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LANDSLIDE DAMS IN THE CENTRAL ANDES OF ARGENTINA - SHOWING THE NEED OF REVISING THE ESTABLISHED LANDSLIDE DAM CLASSIFICATION

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INTRODUCTION

The Andean cordillera of Argentina is more than 3500 km long and 50 to 550 km wide and characterized by steep relief contrasts throughout. Except for a few valleys, most of this region is scarcely populated. Hence geologic mapping was mainly carried out on a scale (1:250000), which is often too small to map out various Quaternary units and therefore to highlight relations of landslide deposits with lakes or lake deposits. However, in the last years various studies have been carried out, concentrating on large landslides and their relations with valley impoundments (GONZÁLEZ DIAZ & MON, 1996; HERMANNS & STRECKER, 1999; TRAUTH & STRECKER, 1999; GONZÁLEZ DÍAZ *et alii*, 2000; HERMANNS *et alii*, 2000; TRAUTH *et alii*, 2000; FAUQUE *et alii*, 2000; FAUQUÉ & TCHILINGUIRIAN, 2002; TRAUTH *et alii*, 2003; HERMANNS *et alii*, 2003; HERMANNS *et alii*, 2005; FAUQUE *et alii*, 2005; PENNA *et alii*, 2005; GONZÁLEZ DÍAZ *et alii*, 2005). Before that, most attention was given to the catastrophic rock avalanche dam failure in the Barrancas valley causing the 1914 Río Colorado flood (GROEBER, 1916; GONZÁLEZ DÍAZ *et alii*, 2001; SCHUSTER *et alii*, 2002; HERMANNS *et alii*, 2004a).

In this paper we will focus on two regions: one in the NW Argentine (24° - 27.5° S) and one in northern Patagonia (36° – 38° S). In both regions the authors have carried out systematic studies related to landslides with volumes in excess of 10^6 m^3. These landslides formed at least 16 and 48 landslide dams in the two regions, respectively (Figure 1). In the following, due to the briefness of this paper, only peculiarities of the various cases will be described which will help to better understand large landslide dams in other regions as well. For the complete data set of both study areas we refer to the comprehensive paper, which will be published within the related NATO Science Series book. Likewise, we omit a setting description of the regions and refer here to the papers cited above.

This paper is dedicated to Mario Alberto Deza, who died in the river during field work in the Patagonian Andes downriver a lake dammed by a complex landslide. This site is described in (GONZÁLEZ DÍAZ *et alii*, 2005)

(*) This study was carried out and written at the GeoForschungsZentrum Potsdam, Germany

Fig. 1 - Position of study areas (boxes) in Argentina

LANDSLIDE DAM TYPES

Most landslide dams in the Argentine Andes can be described by 6 types of landslide dams (Figure 2, types I-VI) as defined by COSTA & SCHUSTER (1988), which is the commonly used classification (SCHUSTER, 2000; ERMINI & CASAGLI, 2003). The most common types of landslide dams are types II and III. All other types of landslide dams except for type VI have been identified as well, however there are only 2 examples of landslide dams representing type IV.

In addition to the dam types described earlier there are landslide dams in the Argentine Andes which do not fit with the commonly used classification, and new types of landslide dams must be defined (Figure 2, types VIIa-IX) to adequately describe them, understand their stability, and/or understand their occurrence. There are a few examples in the study areas where the drainage system was rearranged by the impoundment of the valley, and in other regions of the Argentine Andes comparable relations have been observed also

(FAUQUE *et alii*, 2000). In these cases the landslide dam does not represent the lowest part in the valley profile, causing a shift of the drainage away from the original streambed and into areas where a new drainage system develops over bedrock outcrops. This type of dam is very stable because a failure of the landslide dam is unlikely when no dam overtopping takes place, which is the most frequent process of catastrophic dam erosion (COSTA & SCHUSTER, 1988; ERMINI & CASAGLI, 2003). In Argentina, this type of dam has persisted for several thousands to tens of thousands of years as indicated by the history of fill up of the basins behind (FAUQUE & TCHILINGUIRIAN, 2002) or as indicated by the landslide deposit morphology. Such dams do not indicate any signs of destabilization, or basins behind have entirely filled up with sediments. The newly defined type of landslide dam can be subdevided into two subgroups: The first subgroup (type VIIa, Fig. 2) represents landslide dams forming higher barriers than the surrounding bedrock in the valley, causing the development of the new drainage over the bedrock within the same valley. The second one (type VIIb, Fig. 2) stands for landslide dams higher than the lowest drainage devide in the valley, causing lake fill up to the altitude of the drainage devide and the drainage to develop in the neighbouring valley.

