of Glacier 511. The debris flow immediately began to entrain material from the channel sides of the Quebrada Armapampa (Morales Arnao, 1966) as indicated in Table 1, but soon after, began to deposit material in its path (see photographs in Schneider, 1983). The debris traveled down the Quebrada Armapampa where it joined the main stem of the Rio Ranrahirca (Shacsha) at el. 3000 m a.s.l. At a number of points in the upper path the debris spilled over the upper edges of the steep ravines of the Quebrada Armapampa and the Rio Ranrahirca and, as can be seen in a dramatic oblique aerial photograph in McDowell and Fletcher (1962, p.867) almost over-topped the Cerro de Aira, a portent of the events of 1970. The debris continued downstream and ran out on the Ranrahirca fan (Fig. 10) where most of the debris was deposited (Fig. 11).

The debris flow reached the channel of the Rio Santa at 2400 m a.s.l., the debris coming to a halt and damming the river for several minutes (Morales Arnao, 1966). A small lobe of the debris ran-up the opposite bank of the Rio Santa to a point 30 m above the river and damaged part

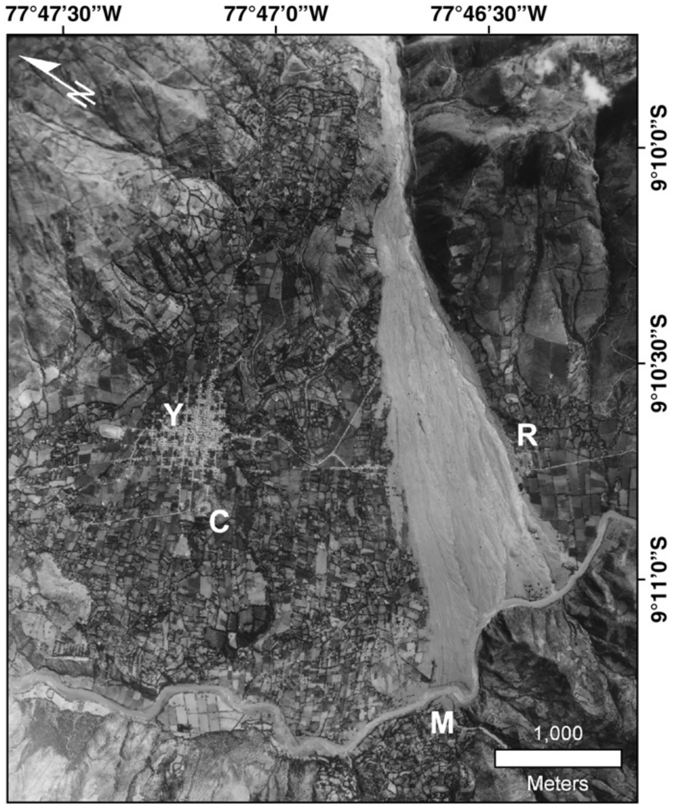

Fig. 10. Vertical aerial photograph of the runout of the 1962 debris flow on the Ranrahirca fan taken the day after the event. Note location of the part of Ranrahirca undamaged by flow, and the location of Yungay (Y), Cemetery Hill (C) and Matacoto (M). Rio Santa runs from right to left. (Servicío Aerofotografíco Nacional de Perú 8600-62-3; January 11, 1962).

Fig. 11. Oblique aerial view of the 1962 debris flow path near the apex of the Ranrahirca Fan. Populated terrain to the left of the 1962 debris was covered by the 1970 debris flow. Note very large boulders on the surface of the fan to the left of the 1962 debris (left foreground). View is towards the east. (Servicio Aerofotografico Nacional de Peru O-19709; January 11, 1962).

of the village of Matacoto (Morales Arnao, 1966; Fig. 10). The river soon broke through the debris dam, the volume of the escaping water being described as "quite large" (Morales Arnao, 1966). The debris flow thus mixed with the waters of the Rio Santa to further increase the water content and decrease the concentration of solids as it continued downstream as a distal debris flood/aluvión (Table 1).

3.1.2. Velocity

Very high velocities were generated in the upper part of the debris flow path (Morales Arnao, 1966). These caused high-velocity winds which stripped and snapped quinulaes trees growing on the terminal moraine of Glacier 511 (Morales Arnao, 1966). Velocities in the order of 27 m/s have been suggested for this part of the path (Morales Arnao, 1966). As the debris approached the Rio Santa across the Ranrahirca fan the flow velocity had reduced to about 8 m/s (Dollfus and Penaherrera, 1962).

The average velocity of the 1962 event from its source to the Rio Santa, a distance of about 15.5 km, has been estimated as being about 17 m/s by Morales Arnao (1966) and Dollfus and Penaherrera (1962) based on a definitive travel time 15 min. McDowell and Fletcher (1962) citing the observations of eyewitnesses indicate that the initial fall occurred at 6:13 p.m. and that the debris flow struck Ranrahirca at a path distance of 14.2 km at 6:18 p.m.[4], implying a mean velocity to Ranrahirca of 47 m/s. The debris flow reached the Rio Santa at about 6:20 p.m. This indicates a travel time of 7 min and an average velocity to the Rio Santa of 37 m/s, just over twice the estimate of Morales Arnao (1966) and Dollfus and Penaherrera (1962). The discrepancy in the mean velocity estimates is due to the difference in the estimate of the time of the initial fall.

3.1.3. Distal debris flood/aluvión in the Rio Santa

As would be the case in 1970, the 1962 debris flow continued its travel downstream as a distal debris flood/aluvión in the Rio Santa and appears to have been arrested by the Canon del Pato storage dam, 46.5 km downstream. Between Yungay and Caraz (18 km downstream; Fig. 3), the water level of the river rose 10 m (Morales Arnao, 1966). Parts of the road were flooded depositing sand, silt and chunks of ice (Morales Arnao, 1966). In contrast to the 1970 downstream flow, however, no data are available on travel times of this flow.

3.2. The mass movement of May 31st, 1970

The 1970 mass movement from Huascarán was triggered by seismic shaking at 3:23 p.m. local time on Sunday May 31st 1970; the duration of the shaking was approximately 45 s. It was remarkably similar in process and mechanism to the 1962 event described above with the exceptions that a) the 1970 event was triggered by the M7.9 Chimbote earthquake which shook a large area of Ancash with considerable destructive effect (Ericksen et al., 1970; Cluff, 1971), b) both the initial fall, and subsequent debris flow, were significantly larger in volume, and c) the event moved with much higher velocities. As noted by Plafker and Ericksen (1978, p. 284) the 1970 event had been predicted by climbers C. Sawyer and D. Bernays based on their observations, in September 1962, of a pervasively fractured rock slope and a very high overhanging rock face left by the January 1962 event.

3.2.1. Process, volume estimates and entrainment

As in the 1962 event, the 1970 mass movement originated in a fall of ice and rock from the west face of Huascarán's North Peak (Figs. 1, 12 and 13). Comparing photographs of the peak with digital terrain data and Google Earth images, the source of the initial fall was between 5600 and 6400 m a.s.l., in the same area as the 1962 source (Fig. 12). The width (along the contours) of the initial mass was roughly 350 m and the thickness (perpendicular to the contours) of the initial mass was no more than 50 m at the top of the face tapering down to zero at the base of the failure. We examined the west face of the North Peak in July 2008 through binoculars under a clear blue sky; the exact source of the 1970 fall is no longer apparent and the event has not left a distinct scar (Fig. 12B). Detailed photogrammetric comparisons of the west face before and after the 1970 event have not been made. This means that estimates of the volumes of ice and snow

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[4] McDowell and Fletcher (1962) show a photograph of a clock in Ranrahirca stopped by the impact of debris at 6:18 p.m.

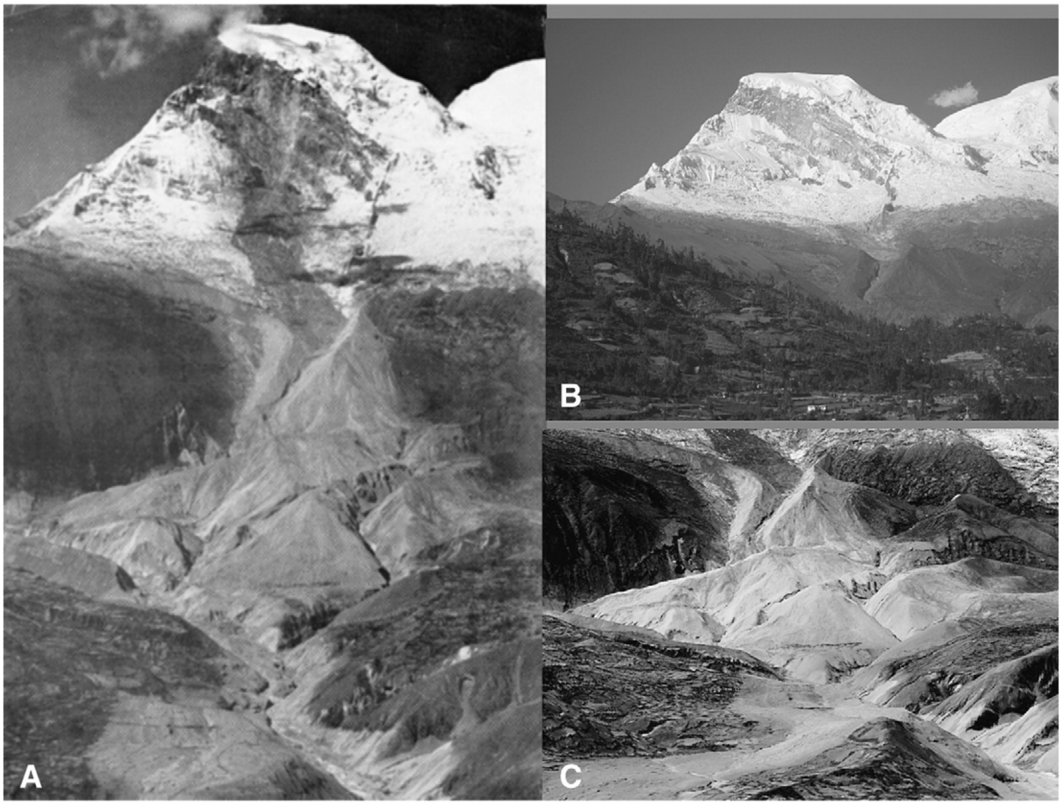

Fig. 12. Photographs of upper part of the path of the 1970 mass movement originating in a fall the North Peak of Huascarán. A: Note summit glacier, source rock slope, and path of debris over Glacier 511. The very large area over which massive entrainment (estimated in this study to be in the order of 43 Mm^3), occurred is visible below Glacier 511. This generated a debris flow which ran down the Rio Ranrahirca (Shacsa) towards the bottom right of the photograph. (Photograph by W. Welsch, July 1970; Welsch, 1984) B: North Peak of Huascarán from the former site of Yungay, July 3, 2008. C: digital elevation model draped with July 1970 NASA air photographs showing area of entrainment immediately below the end moraine of Glacier 511. Yungay lobe is visible at bottom left.

involved in the initial fall must still remain uncertain and even speculative in nature. Three previous estimates have been made;

1) Ghiglino Antunez (1971) estimates that the initial fall had a total volume of 14 Mm^3, which included 5 Mm^3 of rock and 9 Mm^3 of ice. In its travel over the surface of Glacier 511, Ghiglino Antunez (1971) estimates that up to 6 Mm^3 of snow and firn could have been incorporated in the movement, implying an entrainment depth of 4.25 m and a water equivalent of 3 Mm^3.
2) Lliboutry (1975) estimates an initial fall of 7–8 Mm^3 of rock and 1 Mm^3 of ice (a total volume of 8–9 Mm^3). Of this he estimates 2 Mm^3 of rock was deposited on the surface of Glacier 511; this deposit is visible on immediate post-event photographs (e.g., Figs. 12 and 14). Lliboutry further estimates that 4–5 Mm^3 of snow was entrained from the glacier surface, when if melted would yield ca. 2–2.5 Mm^3 of water.
3) These initial fall volume estimates are in strong contrast to those in the well-known paper by Plafker and Ericksen (1978) who assumed (p. 285) that the total deposited volume (ca. 50 Mm^3) of the solid component of the 1970 mass movement originated from the North Peak of Huascarán. Plafker and Ericksen (1978) estimate the volume of ice contained in the fall as 5 Mm^3.

