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The Alemania rockfall dam: A record of a mid-holocene earthquake and catastrophic flood in northwestern Argentina

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Abstract

A prehistoric rockfall, probably caused by an earthquake with a magnitude of 5.0 or greater, blocked Río de las Conchas 2 km upstream from Alemania (Salta Province, Argentina) in the southern part of the Cordillera Oriental. The rockfall created a dam that formed a lake at least 16 km long. Shells of *Biomphalaria*, preserved in the lake sediments and, dated by radiocarbon, established the time of this event to be about 5500–6000 years ago. When the natural dam failed, probably either by piping or overtopping, the lake drained catastrophically, eroding a trench through the chaotic mass of sandstone rubble.

Keywords: rockfall, dam, Holocene, Salta, Argentina

1. Introduction

Steep slopes of the streams that drain mountains and other regions of high relief are places where masses of rock are likely to become unstable and, under the influence of gravity, fall or slide toward the valley floor. Centuries of exposure to the atmosphere weakens rock so that it loses some of the strength that keeps it in place. Small rock fragments and even large joint blocks break off and fall spontaneously from time to time, building and maintaining a talus at the base of the slope or cliff. Huge masses rarely break free, however, unless the event is triggered, generally by a seismic event or severe storm.

Mass wasting is an important aspect of slope erosion in the Andean Cordillera. In a recent study Wayne (1994) identified more than 150 landslides

and debris flows larger in area than 100×200 m in the mountainous parts of the Province of Salta. Located by stereo study of aerial photographs with scales of 1:50,000 and 1:70,000, many were examined in the field. Landslides are present throughout the parts of the province where steep slopes exist.

The Cordillera Oriental in northwestern Argentina is a north–south trending belt of subparallel folded and faulted mountains that lies between the high basinal plateau of the Puna and the lower folded ranges of the Sierras Subandinas and the Sistema de Santa Barbara (Figure 1). This tectonically active region extends southward from Peru, through Bolivia, to the southern part of the Province of Salta in Argentina. As a morphostructural region, the Cordillera Oriental is characterized by a meridional series of reverse faults, many of which thrust late Precambrian slates and phyllites

Figure 1. Morphostructural regions of the Provinces of Salta and Jujuy in northwestern Argentina. Boundaries are based on data and descriptions in Turner (1970), Mon, 1976a, Mon, 1976b and Mon, 1979, Rolleri (1975), Turner and Mon (1979), Mingramm et al. (1979), Greer et al. (1991), Allmendinger et al. (1983), Igarzábal (1991), Marcuzzi et al. (1994).

Figure 2. South part of the Province of Salta with major morpho-structural regions and topographic elements mentioned in text.

over mostly clastic rocks of Paleozoic, Mesozoic, and early Tertiary age (Turner and Mon, 1979; Allmendinger et al., 1983). Relief is great; major drainage lines are located in tectonic troughs and along

fault lines. This geologic environment, coupled with the steep slopes along the rivers that have eroded trenches through the ranges and the active seismicity of the belt, have set the stage for frequent

landslides and debris flows, many of them large and damaging to transportation routes and structures. Elevations rise from east to west; the highest peaks exceed 6000 m, and the floors of valleys are as low as 500 m. Precipitation ranges from more than 1200 mm/yr along the east side to less than 200 mm/yr in the west (Marcuzzi et al., 1994).

Río Calchaquí, which flows southward through the Valles Calchaquíes, turns abruptly to the east at Cafayate, where it is joined by Río Santa María (Figure 2). From this junction northward, called Río de las Conchas, it follows a fault line through badland topography eroded on folded clastic sediments of early Tertiary age and horizontally bedded diamictos and lake silts of Quaternary age. Where the river leaves this structural trench and enters the wider Valle de Guachipas-Valle de Lerma north of Alemania, its name becomes Río Guachipas; it joins Río Rosario to become the eastward-flowing Río Juramento at Cabral Corral Reservoir (Figure 2).

2. The Alemania rockfall dam

National Route 68 follows Río de las Conchas from Cafayate to Alemania, where the valley widens abruptly. Cretaceous sandstone, limestone, and shale with intercalated layers of basalt make up the valley walls in this reach.

About 2 km southwest of the village of Alemania, the river has eroded a gorge through a large mass of chaotically broken red sandstone. For about 1200 m the stream threads through this jumbled pile of red rock that rises more than 100 m above its bed.