A further landslide dam type (type VIII, Fig. 2), which needs to be defined, is a dam forming exactly at the drainage divide. In this case catastrophic dam failure might occur in both valleys, in the one where surficial drainage occurs by overtopping and in the other one by seepage. In the only known example from the Argentine Andes the dam composed of 3.5×10^9 m^3 existed apparently for several kyr to tens of kyr with a powerful river discharge over the dam (GONZÁLEZ DÍAZ *et alii*, 2000). However, in this valley, dam stability is further controlled by the factor that river discharge over the dam is directly into another large landslide-dammed lake.

A further type of landslide dams (type IX, Fig. 2) or (better) chains of landslide dams must be defined based upon the case history of the catastrophic failure of a rock-avalanche dam in Barrancas valley in 1914. During this event 1.2×10^8 m^3 were eroded from the landslide dam forming a giant debris flow, which deposited terraces decreasing in thickness with increasing distance from the dam toe from 20 m to 3.5 m at 60 km downriver the dam. These terraces impounded tributary valleys of the Barrancas valley. Most of the impoundments were eroded, most likely shortly after formation, however the tributary valley closest to the failed dam is still impounded up to an elevation > 17 m forming a lake with a surface area >1 km^2. Similar chains of lakes have been reported on the opposite slope of the Andes in Chile related to the giant outburst flood generated by the failure of the dam formed by the Antuco volcano collapse (MARDONES FLORES, 2002).

In addition to these newly defined cases, small lakes occur frequently in the Andes in ponds of the hummocky surface on top of the landslide deposits. Their size is mainly related to the size of the landslide dam (e.g. GONZÁLEZ DÍAZ *et alii*, 2000). They can be related to all types of landslide dams and are in general very stable, however they might represent a local hazard when eroding rivers get close to their limits.

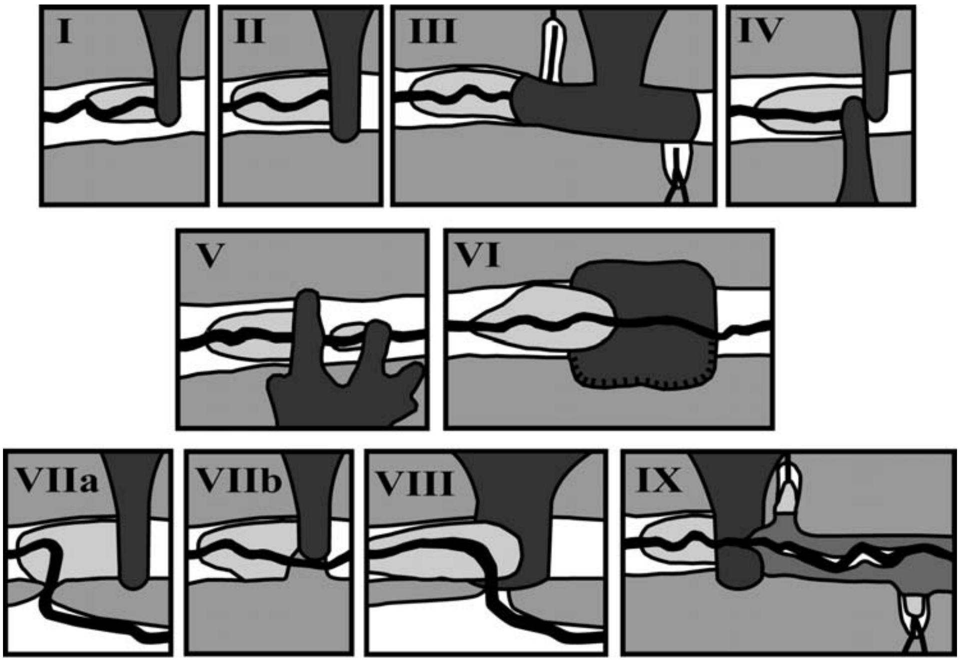

Figure 2 - Classification of landslide dam types, I – VI after COSTA & SCHUSTER (1988), VII – IX defined based on examples from the Argentine Andes