In the analysis of digital terrain data obtained for the present study, our estimate of the volume of rock lost from the southwest face is 6.5 Mm^3. Lliboutry's estimate of ice loss appears to be reasonable given the thickness and extent of the summit glacier ice cap. Thus the total volume of the fall would be in the order of 7.5 Mm^3 (including

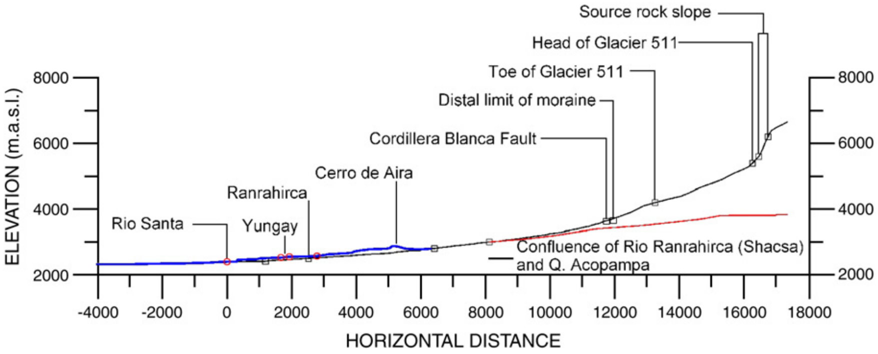

Fig. 13. Topographic profile of 1970 Huascarán event constructed from Department of Ancash 1:25,000 topographic map. Blue line is the profile of the Yungay Lobe and its continuation into the Rio Santa. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

1 Mm^3 of ice), a volume approximately 2.5 times greater than the 1962 initial fall.

If we assume that at least 2 Mm^3 (based on a deposit area of 1.4 Mm^2 and an average deposit thickness of 1.5 m) was deposited on the surface of Glacier 511, this leaves a mass with a volume of 5.5 Mm^3 which was transformed into a debris flow as it traveled over and down from Glacier 511.

As Plafker and Ericksen (1978) suggest, the debris was channeled and air launched at the terminal moraine complex of Glacier 511 (Figs. 12 and 14). After surmounting the moraine, it spread out and impacted on a wide area on the moraine-covered slopes below the terminal moraine (Fig. 14), creating the mud splatter and mud blast zone noted by Plafker and Ericksen (1978). The mud blast and splatter zone may have one of two (or a combination of) two origins 1) fluidization of material eroded from the terminal moraine, 2) the sudden liquefaction of moraine and colluvial material by the impact of airborne rock, ice, snow and moraine material on the surface of the slope below Glacier 511. It was here that the developing debris flow/debris avalanche entrained a massive amount of material, a fact first noted by Ghiglino Antunez (1971) yet not considered by Plafker and Ericksen (1978).

Ghiglino Antunez (1971) estimates a total entrainment of 30 Mm^3 from this zone. However, based on an analysis of digital terrain data and field observations, we estimate an entrainment of 43 Mm^3 between the elevations of 2900 and 3800 m.a.s.l over an area of 11 km^2, an average entrainment depth of approximately 4 m. This is equivalent to an entrainment ratio (Hungr and Evans, 2004) of about 6.6, double that of the 1962 event.

Evidence of entrainment is cited by Plafker and Ericksen (1978). They indicate (Plafker and Ericksen, 1978, p.287) that the end moraine of Glacier 511 was lowered by as much as 10 m by the erosion of the overriding ice/rock avalanche. Further, slopes in the area below the terminal moraine were extensively scoured and grooved (Fig. 14) by the passing debris and some high points and ridge crests were perceptibly lowered by erosion (Plafker and Ericksen, 1978, p. 288).

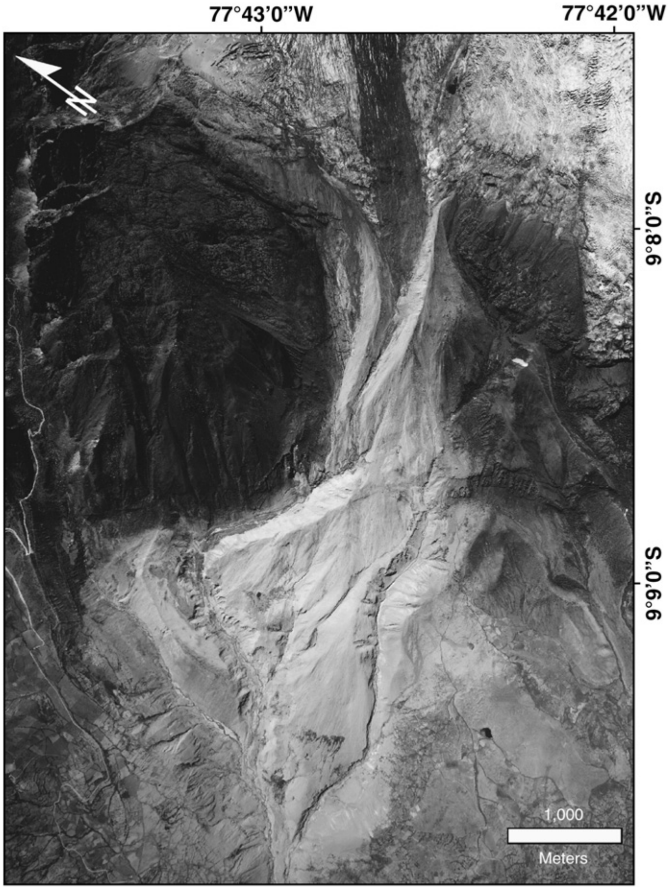

Fig. 14. Vertical aerial photograph of Glacier 511, terminal moraine complex, and entrainment zone of the 1970 event. Note narrow debris path over the surface of Glacier 511, the terminal moraine system overrun by the ice/rock avalanche and the extensive entrainment zone immediately below the moraine (NASA aerial photograph; July 14, 1970).

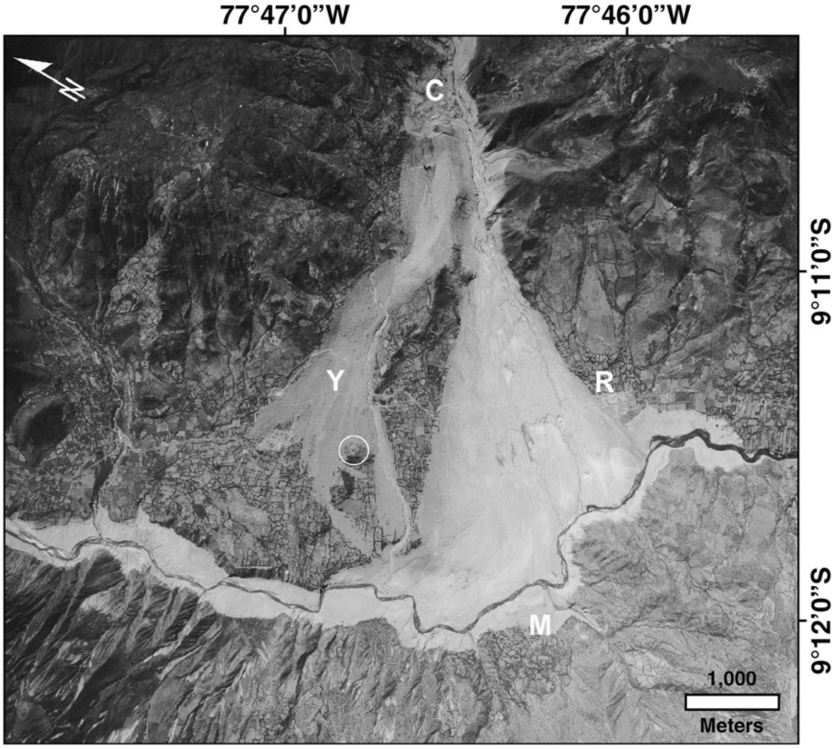

Fig. 15. Aerial photograph of deposits of the 1970 Huascarán debris flow. Debris flow surmounted Cerro de Aira at C. Y = Yungay Lobe; R = Ranrahica; M = Matacoto. Cemetery Hill is circled. Note the trace of significant downstream debris flood (aluvión) moving down the Rio Santa to the left (NASA aerial photograph, July 14, 1970).