Frenguelli (1936) (p. 263–265), in his extensive investigation of the geology along Río de las Conchas, called this location ‘Paso Iriondo’ and described the chaotic pile of rocks as the remains of ‘conoides de deyección.’ He interpreted the feature as an old mudflow or debris flow (‘volcán’), and evidently regarded it to be late Pleistocene in age.

Ruiz Huidobro (1949) called this location ‘Piedra Colgada;’ he followed Frenguelli’s interpretation that the feature is a mudflow deposit (‘torrente de barro’) that was derived by erosion during intensive rainstorms from Cerro Quitilipi (Figure 3 and Figure 4).

This mass of fractured sandstone, through which the river eroded its trench, is the remains of a rockfall that dropped from the cliffs of sandstone 200 m above it (Figure 4 and Figure 5). The sandstone is in the upper part of the Cretaceous Pirgua Subgroup (Vilela and Garcia, 1978; Omarini et al., 1987); in this location it is a thick-bedded red sandstone (Los Blanquitos Formation) that dips steeply (about 30°) toward the east, away from the river. The beds are noticeably broken by joints. The sandstone cliffs stand at a slope of about 40° (Figure 5) and may have been steeper before the top became detached and fell. Three slump scarps, present around the crown of the ridge above the place where the fall started (Figure 4), suggests that some sliding took place where the rockfall removed support (see Varnes, 1978; Cruden and Varnes, 1996).

Although the river has removed a large part of the original mass, the jumble of sandstone blocks in a matrix of sand once extended 2000 m northward from the cliff and buried a segment of the channel 1200 m long beneath material at least 75 m thick. The original volume of the rockfall probably exceeded 60×10^6 cubic meters.

3. Lake sediments

Remnants of stratified, fine grained sediments are present on the slopes of the main valley and in the tributaries that drained into it. The distribution of these sediments records a lake that was created by the rockfall dam (Figure 4). The most southerly (upstream) exposure of the lake sediments observed was 16 km upstream from the remains of the landslide (Table 1). This exposure is about 60 m higher than the valley floor at the rockfall dam, and, thus, still lower than the top of the landslide deposit.

Most of the lake sediments are light brown to nearly white beds of loose to compact sand and clayey silt that are horizontal; they contrast distinctly with the brown sandstones and conglomerates and the interbedded basalts that form the slopes of the valley. The base of the lake sediments is from 7 to 10 m above the bed of the river and slightly above the surface of the present floodplain.

Figure 3. Map of the valley of Río de la Conchas-Río Guachipas, showing locations of fault scarps north of Guachipas. The landslide debris 2 km west of Alemania is the rockfall dam.

Figure 4. Map of Alemania rockfall dam and impounded part of Río de las Conchas (prepared from aerial photos of the Instituto Geográfico Militar de Argentina).

Figure 5. Sketch of the Alemanía rockfall, looking upvalley from near km 78 on Route 68. Eastward-dipping sandstone beds of Los Blancitos Formation (Pirgua Subgroup, Cretaceous) stand above the rockfall debris. No vertical exaggeration.

This incision probably resulted from uplift within the Cordillera Oriental since the time of the rockfall. The lake sediments are at least 3 m thick and are overlain by floodplain sediments that contain a lens or a thin layer of white volcanic ash. These alluvial sediments are covered by colluvium that contains fragments of basaltic volcanic rocks interbedded with sandstone of the Pirgua Subgroup in this segment of Río de las Conchas. Frenguelli (1936, pp. 359–362) described two terrace surfaces along Río de las Conchas and noted the presence of volcanic ash in sediments beneath the younger one on which basalt fragments have accumulated.

Lake sediments exposed along route 68 about 12.5 km south of the rockfall debris indicate that at that location (Figure 4 and Figure 6; Table 1), first beds of sand, then clayey silt accumulated. Remains of the fresh-water snail genus *Biomphalaria* are relatively abundant in a bed near the top of the deposit (Figure 6), but a few minute shells of *Lymnaea* sp. and *Physa* sp. were also recovered. All of these taxa live today in shallow quiet water near the edges of lakes that have a mud bottom. Living specimens were observed and recovered from the edge of a small reservoir west of Coronel Moldes (Figure 3).

4. Dating the rockfall

Little is known about the rates of incision of the rivers that drain the east side of the Cordillera Oriental and the Sierras Subandinas of the Province of Salta. Río de las Conchas has cut a trench through the rockfall debris. The sediments that accumulated in the lake before it was breached stand well above the modern floodplain. My field interpretation suggested that the events may have taken place during the last major glaciation, 20,000 to 10,000 years ago.