LANDSLIDE DAM STABILITY

In the NW Argentine focus region most of the dams have been eroded in the geological past. There is only one dam still impounding a lake (HERMANNS *et alii*, in press), and two basins have been filled up with sediments. In the N Patagonian focus region ~ 50 % of the landslide dams, all of them formed in prehistoric times, still impound the main valley, in addition there are several localities where water bodies occur on top of landslide deposits. When compared to landslide dam stability concepts as suggested by ERMINI & CASAGLI (2003), which base on geomorphic parameters (landslide dam volume, dam height, and size of catchment area upriver the dam) and are expressed in a dimensionless blockage index (DBI), the stability of most studied Argentine landslide dams behaved like suggested by stability/instability boundaries obtained from world wide data sets. However there are exceptions. In these cases landslide dams existed for several hundreds or thousands of years but failed finally (named “quasi-stable dams” by HERMANNS *et alii*, 2004b). A further example is the catastrophic dam failure in Barrancas valley in 1914 where exceptional climatic conditions governed the year before dam failure; the dam had existed for more than 427 yrs (HERMANNS *et alii*, 2004a).

The nature of erosion of the major fraction of landslide dams is difficult to define as it occurred in prehistoric times often several kyr ago or even in the Pleistocene (e.g. HERMANNS *et alii*, 2000; TRAUTH *et alii*, 2000; HERMANNS *et alii*, 2005). In the Patagonian focus region, there was only one catastrophic failure in historic time (GROEBER, 1916; GONZÁLEZ DÍAZ *et alii*, 2001; SCHUSTER *et alii*, 2002; HERMANNS *et alii*, 2004a). For the major part of eroded dams, both the dam and the related deposits are so strongly eroded that the nature of dam erosion cannot be assessed. However, in both focus regions erosion histories of dams could partially be reconstructed based on analyses of related deposits, which have been preserved (HERMANNS *et alii*, 2004b).

LANDSLIDING INTO A LANDSLIDE-DAMMED LAKE

Landsliding into a landslide-dammed lake occurred at least 3 times in the focus regions, however the tsunami waves resulting from the landslide impacts into the lakes are interpreted to have caused failure in one case only. In the other cases either a deeply eroded channel into the landslide dam or an extensive flood deposit downriver the dam indicate that the dam was overtopped by a large wave, however it did not fail. In one of these events the channel was most likely eroded down to the bedrock at a position not coinciding with the valley profile prior to landsliding (Laguna Varvarco Tapia, GONZÁLEZ DÍAZ *et alii*, 2000), preventing the dam to fail. Another landslide event (rock block slide) impacted a lake in Ñireco valley (Patagonia) impounded itself by a rock-block slide, where the deposit had a low erodibility due to its low grade of fracturing, hence the dam was overtopped by a tsunami as indicated by deposits downriver but did not fail.

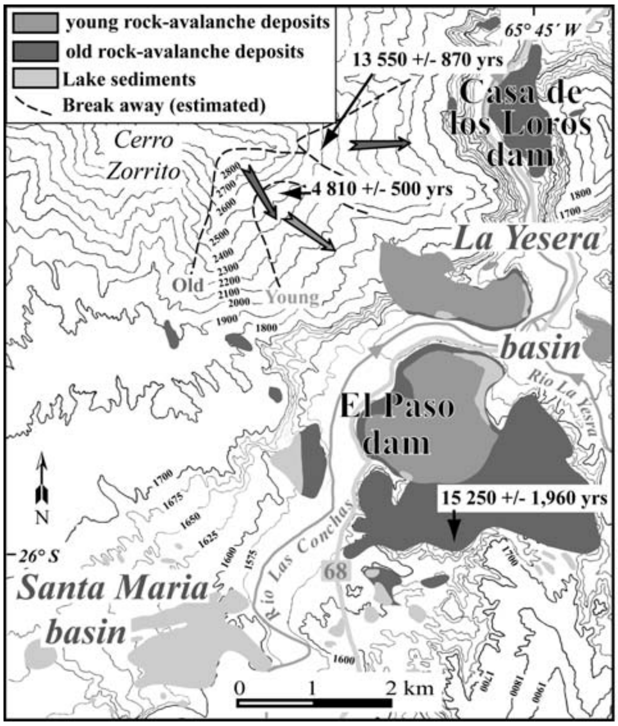

Figure 3 - Topographic map of Cerro Zorrito showing the distribution of rock avalanche deposits and related lake sediments as well as surface exposure datings (SED) of break away scars and landslide deposits (after HERMANNS et alii, 2004). Structures in the lake deposit together with SED indicate that a dam formed La Yesera basin at Casa de los Loros at 13.5 kyr ago, generating a lake in which a rock avalanche fell at El Paso at 4.8 kyr ago