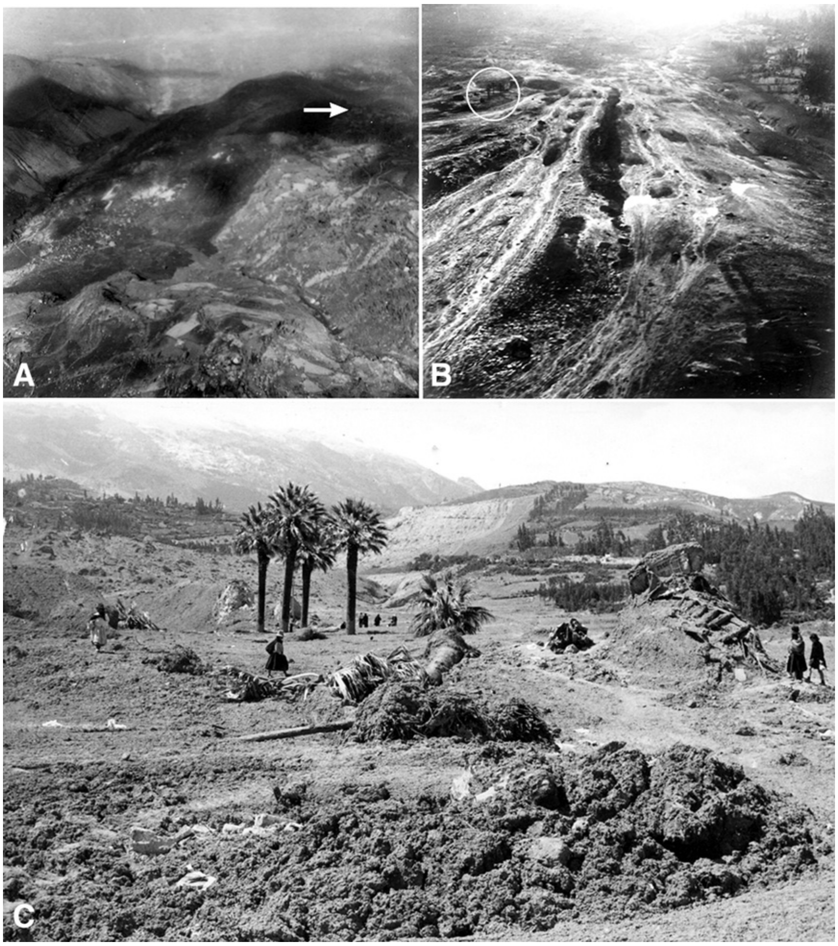

Fig. 16. Nature of the mud-rich debris that overwhelmed Yungay. A: Oblique aerial view downstream of Cerro de Aira where debris overtopped the valley side and swept down on Yungay (off picture to the right in direction of arrow). Notice blocks of glacier ice in debris at the base of the run-up. B: View (upstream) of the site of Yungay covered with very fluid mud-rich debris. The famous four palms that mark the former location of the Plaza de Armas are circled. Date of photographs June 2, 1970. Photographs A and B by Jaime Fernandez Concha. C: Surface of the 1970 debris burying the Plaza des Armas at the former site of Yungay. The famous four palms are buried to a depth of 5 m. Note the fine-grained characteristics of the debris flow deposits and the absence of large blocks of rock (photograph by G. Plafker, United States Geological Survey; June–July 1970).

Thus by el. 2900 m a.s.l. a massive debris flow/debris avalanche had developed on the slopes below Huascarán. Applying a bulking factor of 20%, the volume of solids (including ice) in this extremely rapidly moving mass is estimated to be in the order of 58 Mm^3, including 6.6 Mm^3 from the original fall, and 51.6 Mm^3 from entrainment below Glacier 511.

The high-velocity flow traveled down the Rio Ranrahirca (Shacsha) (Figs. 13 and 15) and was split into two lobes by impact against the Cerro de Aira (Figs. 15 and 16A). Unlike 1962, some of the debris flow overtopped Cerro de Aira and, deflected by a topographic ridge in the pre-Columbian rock avalanche deposit, ran down onto the town of Yungay (Figs. 15 and 16). The main part of the debris carried on down the Rio Ranrahirca (Shacsha) and spread out on the Ranrahirca fan (Fig. 15). Based on field estimates of debris depth and an analysis of digital terrain data in GIS, we have estimated the total volume of deposition in the Ranrahirca (Shacsha) valley, on the Ranrahirca fan and in the Yungay lobe to be 52.2 Mm^3. The volume of the Yungay lobe is estimated to be 3.6 Mm^3 assuming an average depth of 5 m suggested by field observations.

Eyewitness reports (Oliver-Smith, 1986) and a cursory examination of the aftermath of the 1970 event (e.g., Browning, 1973) indicated that the rapidly moving mass showed marked fluid behavior. Survivors in the Yungay area referred to the “hail of mud” and some people were partly buried in “icy mud” but survived. Fernandez Concha (1970) refers to the deposit, which he observed on June 1, 1970 in the Yungay–Ranrahirca (and downstream in the Rio Santa) area as “barro” (Spanish: mud). Remarkable unpublished photographs taken by Fernandez Concha on June 2, 1970 show the deposits in the vicinity of Yungay and Ranrahirca to consist of a fluid black slurry, similar to a very wet mudflow or lahar (Fig. 16A, B).

3.2.2. Velocity

Numerous eyewitness reports indicate that the 1970 mass movement from Huascarán was triggered during the seismic shaking of the Chimbote earthquake. This occurred at 3:23 p.m. local time in the afternoon of Sunday May 31st. Numerous authors report extraordinary velocities for the 1970 event (Ghiglino Antunez, 1971; Cluff, 1971; Lliboutry, 1975; Plafker and Ericksen, 1978; Koerner, 1983, 1985). Peak velocities may have exceeded 125 m/s during the fall phase and subsequent travel over Glacier 511 (Erismann and Abele, 2001).

Estimates of the mean velocity have been calculated from the reports of eyewitnesses, including those who managed to outrun the approaching debris to the safety of Yungay's Cemetery Hill, located at a path distance of 15 km (Cluff, 1971). The vivid account by Señor Mateo Casaverde (Casaverde, 1971), a geophysicist, given to Cluff (1971) gives some idea of the travel times to Cemetery Hill. He reports an elapsed time of no less than 3 min (180 s). This account suggests an average velocity of 83 m/s and an arrival time of 3:26 p.m. One of us (PVM) recently interviewed Señor Casaverde in Yungay and confirmed the location where he first became aware of the initial fall and where he started to run for safety at the top of Cemetery Hill. The run was repeated and timed and the elapsed time of 180 s is plausible. We suggest that this is an upper estimate of velocity.

Señor Casaverde has also reported that the elapsed time to Cemetery Hill was “no more than 4 min” (Kuroiwa, 2004). This suggests an average velocity of 62.5 m/s for the 15 km distance.

A more detailed reconstruction based on eyewitness reports is given by Ghiglino Antunez (1971) who reports on an interview with a Señor Huamani. He estimates that the debris flow took about 3 min to reach the Cerro de Aira (path distance of 11.5 km — equivalent to a mean velocity of 64 m/s) and a further 1.5 min to reach Yungay (mean velocity of 33 m/s), for a total run of 4.5 min (270 s) to Yungay. For a distance of about 14 km this suggests a mean velocity to Yungay of about 52 m/s, about 2/3 that of Casaverde–Cluff estimate, and suggestive of a lower average velocity. We suggest that this is a lower bounding estimate. Thus, two credible eyewitness accounts suggest an average velocity to Yungay of between 50 and 85 m/s.

Velocity estimates have also been made at a number of points along the path based on run-up and superelevation geometry (Plafker and Ericksen, 1978; Koerner, 1983, 1985). The run-up (230 m) over Cerro de Aira indicates a minimum velocity of 67 m/s and the run-up at the Rio Santa (83 m), which overwhelmed part of Matacoto, indicates a minimum velocity of 40 m/s. However, these velocities are probably overestimated due to the effect of flow depth on the value of h in the energy-head equation ($v=(2gh)^{-0.5}$; e.g., Evans et al. 2001) used to calculate the velocities at run-up locations.

The 1970 debris flow generated strong displacement winds in the middle and lower parts of its path (Plafker and Ericksen, 1978). In the area of Yanamachico, upstream from Yungay, eyewitnesses reported that the arrival of the wall of mud was preceded by a wind blast so violent that “it stripped leaves, branches, and even the papery bark from the eucalyptus trees near their house, leaving them standing denuded “like telephone poles” (Oliver-Smith, 1986, p. 4–5).

The debris flow blocked the flow of the Rio Santa river for about 30 min (Ghiglino Antunez, 1971; Benjamin Morales Arnao, personal communication, 2004) leading to temporary upstream flooding in the vicinity of Mancos (Fig. 1). However, it is clear both from eyewitness reports (Oliver-Smith, 1986), and from the travel times of the downstream distal debris flood discussed below, that some considerable volume of the debris continued downstream without stopping.

3.2.3. Distal debris flood/aluvión in the Rio Santa

As can be seen in Fig. 15 a significant volume of the flow turned north and carried on downstream in the Rio Santa valley as a debris flood (aluvión) (Fig. 17). Our estimates of debris volume suggest that the deposition of debris in the path above the Rio Santa still leaves a total of about 6 Mm^3 of solid material available for the downstream distal debris flow/debris flood, an estimate comparable to that of Lliboutry (1975). Fluidised by a large volume of water (see calculations below) the distal debris flood (aluvión) flowed down the Rio Santa (Fig. 17) all the way to the Pacific Ocean at Santa, a distance of 180 km. The aluvión destroyed the Cañon del Pato storage dam at a distance of 46.5 km.

Ghiglino Antunez (1971) reports that the aluvión in the Rio Santa passed Caraz, a distance of about 17 km downstream from Ranrahirca, 15 min after the earthquake, an equivalent time of 3:38 p.m., suggesting a mean flow velocity between Ranrahirca and Caraz of 28 m/s. The flow reached Huallanca, 56 km downstream from Ranrahirca at about 5:00 p.m. (Ericksen et al., 1970) suggestive of a velocity between Caraz and Huallanca of about 8 m/s, and an average velocity from Ranrahirca of 10 m/s. The aluvión continued beyond Huallanca and reached the Mirador railway station (100 km downstream) at 6:00 p.m. and Tablones (130 km downstream) at 7:00 p.m. (Ericksen et al., 1970; Lliboutry, 1975) (Fig. 17).

3.2.4. Characteristics of the debris

The characteristics of the 1970 debris flow deposit were examined in the area of the Yungay lobe, the Ranrahirca fan, and in exposures of the downstream distal debris flood/aluvión deposits. The debris in the Ranrahirca–Yungay area is typical of a debris flow deposit (Figs. 16 and

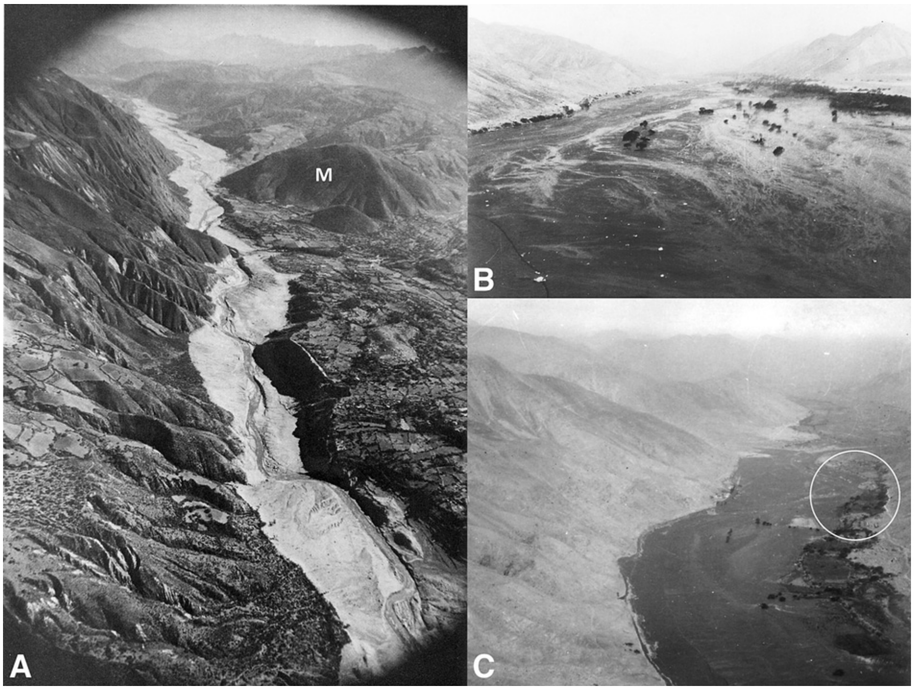

Fig. 17. Oblique aerial photographs of downstream mud flood (aluvión) in the Rio Santa valley. A: Aerial view of 1970 downstream debris flow in the Rio Santa looking north toward Carás. Note wide swath of destruction in the Rio Santa valley and deposits on both sides of the river channel in valley floor. Hill at M is 7 km downstream from Ranrahirca (Photograph by W. Welsch, July 1970; Welsch and Kinzl, 1970). B: View of the Santa Valley, looking upstream, between Tablones (130 km downstream) and Vinzos. C: Tablones railway station (circled; 130 km downstream) completely covered by the debris of the aluvión. Date of photographs B and C June 3, 1970. Photographs B and C by Jaime Fernandez Concha.