In December 1994, I submitted a small sample of the *Biomphalaria* shells collected from the lake sediments stratigraphically related to the rockfall to be radiocarbon dated by the atomic mass spectrometer (AMS) method. The AMS conventional ^{14}C age obtained was 5180 ± 50 yBP (Beta 78600).

The radiocarbon age of the shells does not take into consideration the reservoir effect of the lacustrine environment. Organisms that live in lakes generally have apparent ages in ^{14}C years that are greater than the actual age of the samples. Aquatic mollusks have a ^{14}C content that is in equilibrium with the host water, which normally has a ^{14}C

Table 1. Locations of exposures noted in the text relative to kilometer posts along the highway north of Cafayate and distances from the rockfall dam

	km from Cafayate	km from dam
Boulder accumulation	82	-4
Bridge at Alemania	80	-2
Rockfall dam	78	0
Ash lens in alluvium	70	8
Lake sediments with snails	64.4	13.6
Alluvium with ash/lake sediments	62.2	15.8
Southernmost exposure of lake beds	62.1	16
Morales bridge	61	17

activity somewhat lower than that of the atmosphere. The ^{14}C activity of lake water depends on the dissolved organic and inorganic carbon content of the streams that feed the lake and on the depth and aeration of the water in the lake. High rates of evaporation in arid regions and stream discharge, which brings additional dead carbon into lakes, tend to reduce the ratio of ^{14}C to other C in lake water, although few carbonate rocks, which release dead carbon, exist in the drainage basin upstream from Alemania.

Well mixed shallow water is likely to have a ^{14}C activity relatively close to that of the contemporary atmosphere. The apparent age of 5180 ± 50 yBP

for these shells probably is somewhat greater, although perhaps no more than a few hundred years, than the actual age of the specimens dated.

If the reservoir effect of the ^{14}C in the samples is assumed to be 200–500 years, the snails would have lived 4800–5000 years ago. The snail-rich bed is in the upper part of the sediment that filled the lake, and the snails recovered characteristically live in shallow water with a mud bottom. Enough time must have lapsed after the impoundment formed for more than 3 m of clayey silt to accumulate at this location, 16 km upstream from the dam. If we assume that the sediment fill took a few hundred years, the rockfall probably took place 5500–6000 years ago.

In a first effort to discover how long ago the rockfall took place, Dr. June Mirecki (letter, August 31, 1994) made 10 runs on 5 individual shells to determine the ratios of the amino acids alloisoleucine/isoleucine (alle/Ile) in some of the shells of *Biomphalaria*. The mean value of the ratio determined in these analyses, 0.17 ± 0.04 (Table 2), is a little higher than those of shells collected from the Peoria Loess of Illinois, which accumulated 16,000 to 21,000 years ago. She pointed out, however, that if climatic factors should be significantly different, which they are, a late Wisconsinian estimate, based on these values, would be in error. The ratio of alle to Ile increases through time, so that the ratio in some early Pleistocene shells approaches 1.0.

Analysis of the alle/Ile ratios in mollusk shells is a valid technique to estimate the age of a sample;

Figure 6. Sketch of the outcrop of lake sediments at km 64.4 on Route 68 where dated snail shells were collected.

Table 2. Amino acid alle/Ile values from *Biomphalaria*, Salta Province, Argentina. (Prepared by Dr. June Mirecki)

MSU lab no.	Sample No.	Run No.	Alle/Ile Peak AR	Alle/Ile Peak HT	Total Hyd or Free
94070	S-93-65T1	81	-	0.09	Tot Hyd
		83	-	0.08	
94071	S-93-65T2	88	-	0.19	Tot Hyd
94072	S-93-65F1	102	-	0.27	Free
94074	S-93-65T3B	92	-	0.16	Tot Hyd
		93	0.24	0.17	
		97	0.16	0.14	
		98	-	0.12	
		101	-	0.13	
				0.17±0.04	
94075	S-93-65F3B	103	-	0.27	Free

however, unknowns such as temperature affect the results and interpretations. Rate of racemization is strongly temperature dependent. Shells collected from the Peoria Loess in the upper Mississippi valley region of North America have been enclosed in a sediment that has varied little in temperature from 10°–12°C since the fossils were buried 16–20 ka. In contrast, the lake in which these *Biomphalaria* lived probably was warmer, but more importantly, the fossil-rich bed was buried beneath only 30–40 cm of sediment in the ridge-like remnant of the sediment (Figure 6). Summer daytime temperatures at the surface undoubtedly exceeded 40°C regularly. The thin sediment cap may have been inadequate to keep the increased warmth from penetrating through to the fossil layer. If an exposure could be located where they were buried more deeply and not affected by diurnal and seasonal temperature changes, very likely the alle/Ile ratio would be lower.