Cerro Zorrito rock avalanches

In Las Conchas valley two rock avalanche dams, El Paso dam and Casa de los Loros dam, formed at 15300±2,000 yr and 13550±900 yr ago, respectively, or perhaps simultaneously at 13830±790 yr ago. These dams impounded lakes with surface areas of ~600 km^2 and 8 km^2 in the Santa Maria and the La Yesera basins, respectively (HERMANNS *et alii*, 2004b). Both dams existed until a second rock avalanche impacted into La Yesera basin at 4.8 kyr ago. This impact pushed water in the order of 107 to 108 m^3 out of the lake, causing most likely a tsunami wave high enough to overtop the Casa de los Loros dam. Based upon coarse terrace deposits downriver the Casa de los Loros dam and flood deposits of the same age in a further landslide-dammed lake 30 km downriver, it is interpreted that the Casa de los Loros dam failed catastrophically due to this tsunami (HERMANNS *et alii*, 2004b). Following the concept of DBI (ERMINI & CASAGLI, 2003), with a DBI of 4.3 these dams would have fallen into the instability domain. Nevertheless the dams existed for several kyr, which is most likely due to the arid climate in the 19760 km^2 large catchment combined with the size of the upper lake (Santa Maria basin in Figure 3) of 600 km^2 giving rise to strong evaporation (BOOKHAGEN *et alii*, 2001).

FURTHER INFLUENCES ON DAM STABILITY

As mentioned before, the rock avalanche dam in Barrancas valley failed in 1914. This dam has a DBI of 2.39 – 2.83 (uncertainty related to limited precisions of dam altitude (dam is not eroded to the base) and dam volume) and should therefore have been rather stable. The water table of that lake has been stable throughout a considerable time resulting in a palaeoshoreline several m wide eroded in the valley walls all along the former lake (GROEBER, 1916; GONZÁLEZ DÍAZ *et alii*, 2001; (HERMANNS *et alii*, 2004a). Failure occurred after the warmest summer in the Argentine weather record (related most likely with important retreat of glaciers) and an exceptionally wet winter and spring both increasing discharge of the rivers in the drainage area (GONZÁLEZ DÍAZ *et alii*, 2001; HERMANNS *et alii*, 2004a). Laguna Navarete landslide dam (N Patagonia, see a more detailed description in PENNA *et alii*, (2005)) is a further example, geomorphic parameters of that dam indicate a stable dam (DBI < 2) however our aerial photo interpretation strongly suggests a catastrophic failure (see below).

Morphologic features related to catastrophic dam failures

Both the collapse of the rock avalanche dam in Barrancas valley (GONZÁLEZ DÍAZ *et alii*, 2001; HERMANNS *et alii*, 2004a) and that of the dam forming Laguna Navarete (Figure 4) are ideal examples from N Patagonia showing clear morphologic indications that A) lakes existed for a long time and B) they still failed catastrophically. At both sites a several-meter-wide palaeoshoreline is eroded into the valley walls (Figure 4) indicating a stable water level of the impounded lake for a long time. In Barrancas valley the altitude of this palaeoshoreline above the present lake level indicates that during failure the water level dropped by at least 85 m, and in the case of Laguna Navarate by at least 40 m. At both sites the outburst event eroded a steep sloped gorge into the landslide dam and deposited a several-meter-thick outburst flood deposit downriver the dam (in Barrancas valley at least 20 m thick just downriver the dam and 3.5 m thick 60 km downriver). During the event of failure these outburst flood deposits were eroded in a later stage forming a second steep sloped gorge and turning the outburst flood deposit into a terrace with decreasing thickness in downriver direction. The presence of a "rest lake" at both sites upriver the dam together with the incision into the outburst flood deposit indicates that dam erosion slowed down when erosion of the outburst flood deposit started and that dam erosion is unlikely to proceed down to the river bed level prior to dam formation. The resulting dam is likely to be more stable and unlikely to fail again, which finally results in the sedimentary fill up of the "rest lake".

The dam of Laguna Navarete has a DBI < 2 and is therefore clearly within the stability domain. Failure was prehistoric and is hence unknown. There are landslide scars within the slopes surrounding the lake and related deposits along the shoreline. However, the temporal relation with the dam erosion is not completely defined.