Fig. 18. Exposure of 1970 matrix-supported debris flow material. A: roadside exposure at crest of Cerro de Aira. Note fragments of granodiorite and person for scale (bottom left). B: exposure alongside the steps up Cemetery Hill, Yungay. Angular light-coloured clasts are fragments of granodiorite from the source slope on Huascarán. Material is typical of deposits in the Yungay Lobe. Cavities discussed in text are visible. Note geological hammer for scale.

18). The deposit is matrix supported (Fig. 18). The matrix contains between 5 and 30% fines (material that passes the #200 sieve, particle diameter <75 μm) (Fig. 19; Table 1) and <10 mm diameter cavities which may result either from entrapped air at the time of deposition or cavities resulting from the melting of enclosed snow or ice. Clasts consist of large angular fragments of granodiorite derived from the source slope on Huascarán (Fig. 18). We note that many of the giant granodiorite boulders observed in the 1970 debris pre-existed on the ground surface in the Ranrahirca–Yungay area. These are visible in Fig. 11 and represent a type of lag deposit formed by the erosion of the finer debris of the Pre-Columbian rock avalanche that underlies the entire area affected by the 1962 and 1970 events.

Atterberg Limit tests carried out on 19 matrix samples indicated that most of them were non-plastic (Table 2). Liquid Limits ranging from 16.6 to 20.5 were obtained from some non-plastic materials (Table 2). However, matrix material from the Yungay Lobe has the highest fines content (Fig. 19; Table 1) and exhibits significant plasticity, with Plasticity Indices in the range of 10–11 and Liquid Limits of about 30 (Table 2). The matrix is a non-plastic to low-plasticity gravelly silty sand derived from the moraine of Glacier 511 and from the moraine/colluvial cover of the slopes below the moraine where the massive entrainment took place. It is highly unlikely that it derived primarily from the comminution of the Huascarán granodiorite during movement as implied by Plafker and Ericksen (1978, p. 298).

3.2.5. Downstream change in velocity for the entire 1970 mass movement event

The velocity of the advancing debris front was reconstructed over the entire distance of the 1970 movement from the source on Huascarán to the end of its path at the Pacific (Fig. 20) from travel times reported in Ghiglino Antunez (1971), Lliboutry (1975) and Ericksen et al. (1970). The velocity decays as a power law relationship similar to that obtained for lahars by Pierson (1995, p. 286). It is noted that the velocity of the debris flood/aluvión was in excess 5 m/s throughout its entire distance of travel to the sea (Fig. 20).

4. Mechanism for the generation of a fluid mud-rich mass flow

Eyewitnesses report that both the 1962 and 1970 mass movements were extremely fluid mud-rich events in the mid to lower parts of their paths. Further, the extensive mud splatter zone identified by Plafker and Ericksen (1978) in the upper path of the 1970 event suggests a highly fluid mass generated by entrainment. Questions thus arise as to how much water was needed for this fluidization and where did it come from? (cf. Pierson et al., 1990; Casassa and Marangunic, 1993; Scott et al., 2005).

4.1. Water required for fluidization

No measurements or detailed observations were made of the water content of the debris flow immediately after the 1962 and 1970 events. However, we may take the Liquid Limits of the debris flow matrix as a rough indication of the minimum water content for fluidization and then use these data to approximate the maximum solid concentration (by volume) of the debris flow in each case. The average Liquid Limit of the debris flow matrix is about 20 (Table 2); this corresponds to a solid concentration of 65% by volume.

This estimate is quite close to the transition between debris flow and hyperconcentrated flow defined by Vallance (2000) at a sediment concentration (by volume) of 60% (cf. Lavigne and Suwa, 2004; Scott et al., 2005). Since both the 1962 and 1970 flows were very fluid it is assumed as a first approximation that sediment concentration was roughly 65% for most of their travel below Glacier 511 down to the Rio Santa.

Based on our estimates of the material entrained downslope of Glacier 511, in 1962, to produce an average sediment concentration of 65% in a fluidized entrained volume of 10 Mm^3 (including pore water — see below), 4.1 Mm^3 of water is required. In 1970, to achieve the same sediment concentration in a fluidized entrained volume of 43 Mm^3 (including pore water — see below), 17.8 Mm^3 of water would be needed, a volume five times greater than 1962. These estimates of water volumes are considered to be minimum estimates and constrain the calculations below.

4.2. Source of water

The water required for fluidization in the 1962 and 1970 mass movements has three possible sources; 1) melted glacier ice that fell from the summit ice cap 2) melted snow incorporated from the surface of Glacier 511, and 3) water contained in the pore spaces of the material entrained downslope of Glacier 511. As noted above, we assume that no ice was entrained from Glacier 511 and that the contribution of shattered and fragmented ice from the summit ice cap was insignificant in both events. As Plafker and Ericksen (1978) note, the contribution from the melting of glacial ice was probably minimal yet the occurrence of ice rain does suggest some degree of partial pulverization.

To approximate the volume of water contained in the entrained material we reviewed the geotechnical properties of glacier end-moraines. Typically, end-moraines exhibit void ratios in the range 0.25–0.32 (e.g., Springman et al., 2003). If we assume an average void

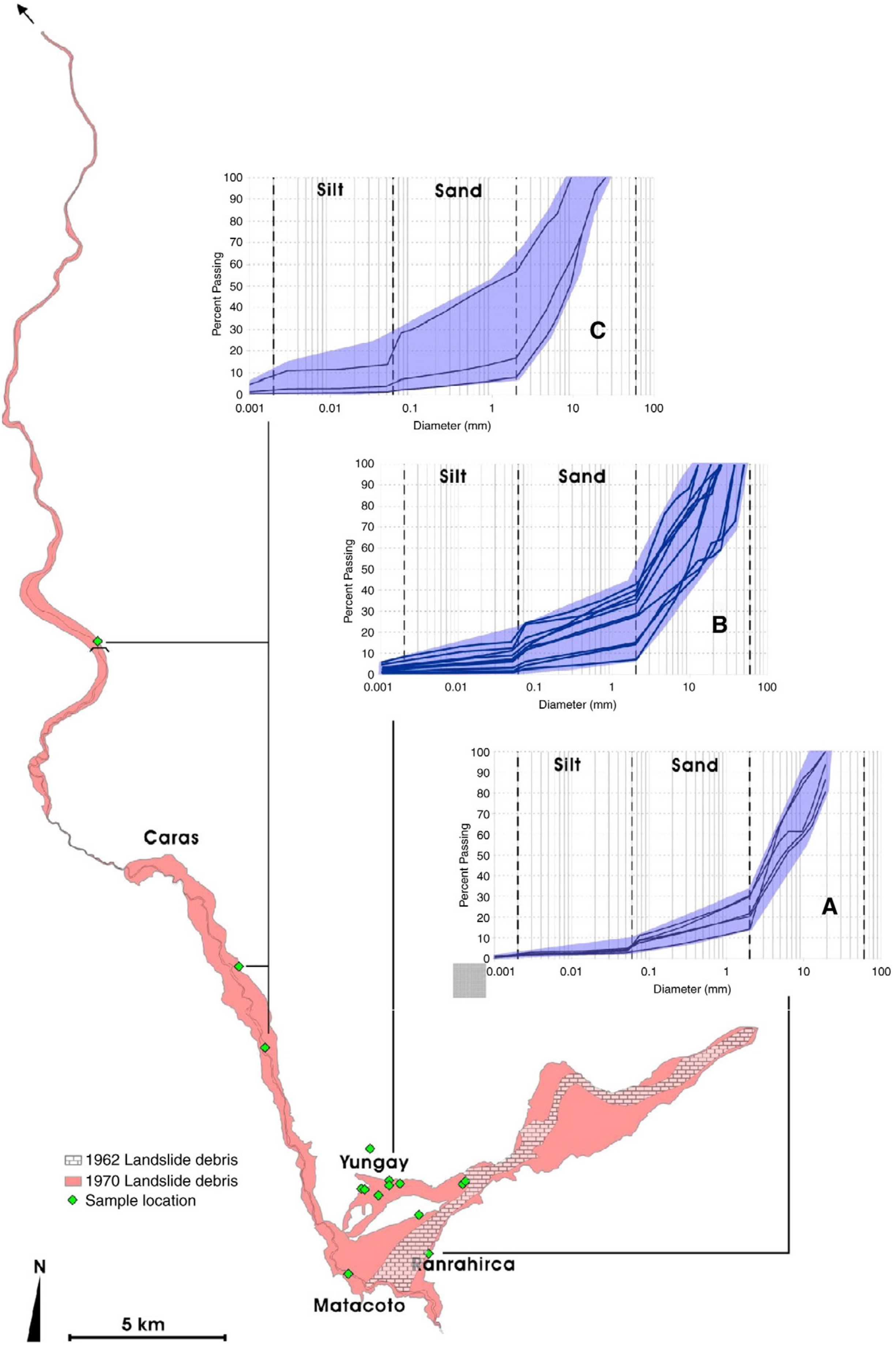
Silt
Sand
C
Percent Passing
100
90
80
70
60
50
40
30
20
10
0
0.001
0.01
0.1
1
10
100
Diameter (mm)
Silt
Sand
B
Percent Passing
Diameter (mm)
Silt
Sand
A
Percent Passing
Diameter (mm)
Caras
Yungay
Ranrahirca
Matacoto
1962 Landslide debris
1970 Landslide debris
Sample location
N
5 km

Table 2
Grain size and atterberg limits on 19 samples of 1970 debris flow matrix in Ranrahirca–Yungay area and four downstream locations in the Rio Santa valley (located in Fig. 19).

Sample	% Passing #200 sieve	Plastic Limit	Liquid Limit	Plasticity Index	Location
H1	24.7	19.2	30.2	11.0	Yungay Lobe
H2	23.6	19.5	30.0	10.4	Yungay Lobe
H3	13.0	NP	18.1	NP	Yungay Lobe
H4	2.2	NP	NP	NP	Yungay Lobe
H5	5.9	NP	19.9	NP	Yungay Lobe
H6	4.0	NP	NP	NP	Yungay Lobe
H7	13.4	NP	NP	NP	Yungay Lobe
H8	14.4	NP	19.8	NP	Yungay Lobe
H9	17.2	NP	18.1	NP	Yungay Lobe
H10	11.4	NP	18.5	NP	Yungay Lobe
H11	11.5	NP	18.7	NP	Yungay Lobe
H12	3.8	NP	NP	NP	Ranrahica Lobe
H13	8.6	NP	20.5	NP	Ranrahica Lobe
H14	7.5	NP	16.6	NP	Ranrahica Lobe
H15	11.1	NP	20.8	NP	Ranrahica Lobe
H16	8.9	NP	17.3	NP	Downstream
H17	28.4	15.5	25.7	10.2	Downstream
H18	7.0	17.0	24.7	7.7	Downstream
H19	2.4	NP	17.9	NP	Downstream

ratio of 0.3, this is equivalent to a porosity (n) of 23%. This value of n is thus the required water content, by volume, for full (100%) saturation and represents the maximum in-situ water content possible in the moraine. Full saturation at this porosity is equal to a water content, by weight, of 11% (Fig. 1.10 in Craig, 2004). Water contents measured within several metres of the surface of moraines are typically in the range 4–6% (Whalley, 1975; Springman et al., 2003).

If we assume full saturation (water content ~11%) the material entrained (10 Mm^3) in the 1962 event would have contained 2.3 Mm^3 of water. For the assumed sediment concentration noted above (65%) this leaves a water deficit of 1.8 Mm^3 which must have its source in melted snow entrained from the surface of Glacier 511 and in melted fragmented ice from the summit ice cap. With the same assumptions as in 1962, water liberated from in-situ moisture during entrainment in the 1970 event is approximately 10 Mm^3, indicating a deficit of 7.8 Mm^3.

If it is assumed that the contribution of melted glacial ice was negligible in both events, then the deficit must be made up from the melting of snow entrained from the surface of Glacier 511. With the assumption that the average density of ice/firn is 500 kg/m^3, then the volume of snow required in 1962 is 3.6 Mm^3 and in 1970 the volume of snow required is 15.6 Mm^3. In 1962, the path of the rock/ice fall down Glacier 511 had an area of about 1 Mm^2, suggesting an average depth of snow entrainment of ca. 3.6 m. In 1970 the path had an area of 1.74 Mm^2 indicating an average depth of snow entrainment on Glacier 511 of about 9 m.

It is noted that our estimated volumes of entrained snow are quite comparable to the field estimates by Schneider (1983) for the 1962 event and Ghiglino Antunez (1971), and Lliboutry (1975) for the 1970 event quoted above. With reference to the 1970 mass movement, Plafker and Ericksen (1978) note that it occurred at the end of the "wet" season, when snow accumulation was at its maximum.

It is emphasized that these are approximations to initial conditions for the onset of fluidization. Conditions before the events are not known precisely so the foregoing is necessarily speculative. However, it is thought to approximate the flow mechanisms involved and the relative contributions of soil moisture and melted entrained snow to the water required for fluidization in the 1962 and 1970 events and the generation of high velocity mud-rich mass flows. Further, sediment concentration varied as the flows developed. It is unlikely that all the entrained snow melted instantaneously and it is more plausible that the fluidization of the debris by the addition of water from melted snow was progressive with downslope movement before and after the massive entrainment below 3800 m a.s.l. It is probable that when deposition started to take place below 2900 m a.s.l., the volume of solids in the moving mass began to decrease at the same time as the water content increased due to progressive snow melting, thus increasing the fluidity of the flow with distance traveled toward the Rio Santa.

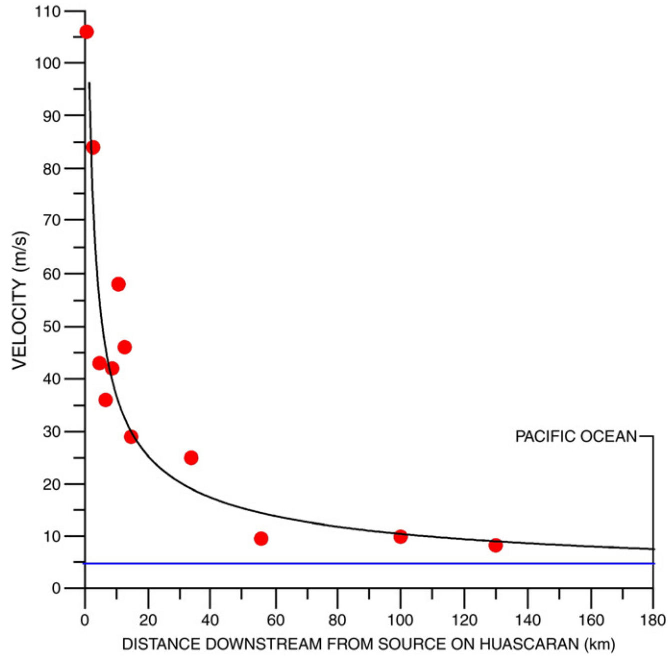

Fig. 20. Velocity plot of entire path of the 1970 mass movement originating on Huascarán and continuing downstream as a debris flood (aluvión) in the Rio Santa to the Pacific, a distance of 180 km. Black line is fitted power law. Blue horizontal line is drawn at 5 m/s indicating that the velocity of the distal debris flood (aluvión) exceeded this velocity in its travel to the Pacific Ocean. Data calculated from information in Ghiglino Antunez (1971), Ericksen et al. (1970), and Lliboutry (1975).

4.3. Sediment concentration in the distal flow (aluvión) in the Rio Santa

Since mass flows become progressively more dilute as they flow, as a result of deposition, the concentrations noted above would be expected to drop to those of a mud flood (or hyperconcentrated flow) as observed in the aluvión downstream in the Rio Santa both in 1962 and 1970. If we assume that the entrained material deposited in the Yungay–Ranrahirca area in both events was deposited at water contents ~10% (cf. Berti et al., 1999) then in 1962 about 3 Mm^3 of water was injected into the Rio Santa. This produced a debris flood/hyperconcentrated flow with a sediment concentration, by volume, of roughly 48%. In 1970, using the same assumptions, about 10 Mm^3 of water was introduced into the Rio Santa producing a hyperconcentrated flow with an initial sediment concentration, by volume, of about 37%.

5. First-order two-dimensional dynamic analysis

A first-order two-dimensional hindcast dynamic analysis of both the 1962 and 1970 events was carried out using the numerical simulation model DAN/W (Hungr, 1995; Hungr and McDougall, 2009). DAN/W has been used to simulate the behaviour (i.e., runout distance, velocity and debris thickness) of over 25 well-documented rock avalanches and rockslide-debris avalanches (Hungr and Evans, 1996; Evans et al., 2001; Hungr and Evans, 2004; Evans et al., 2007; Sosio et al. 2008), as well as debris flows (Ayotte

Fig. 19. Location of matrix samples and results of grain size analysis of material collected during field survey of debris flow deposits in the Ranrahirca (A) and Yungay (B) areas and debris flood (aluvión) deposits downstream (C). Individual grain size curves (blue lines) and grain size envelopes (blue tone) for the three groups of deposits are shown. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

and Hungr, 2000; Jakob et al., 2000; Revellino et al. 2004). In the model, the basal resistance of the moving mass is approximated by the selection of one of eight rheologies as outlined by Hungr (1995).

5.1. Inputs to the simulation

5.1.1. Input 1 — profile of path

The profile used for the both the 1962 and 1970 Huascarán simulations is shown in Figs. 8 and 13. DAN/W is a two dimensional model and does not have the capability to simulate multiple offshoots (or lobes) from the main moving mass. Because of this limitation, a simplifying assumption was necessary to simulate the 1970 event where debris spilled over the main valley side to form the separate Yungay lobe. This involved neglecting the Yungay lobe, which formed only 7% of the material involved in the 1970 event, and assuming that all the material in the flow moved down the Rio Ranrahirca and onto the Ranrahirca fan. The path distance to Yungay was obtained by projecting the distance onto the main profile.

5.1.2. Input 2 — entrainment and selection of rheology

Based on estimates of entrainment in Table 1, erosion depths of 6.0 m and 4.5 m for the 1962 and 1970 events, respectively were assigned within the model between elevations 4170 and 2912 m a.s.l. to account for the material entrained by the mass movements below Glacier 511. Further, as suggested by Hungr and Evans (1996, 2004) and Revellino et al. (2004) a Voellmy rheology (Hungr, 1995) was selected to characterize the behaviour of material in both the upper and lower segments of the path. In this rheology basal resistance is characterized by two parameters, a friction coefficient (μ) and a turbulence coefficient (ξ) (Hungr, 1995).

5.1.3. Input 3 — Voellmy parameters

For the simulation of the 1962 and 1970 events, a range of values for the Voellmy model rheological parameters were considered based on previous well-documented case histories of rock avalanches on glaciers, and debris flows. In order to narrow the range of Voellmy parameter values to be used in the Huascarán simulation, a dynamic analysis of the Pandemonium Creek rock avalanche was carried out. The event occurred in 1959 when a rockmass of approximately 5 Mm^3 fell onto a glacier in the Coast Mountains of British Columbia and resulted in a highly mobile rock avalanche — debris flow in Pandemonium Creek (Evans et al., 1989), a mass movement which exhibited very similar behaviour to the Huascarán events.

The Pandemonium event was best simulated by dividing the path into an upper part (involving travel over the glacier) and a lower part (involving the more fluid debris flow below the glacier) and applying different values of the Voellmy parameters to these path segments. For the upper portion of the avalanche involving initial travel over the glacier surface, a Voellmy rheology with a friction coefficient (μ) of 0.03, and a turbulence coefficient (ξ) of 1000 $\mathrm{m/s}^2$ was applied. For the lower part of the rock avalanche–debris flow path downslope of the glacier a Voellmy rheology, with a friction coefficient (μ) of 0.02, and a turbulence coefficient (ξ) of 500 $\mathrm{m/s}^2$, was used. These parameters simulated the runout distance and provided a good match to velocities estimated by Evans et al. (1989) on the basis of superelevation and run-up geometries. It is noted that the parameters adopted for the upper part of the path are identical to those used to best simulate the behaviour of the 1964 Sherman Glacier rock avalanche (Hungr and Evans, 1996) and the parameters adopted for the lower path are closer to those that best simulate fluid debris flows (e.g., Revellino et al. 2004).