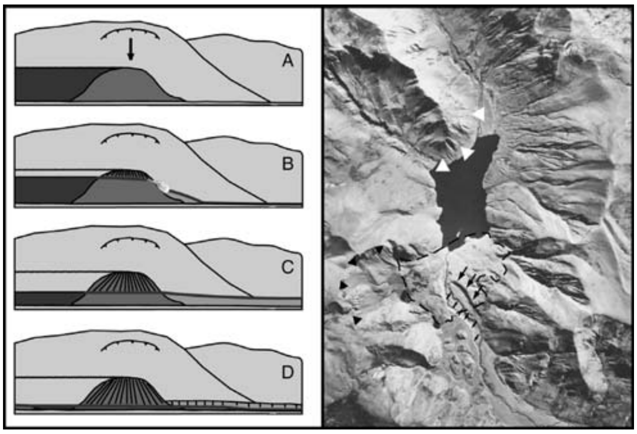

Figure 4 - Model of geomorphic evolution of a landslide dam failure: A) Landslide impoundment of a valley and erosion of a shoreline in the valley wall in the case that the dam stays stable for a longer time (in aerial photo of Laguna Navarete indicated by dashed line and white triangles, respectively). B) failure of dam by overtopping related with sedimentation of outburst flood deposit which propagates away from the dam in the process of dam incision (erosion of steeply walled gorge, large arrows on aerial photo). C) Erosion of the dam down to the level of the outburst flood deposit and slowdown of dam erosion related to the much larger surface to be eroded. D) Further erosion of the dam and of the outburst flood deposit, leaving behind a terrace deposit all along the valley (small arrows on aerial photo), is going on until the energy of the outburst flood becomes too low to further erode the deposits of both the landslide and the outburst flood, resulting in a small rest of the previous lake (in case of Barrancas dam still 4 km long) and in sedimentary fill-up of the basin

DISCUSSION AND CONCLUSIONS

Our study shows that although statistical investigations which base on data sets of landslide dams from all over the world do not contain many examples from the Andes (COSTA & SCHUSTER, 1988; ERMINI & CASAGLI, 2003), landslide damming is a frequent phenomenon there. The under-representation in these data sets is most likely due to a lack of available data. In our study areas, although representing only a small portion of the Argentine Andes, we concentrated on dams with a size > 10^6 m^3 and found 41 landslide dams.

Like in other parts of the world, type II and III dams of the classification by COSTA & SCHUSTER (1988) are the most frequent types of dams and others are relatively rare. More importantly, our data show that not all Argentine landslide dams fit into this well-established classification so that we needed to define three further dam types to describe them properly, although examples of these types are also not too frequent in the Argentine Andes. These dam types are 1) dams which are higher than the surrounding bedrock so that the new drainage develops over the bedrock (type VII), 2) landslide dams which occur within a watershed where failure can occur into two different valleys (type VIII) and 3) chains of lakes impounded by outburst floods, which may themselves represent a hazard in the valleys during rehabilitation (type IX). In addition, small basins on top of large landslide deposits are also frequent and their size and number depends mainly on the size of the landslide. However, their hazard potential is often locally restricted.

The most surprising result of our data is the longevity of the landslide dams, with 50% of prehistoric landslide dams in N Patagonia still existing, compared to 90% of landslide dams failing within their first year of existence according to worldwide datasets (COSTA & SCHUSTER, 1988). This might be related to the restriction of our data set to a minimum size of dam volumes related with no temporal restriction of our data set. Using the dimensionless blockage index (DBI) suggested by ERMINI & CASAGLI (2003), most landslide dams in Argentina fit within their concept and the boundaries given by worldwide data. However, again there are exceptions, which are related in two areas to special climatic situations governing the stability of dams which should be considered unstable, and vice versa.

Landsliding into a landslide-dammed lake, related with overtopping of the dam by a tsunami wave, is like in other places of the world (HANISCH, 2000) a special constraint on the dam stability. However not in all cases this phenomena has resulted in catastrophic failure of the dam. Dam stability is in these cases strongly controlled by the type of the landslide deposit and the position where the tsunami wave affected the dam.

Various well-preserved and one historic example of landslide dam failure show morphologic features related to dam failure, which can be used (and will be used in our final paper for the complete data set) to reconstruct the landslide dam history and the type of its erosion. These features are: 1) a palaeoshoreline eroded into the slopes surrounding a landslide dammed lake indicating that the water table of the lake was stable for a long time, 2) a steep-sloped deep gorge eroded into the landslide dam related with an outburst flood deposit downriver indicating a catastrophic dam erosion. Sedimentologic features characterizing such outburst flood deposits, based on the dam failure in Barrancas valley, are given in HERMANNS *et alii* (2004a).

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