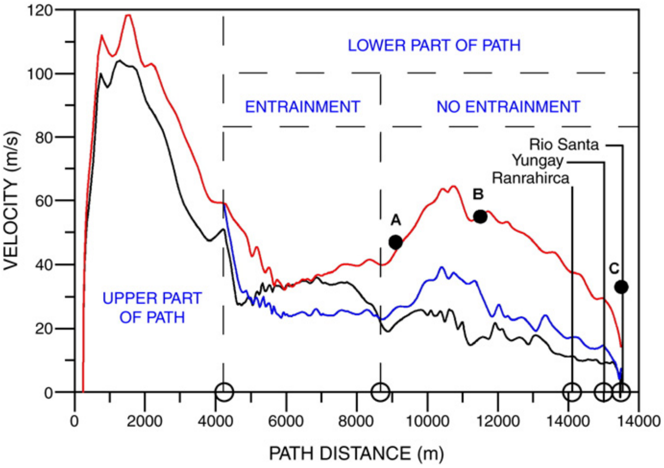

Fig. 21. Results of DAN/W simulation of 1962 (black line) and 1970 events (blue and red lines) using a Voellmy basal resistance model. In the simulation the path was divided into two parts; an upper part covering the source to the terminal moraine of Glacier 511 and a lower part from the moraine to the Rio Santa. A zone of entrainment formed part of the path immediately below the moraine of Glacier 511. For all three simulations the same resistance parameters were used for the upper part of the path ($\mu = 0.03$; $\xi = 1000\ \mathrm{m/s}^2$). For the lower part of the path a different set of resistance parameters ($\mu = 0.02$; $\xi = 500\ \mathrm{m/s}^2$) were used for the 1962 event (black line) and a first simulation of the 1970 event (blue line). As discussed in the text these parameters give a good approximation to the behavior of the 1962 event but the results for the 1970 were much slower than observed velocities. A faster simulation (red line) that better approximated observed velocities was achieved with the application of a second set of resistance parameters to the lower part of the path ($\mu = 0.01$; $\xi = 1500\ \mathrm{m/s}^2$). The points A, B, and C are velocities obtained from superelevation and run-up geometries as reported by Plafker and Ericksen (1978). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

Because of the similarities noted above, the same values for these parameters were applied to upper and lower segments of both the 1962 and 1970 Huascarán events (Fig. 21). The first (upper) segment of the path consists of the initial movement down Huascarán's North Peak and travel over Glacier 511 and terminates at the distal limit of the glacier (el. 4065 m asl). The second (lower) segment consists of the remainder of the path from this point to the Rio Santa (el. 2364 m a.s.l.).

5.2. Results

5.2.1. Run-out distance

Using the two sets of parameters for the two path segments as noted above, the runout distances for the 1962 and 1970 events are well simulated using the Voellmy rheology and the values of the rheology parameters specified above (Fig. 21). Fig. 21 shows the debris in both events sloshing back and forth in the channel of the Rio Santa after running up and back down the steep west side of the valley. The velocity plot for both events indicates that the debris does not stop at the Rio Santa but continues its motion in the downstream flow, reflecting the actual behavior of the two flows in 1962 and 1970.

5.2.2. Velocity

The simulated velocity profiles for both the 1962 and 1970 events are shown in Fig. 21. The profiles are broadly similar. Both show a very rapid acceleration in the initial phase of the movement up to a maximum velocity in excess of 100 m/s. This is followed by a phase of decreasing velocity as the debris travels down the surface of Glacier 511 on decreasing gradients and gaining mass. Before leaving the glacier at path distance of 4237 m, a sudden acceleration is noted as the avalanche is constricted by the terminal moraine. Past the distal limit of Glacier 511 velocity decreases sharply to about 30 m/s as entrainment of debris begins. It is from this point forward that the velocity profile of the 1962 event differs from that of the 1970 event (Fig. 21).

In 1962 at a path distance of 8 km (Fig. 21), the velocity begins to decline after a phase of variable but almost constant propagation speed of about 35 m/s which is associated with entrainment. This is followed by a phase of highly variable velocity as the debris becomes constrained in the narrow valley of the Rio Ranrahirca (Shacsha).

The final deceleration phase begins at a path distance of 12.65 km as the debris enters the Ranrahirca fan and spreads out. No independent velocity estimates are possible within the 1962 path but arrival times at certain landmarks can be approximated. The simulation indicates arrival at Ranrahirca (path distance of about 14.1 km) in an elapsed time of 510 s (8.5 min) and arrival at the Rio Santa (path distance of about 15.5 km) in about 665 s (~11 min). These simulated travel times are well bracketed by those cited in Dollfus and Penaherrera (1962), Morales Arnao (1966), and McDowell and Fletcher (1962). The known arrival time at Ranrahirca was 6:18 p.m. and thus the simulated time to that point indicates initiation at about 6:10 p.m., within 3 min of that suggested by McDowell and Fletcher (1962). The simulated time arrival time at the Rio Santa is 6:21 p.m.; this compares to an estimate of 6:20 p.m. reported by McDowell and Fletcher (1962). The simulated average velocity for the final 1400 m to the Rio Santa (150 s) is 9.3 m/s. This compares to 8 m/s estimated by Dollfus and Penaherrera (1962) and Morales Arnao (1966) and 21 m/s suggested by the report of McDowell and Fletcher (1962). The simulated time to the Rio Santa is 11 min, compared to 7 min (McDowell and Fletcher, 1962) and 15 min (Dollfus and Penaherrera, 1962; Morales Arnao (1966). The simulated mean velocity for the 1962 event is 23.5 m/s compared to 18 m/s estimated by Morales Arnao (1966) and 38 m/s implied in McDowell and Fletcher (1962). In the case of the 1962 event, it is concluded that the simulated velocity compares very well to the observed mean velocity to the Rio Santa, the velocity to Ranrahirca, and to the final velocity over the Ranrahirca fan.

In 1970 (Fig. 21), onset of significant and dramatic entrainment at a path distance of 4237 m results in a decrease in velocity below that of the 1962 event, to about 27 m/s, but as the developing debris flow encounters the confinement of the steep sided Rio Ranrahirca (Shacsha) below el. 2950 m, the velocity increases rapidly to 40 m/s at a path distance of 10.4 km. It was shortly after this point that some material ran over the Cerro de Aira to form the Yungay lobe. After this point the velocity fluctuates and declines to the Rio Santa. Velocities at path distances of 9.1 km and 11.1 km have been estimated by Plafker and Ericksen (1978). On the basis of superelevation and run-up geometry, they calculated velocities of 47 m/s and 55 m/s respectively. These velocities exceed the DAN simulated velocities at these locations (Fig. 21) of 26.5 m/s and 35 m/s respectively.

In contrast to 1962 the moment of the initiation of the 1970 event is known, probably to the nearest minute, since the first seismic shaking was recorded at 3:23:28 p.m. As in 1962 arrival times at certain landmarks can be approximated by the eye-witness observations summarized above. Cluff (1971) indicates that the debris flow reached Cemetery Hill (path distance of 15 km) in about 3 min (180 s), indicative of a mean velocity to this point of 83 m/s and an arrival time of about 3:26 p.m. Ghiglino's reconstruction shows an elapsed time of 270 s equivalent to a slower average velocity (55 m/s) and an arrival time of 3:28 p.m. Our simulation suggests an elapsed time of 497 s to Cemetery Hill, an arrival time of 3:32 p.m. and thus a slower mean velocity of 30 m/s to that point. This is less than half the estimate based on the Casaverde–Cluff observation (83 m/s) and much lower than the lower bound estimate suggested by Ghiglino's reconstruction.

Thus it is apparent that in the case of the 1970 event, using the same basal resistance model and the same values for the rheological parameters as in the 1962 case, DAN simulates lower velocities than indicated by point estimates along the path and by arrival times at Yungay, Cemetery Hill, and the Rio Santa based on eyewitness reports. This result suggests that the 1970 flow was more fluid than the 1962 event.

An additional simulation was therefore carried out for the 1970 flow using values of the Voellmy resistance parameters that reflected its more fluid conditions. The same parameters were used in the upper part of the mass movement, but for the lower part of the path involving entrainment below Glacier 511 values of $\mu = 0.01$ and $\xi = 1500$ m/s were adopted. This induced a much faster simulated fluid phase for the 1970 flow (Fig. 21) and a closer correspondence to the field and eyewitness estimates of velocity. Travel time to Cerro de Aira (11.5 km) was simulated as 225 s compared to Ghiglino's estimate of 180 s, travel time to Yungay was simulated as 281 s (average velocity from source ~50 m/s) as compared to Ghiglino's estimate of 270 s (average velocity from source ~52 m/s). Travel time to Cemetery Hill was simulated as 292 s (51.4 m/s), compared to the Casaverde–Cluff estimate of 180 s (83 m/s) and the Casaverde–Kuroiwa estimate of 240 s (62.5 m/s). Travel time to the Rio Santa was simulated as 328 s, equivalent to a mean velocity for the whole path to the Rio Santa of 47 m/s. This estimate is still lower than the 75 m/s estimate of Plafker and Ericksen (1978) based primarily on the Casaverde–Cluff estimate of travel time to Cemetery Hill. As noted above, point estimates of minimum velocities at path distances of 9.1 km and 11.5 km have been estimated by Plafker and Ericksen (1978). On the basis of superelevation and run-up geometry, they calculated velocities of 47 m/s and 55 m/s respectively (Fig. 21). The new simulated values for these locations are 44.7 m/s and 55.4 m/s respectively (Fig. 21).

In the simulation it is significant that the debris does not halt at the Rio Santa (Fig. 21). Indeed, the results indicate a velocity of about 20 m/s at a path distance of 15.5 km (Fig. 21). Plafker and Ericksen (1978) estimate a velocity at the Rio Santa of 33 m/s based on a 83 m runup at Matacoto. The simulated velocity at 15.5 km gives an approximation to the initial velocity of the downstream flow at 3:28 p.m. We noted above that the distal flow reached Caraz, 17 km downstream, at 3:38 p.m. suggesting a mean downstream velocity of 28 m/s for this portion of the distal flow path.

Thus, the simulation of the 1970 event with the more fluid parameters in the Voellmy model applied to the lower part of the path, suggested velocities which are bracketed by minimum and maximum velocity estimates based on eyewitness testimony and field estimates of velocity calculated from superelevation and run-up geometries.

6. Human casualties and damage to infrastructure in the 1962 and 1970 mass movements

6.1. Human casualties

As is evident by comparing Figs. 5, 10, and 15, both the 1962 and 1970 mass movement devastated large areas of populated rural terrain. This resulted in high numbers of fatalities in both events. In 1962 approximately 4000 deaths are reported to have occurred as the result of the destruction of a large part of Ranrahirca and several hamlets in its path in the valley of the Rio Ranrahirca (Shacsha) and on the Ranrahirca fan (Ruegg, 1962; McDowell and Fletcher, 1962; Morales Arnao, 1966). The village of Yanamachico located in the Rio Ranrahirca (Shacsha) upstream of Ranrahirca, for example, had a reported pre-event population of about 800. Only 8 people reportedly survived (McDowell and Fletcher, 1962).

The impact of the mass movement triggered by the 1970 fall from Huascarán was considerable and reportedly involved a massive loss of life (e.g., Plafker et al., 1971). The event is frequently listed as one of the deadliest mass movements in history (e.g., Evans, 2006; Schuster and Highland, 2007). The most detailed summary of casualties is by Plafker et al. (1971) who tabulate data from *Comite Nacional de Emergencia del Peru* as of July 2, 1970. The estimated pre-event population of the town of Yungay is given as 18,830. These data suggest that the dead and missing at Yungay totalled 15,320. At Ranrahirca, reconstructed after the 1962 disaster, dead and missing totalled 1800 out of a total reported population of 1850; Table 1 in Plafker et al., (1971). For Matacoto, no casualty data is given in Table 1 in Plafker et al. (1971) but its population is reported as 1340. However, if we assume that a reported 70% destruction of its buildings (Table 1 in Plafker et al., 1971) resulted in a 70% loss of life of its total population this yields a further 938 casualties. These numbers give a

Fig. 22. The site of Yungay before (A) and after (B) the May 31, 1970 debris flow in georeferenced aerial photographs. A: the urban area of Yungay is outlined by a white line. The outlined area is 0.36 km^2. In the 1961 Peru Census the population of Yungay was recorded as being 3543, a population density of 9980 p/km^2. The Plaza de Armas is visible in the town centre. (Servicío Aerofotografíco Nacional de Perú photograph; January 9, 1962). B: the urban area of Yungay superimposed on the debris of the Yungay lobe deposited on May 31, 1970. The 1970 population of Yungay has been estimated at 4100 (see text), a population density of 11,549 p/km^2. Note the four palms that survived the event are visible at the former site of the Plaza de Armas in the centre of the outlined area. (NASA aerial photograph; July 14, 1970). Cemetery Hill is visible near the lower margin of both photographs.

total of 18,058 deaths in Yungay, Ranrahirca and Matacoto alone. Further, it does not include the probable casualties of buried communities upstream of Yungay and therefore could be considered a minimum estimate, with the total number of deaths in the 1970 Huascarán event, based on these estimates, possibly being in excess of 20,000 given these reported casualties. Indeed, Cluff (1971, p. 516) notes that the debris avalanche “took a toll of about 25,000 to 30,000 lives in Yungay, Ranrahirca, and nearby villages.” A more recent

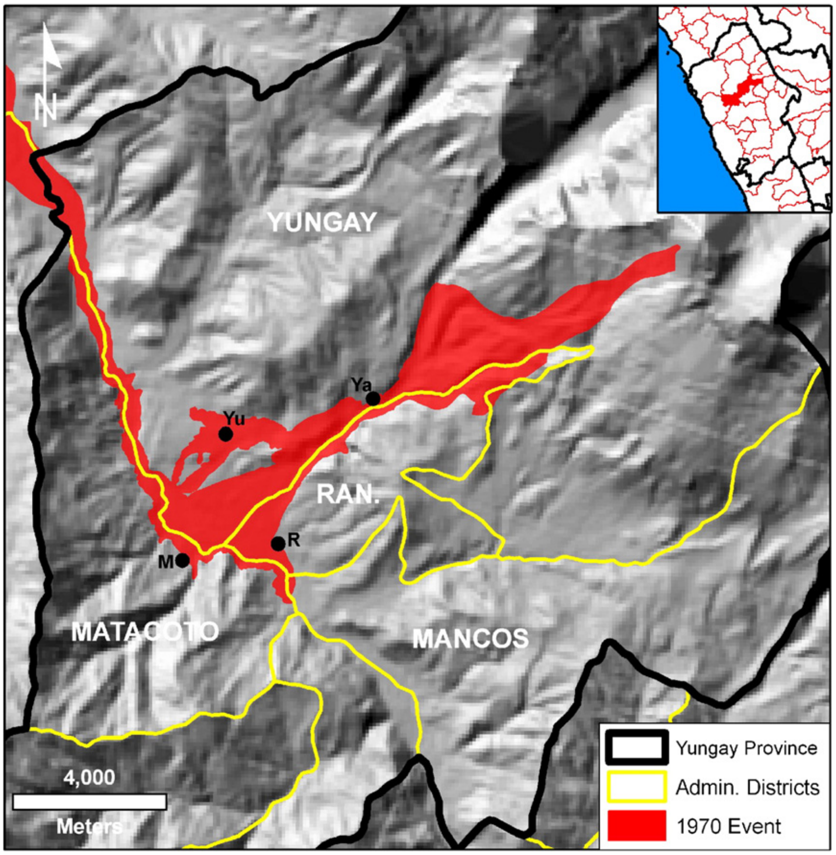

Fig. 23. Path of 1970 Huascarán event in relation to boundaries of Yungay Province and administrative districts within Yungay Province. Districts shown are Yungay, Ranrahirca (RAN), Mancos, and Matacoto. Populated centres are shown with black dots (M — Matacoto; R — Ranrahirca; Ya — Yanamachico; Yu — Yungay). Inset shows location of Yungay Province within the Department of Ancash.

Table 3

Data on population of Yungay province, in the area affected by the Huascarán events, from 1961 Peru census — Department of Ancash (Republica del Peru, 1968).

Place	Census administration unit	Population (males and females)	Area (km^2)	Population density (persons/km^2)
Yungay	Province	36,679	1417.25	24.9
Yungay	District (urban and rural)	15,068	276.68	54.46
Yungay	Town	3543	0.36	9980
Ranrahirca	District (urban and rural)	2410	22.8	105.7
Ranrahirca	Town	417	–	–
Matacoto	Town	210	–	–

estimate of the total deaths in the 1970 event is “in excess of 25,000” (Keefer and Larsen, 2007).

However, there is very strong evidence for suggesting that the loss of life in both the 1962 and 1970 Huascarán events has been grossly overestimated in the geohazard literature by an order of magnitude.

With respect to the 1970 event, the possibility of an overestimate was first suggested by Clapperton and Hamilton (1971) who point out that the 1961 Peru Census indicated that the population of the town of Yungay was 3451. They further suggest that the error originated in the mis-reading of the 1961 Census data (Clapperton and Hamilton, 1971, p. 639). In 1970 the town of Yungay (Fig. 22) was the capital of both Yungay District (276 km^2) within the larger Yungay Province (1417 km^2), which in 1961 had populations of 15,068 and 35,289 respectively (Republica del Peru, 1968; Fig. 23). Further, in 1962 the village of Ranrahirca was the administrative centre of Ranrahirca District (22.8 km^2) within the Province of Yungay and Matacoto village was the administrative centre of Matacoto District (43.65 km^2) within the Province of Yungay (Fig. 23).

We consulted the 1961 Census documents for Ancash (Republica del Peru, 1968) to obtain the official populations of these administrative areas (Table 3) in an attempt to estimate a maximum credible death toll for the 1962 and 1970 Huascarán events.

With reference to the 1962 event, the debris avalanche partially destroyed the village of Ranrahirca and the populated rural places of Huarascucho, Shacsha, Yanamachico, and Armapampa (upstream of Ranrahirca) and Uchocoto (downstream from Ranrahirca). The 1961 population of Ranrahirca village was 417 with an additional population of 1993 in outlying rural areas of Ranrahirca District, for a total of 2410 people for Ranrahirca District (Table 3; Republica del Peru, 1968). The 1962 event also impacted on the more remote areas of Yungay District. Debris devastated a total populated area of approximately 3.0 km^2. The rural population density of the debris covered area is roughly 102 persons/km^2 (data calculated from Republica del Peru, 1968) giving a credible life loss estimate of ca. 310. Only 98 persons survived in the village of Ranrahirca (*Time*, January 19, 1962) indicating a death toll of ca. 320. This together with the rural area life loss noted above gives a probable upper limit of deaths in the 1962 event of roughly 650. It is very unlikely that 4000 people lost their lives in 1962 since this death toll would require a population density of 1320 persons/km^2 in the affected area, more than ten times that calculated from data in the 1961 Census (105.7 p/km^2; Table 3).

In 1961 the population of the town of Yungay is given as 3543 (Republica del Peru, 1968, p. 2). Doughty (1999) estimates that this had risen to about 4100 people in 1970. In addition, a series of publications by Oliver-Smith (e.g., 1977, 1979, 1986) in the social science literature also indicate that the 1970 pre-earthquake population of Yungay was around 4,500 (Fig. 22). This estimate is based on the 1961 Census data and the fact that by 3:23 p.m. on the Sunday afternoon of the disaster many of the rural people who had come to Yungay from outlying areas for morning mass and to visit the market had returned to their villages. We note that if the pre-event population of Yungay was 18,830 as reported in Plafker et al. (1971) and Plafker and Ericksen (1978) the required population density would have had to be 52,305 p/km^2, almost twice that of present-day Mumbai, India. There is no doubt that the 1970 event completely destroyed Yungay (Fig. 22). If, as suggested by many authors, the event killed around 90% of the population of Yungay, this gives a death toll of around 4000 in the town of Yungay alone (Oliver-Smith and Goldman, 1988).

The 1970 event covered 19.2 km^2 of populated terrain (below 3800 m a.s.l.) with 14.9 km^2 in Yungay District and 4.3 km^2 in Ranrahirca District (Fig. 23). If we exclude the area and population of Yungay, and assume the population density for the remaining 18.85 km^2 suggested by the 1961 Census as roughly 102 persons/km^2 (Table 3), for the area covered by debris (Fig. 23) this would represent the loss of roughly 1925 people.

Therefore, together with possible additional casualties in Ranrahirca (97 as reported by Clapperton and Hamilton, 1971) and Matacoto (1961 population of 210 (Republica del Peru, 1968)), we suggest a total death toll of around 6000 is a more credible estimate for the loss of life in the 1970 Huascarán event, an estimate substantially lower than previously published estimates in the geological literature. We note that these estimates are based primarily on the work of Plafker et al. (1971) and Plafker and Ericksen (1978). With reference to Table 1 in Plafker et al. (1971, p. 544) it appears that the estimated populations for the communities listed are those for the larger administrative districts rather than for the actual smaller urban communities of the same name impacted in 1970, an error that resulted in a substantial overestimate of the death toll in the 1970 Huascarán event which has persisted in the geohazard literature to the present.

7. Implications for Hazard Evaluation and Risk Assessment

In agreement with initial observations by the Peruvian engineer Ghiglino Antunez (1971) and in strong contrast to the well known report by Plafker and Ericksen (1978) our re-examination of the 1962 and 1970 Huascarán mass movements indicates they were complex events in which an initial rockslope instability underwent a dramatic transformation into a massive high velocity mud-rich debris flow by entrainment of material from its path. The mechanism of these events appears to have been similar to other complex mass movements that occurred in Canada in 1959 (Evans et al., 1989), and Chile in 1987 (Casassa and Marangunic, 1993; Hauser, 2002). These movements originated in glacier environments and were transformed into high-velocity far-reaching mass flows, largely because of incorporation of snow from glacier surfaces (Petrakov et al., 2008). Because of their complexity, the hazard evaluation of these types of mass movements is extremely difficult. The development and direction of the transformation of these events depends on such factors as the volume of ice involved in the initial fall, the availability of snow in the path, as well as the availability and moisture content of entrainable material.

The initial 1962 and 1970 rock slope failures fell from the scar of the massive Pleistocene rock avalanche, the debris of which fills the Rio Santa valley below Huascarán. The presence of an unstable rock mass structure in the west face predisposes the face to rock slope failure. The structure includes almost vertical persistent joints intersected by less-persistent joints that dip out of the slope. This unstable rock mass structure not only contributed to the initial falls of 1962 and 1970 but was probably an important factor in the massive Pleistocene detachment.

The decrease in glacier ice cap volume may have destabilized the summit ice cap resulting in significant volumes of ice being involved in the initial fall. Further twentieth century ice loss from Glacier 511, manifested in the exposure of its terminal moraine system may also

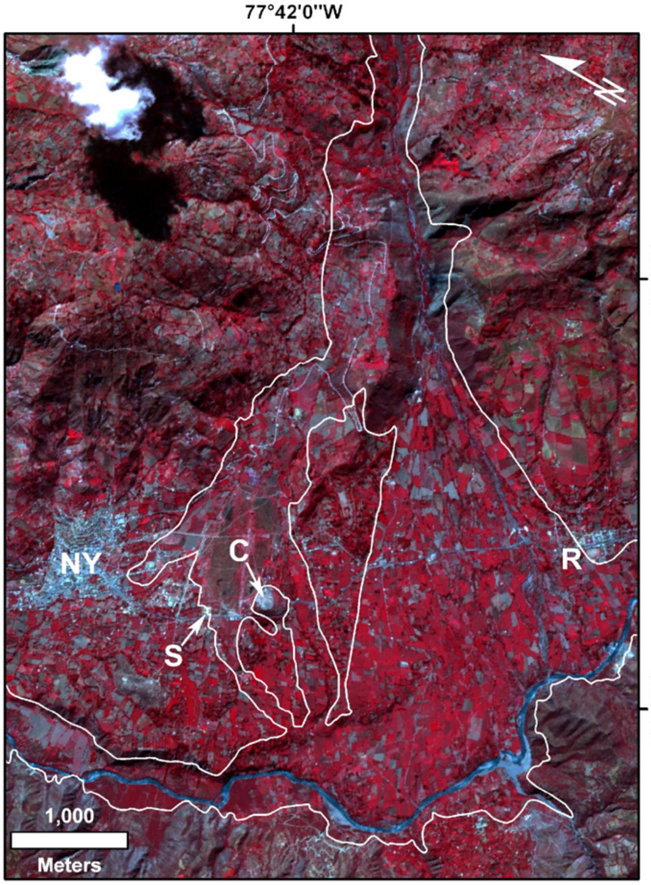

Fig. 24. SPOT image of the Yungay–Ranrahirca area obtained on August 26, 2006, showing the re-occupation of the 1962 and 1970 debris by the local population. Outline of 1970 event are shown with solid white line. NY is location of Nueva Yungay, the site where Yungay was reconstructed after 1970, C is Cemetery Hill, and R is Ranrahirca. S is location of new school shown in Fig. 25. Compare Figs. 5, 10 and 15.

have influenced the stability of the west face, debutressing the base of the failed slope.

Fig. 25. View towards the Rio Santa over the surface of the 1970 debris in the vicinity of the former Yungay. Note characteristics of debris, including large granodiorite block. New infrastructure developed on the 1970 debris includes a new school, visible at upper right. Photograph by SGE (October 2004).

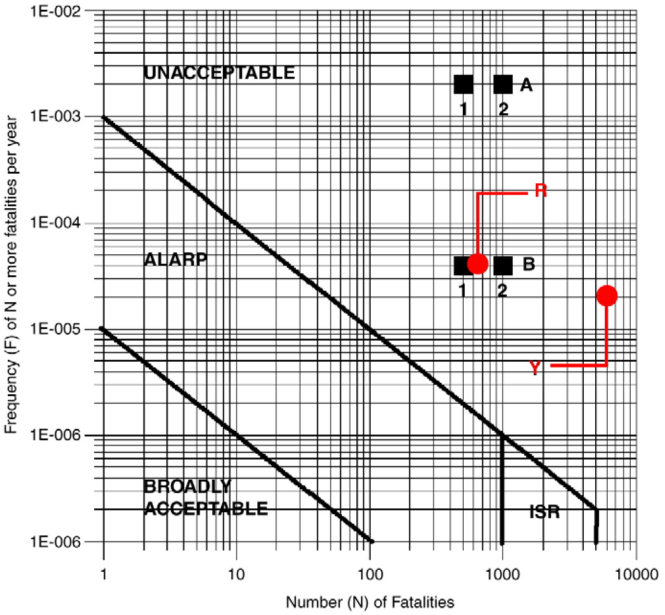

Fig. 26. F/N plot of risk scenarios in the Yungay–Ranrahirca area in relation to societal risk criteria. Boundaries shown are of Unacceptable risk, As Low as Reasonably Practicable (ALARP), Broadly Acceptable risk, and Intense Scrutiny Region (ISR) based on Fig. 4 in Fell et al. (2005). Black squares are scenarios for the Ranrahirca fan. A1 and A2 represent maximum existing hazard scenarios for 500 and 1000 deaths respectively. B1 and B2 represent minimum existing hazard scenarios for 500 and 1000 deaths respectively. The red dots represent the retroactive risk for a single event in 48,000 years at Yungay (Y), i.e., the 1970 event, and two events in 48,000 years at Ranrahirca (R), i.e., the 1962 and 1970 events. See text for detailed discussion. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

The 1962 and 1970 Huascarán mass flows developed much of their destructive power by massive entrainment along the upper part of their path, and the fact that the entrained volume was fluidized by water originating from the melting of large volumes of entrained snow and from the water contained in the soil structure of entrained material. The operation of these factors is difficult to quantify in retrospect and may be impossible to predict in prospect.

As in many other disasters, the lessons of precedent appear to be inescapable. The precedent in this case has two elements; a) the twentieth century events travelled over, in large part, the surface of a Pleistocene rock avalanche that originated on Huascarán; the scar of the Pleistocene event was the source of the initial falls in 1962 and 1970, b) the 1970 event was presaged to a remarkable degree by the smaller 1962 event.

The 1970 debris is being re-populated by the local people (Fig. 24) and new infrastructure is being constructed near the former site of Yungay (Fig. 25). Yungay has been rebuilt and relocated as Nueva Yungay (Fig. 24) and Ranrahirca has re-developed into a thriving community.

We evaluated landslide risk on the Ranrahirca fan, in relation to possible future mass flows originating in falls from Huascarán similar in nature to those of 1962 and 1970. First, we assumed that at least two debris avalanche events, originating on the North Peak of Huascarán, occurred in the 48 ka period since the emplacement of the large-scale rock avalanche from Huascarán that forms much of the surface covered by the 1962 and 1970 events. This is equivalent to an annual probability of occurrence of 4×10^{-5} and constitutes a minimum estimate of hazard. Second, no record of similar events to those of 1962 and 1970 exist for the historical period of ca. 1550 to the present (Plafker and Ericksen, 1978). Thus the two events represent an annual probability of occurrence of 2×10^{-3} and is a maximum estimate of hazard. To estimate risk we assume a minimum and maximum life loss would be 500 and 1000 respectively. This estimate of life loss is based on hypothetical debris covered areas of 4 and 8 km^2 respectively and the 2007 population density of Ranrahirca District of ca. 123 persons/km^2 (Instituto Nacional de Estadistica e Information Peru)). Plotting these points on an F/N curve used to evaluate risk acceptability (Fig. 26; Fell et al., 2005) we find both minimum and maximum estimates of existing hazard and associated life loss fall clearly in the unacceptable risk area and violate the societal risk tolerance criteria (Fell et al., 2005) in wide use in landslide risk assessment in many parts of the world.

Lastly, we estimated retroactive risk for the 1962 and 1970 events. The age of the surface was assumed, as above, to be ca. 48 ka. Ranrahirca was struck twice during this period and Yungay once. Taking this data and the death tolls we have estimated in this paper we may plot the respective retroactive risk for Yungay and Ranrahirca in Fig. 26. Both points plot well into the unacceptable risk zone (Fig. 26) suggesting that the pre-1962 and pre-1970 populations of Ranrahirca and Yungay, respectively, were exposed to unacceptable levels of landslide risk using criteria in use in other parts of the world.

8. Conclusions

We have re-examined the mechanism and human impact of two catastrophic landslides that occurred in the Cordillera Blanca, Peru in 1962 and 1970. Both mass movements originated as rock/ice falls from the North Peak of Nevado Huascarán and transformed into high-velocity mud-rich debris flows by entrainment of material from their paths. The 1962 event was initiated in the scar of a massive Pleistocene rock avalanche from Huascarán and it is probable that the west face was made more unstable by the 1962 event. We may thus view the initial failure in 1970 as the delayed second phase of the 1962 event. The mechanism of transformation in both events involved the incorporation of snow from the surface of a glacier below the North Peak and substantial entrainment of morainic and colluvial material from the slopes below the glacier terminus. Water for the fluidization of the large volume of entrained material originated in the melting of the snow incorporated from the surface of Glacier 511 and liberation of soil moisture within the entrained materials. The depth of entrainable snow on Glacier 511, following the 1970 wet season accumulation, was a major factor in transforming the initial fall and rock/ice avalanche into a highly fluid debris flow. The availability of easily entrainable, relatively fine-grained morainic/colluvial deposits that mantled the slopes below Glacier 511 is postulated to have been a key element in transforming the initial fall into a destructive far-reaching mud-and water-rich debris flow both in 1962 and 1970.

Eyewitnesses report exceptionally high mean velocities for the events; 17–35 m/s in 1962 and 50–85 m/s in 1970. Both events were simulated in terms of runout distance and velocity using the empirically calibrated Voellmy basal resistance model in DAN/W. Both mass movements continued downstream as distal debris floods (aluviones); in 1970 the aluvión in the Rio Santa reached the Pacific Ocean, 180 km from Ranrahirca.

The trigger for the 1970 event was a M7.9 offshore earthquake. However, apart from the fact that it occurred in a warm summer month, the January 1962 failure had no known trigger. The North Peak had withstood severe shaking in a number of historical earthquakes including the 1725 earthquake which triggered a major fall from the peak of Huandoy, 9 km northwest of Huascarán, and the 1946 Ancash earthquake which triggered many rock avalanches in northern Ancash.

We carefully reviewed 1961 Peru Census data for the Province of Yungay. We conclude that in strong contrast to most previously published reports in the geological literature, the death toll in the 1962 Huascarán event was about 650 people, that in the 1970 Huascarán event the death toll was in the order of 6000, and that the total life loss in the two events did not exceed 7000 people.

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