A second factor in using the rate of racemization of amino acids to estimate the age of a sample is that the rates differ for different taxa. Little is yet known about the rate of racemization for *Biomphalaria*; most of the studies in North America have been done on marine mollusks (Wehmiller et al., 1988) and on the terrestrial snails commonly recovered from Pleistocene loesses (Miller et al., 1987). It will be necessary to determine alle/Ile ratios on several dated samples of *Biomphalaria* shells before the method can be used reliably to estimate the age of a deposit that contains this taxon.

A layer of volcanic ash in peaty silt that filled

some shallow depressions in the headwater reaches of Río Escoipe, about 60 km northwest of Alemanía (Figure 2) may be part of the ash fall that is present as lenses interbedded with the alluvial sediments along Río de las Conchas. The ash layer of Río Escoipe has been dated by radiocarbon assay of the enclosing sediments; conventional ¹⁴C dates on organic-rich sediment collected from just beneath the ash layer in two exposures along ravines are 4040±90 yBP (Beta 22194) and 4530±120 yBP (Beta 22196). If these represent the same ash fall, the dates corroborate each other and Frenguelli's statement that the terrace that contains the ash probably is mid-Holocene in age (Frenguelli, 1936p. 265).

Clapperton (1993, p. 459) pointed out that glaciers advanced about 4600 yBP and receded a few hundred years later (4400–3700 yBP) in both northern and southern hemispheres. Iriondo (1993) stated that the northwestern Argentine plains and the Sierras Subandinas were more humid and warmer than they are now from 8500 to 3500 yBP, but that the Puna/Altiplano was more arid at that time. If the ¹⁴C age of these shells is reasonably close to the true age, then the lake may have been fed, in part, by meltwater runoff from glaciers in the western part of the Cordillera Oriental, although the climatic conditions probably did not differ much otherwise from those of today.

5. Cause of the rockfall

Rockfalls of the size that produced this dam and lake rarely take place spontaneously. Weathering

undoubtedly had weakened the sandstone on the escarpment above the river, and the slope was steep, but such a rockfall surely was triggered by an external event. Costa and Schuster (1988) reported that the two most important processes that initiate dam-forming landslides are excessive precipitation and earthquakes. Wieczorek (1996) reviewed the several external stimuli that result in rapid downslope movements. Intense rainfall, especially on surface materials already saturated from previous precipitation, has caused many slope failures, particularly debris flows, in semi-arid and arid regions. That landslides are frequently a product of the vibrations of seismic events has long been recognized (Eisbacher and Clague, 1984; Wieczorek, 1996). After Keefer (1984) had studied data from 40 historic earthquakes and plotted the distance from epicenter to landslide, he concluded that no landslides occurred for earthquakes of less than 4.0 magnitude and few between 4.0 and 5.0. Earthquakes that have a magnitude of 5.0 and greater, however, commonly trigger large rockfalls and landslides. Although magnitude of an earthquake correlates directly with the number of landslides in the area affected, other factors are also major contributors to whether or not a particular slope will fail. Among the contributing factors he noted are depth of focus, distance from epicenter, joint pattern, rock type and degree of weathering, moisture content, and slope angle. Rockfalls are the most abundant kind of slope movement induced by seismic activity. They are most common in rocks that are weakly cemented, have closely spaced joints, and occur on slopes steeper than 40° (Keefer, 1984, p. 415).

The Alemania rockfall is within a zone along the eastern side of the Andes where several significant earthquakes have been recorded since the earliest settlement by European colonists (Castano and Zamarbide, 1992; Marcuzzi et al., 1994). Fault scarps that cut late Quaternary alluvial fans about 20 km to the northeast, near Guachipas, are oriented so that extensions would pass through Alemania (Figure 3). Active movement along one of these fault lines could readily have produced an earthquake of sufficient magnitude (>5.0) to trigger the large rockfall at Alemania. At the time that the radiocarbon date indicates the lake existed, the rocks probably contained greater moisture because of increased

precipitation. This higher moisture content could have contributed to the conditions that led to the precipitous failure.

Costa and Schuster (1988) presented a geomorphic classification of landslide dams with respect to the valleys they blocked; they identified six types of landslide dams. The rockfall dam at Alemania filled the entire valley, putting material high on the opposite slope and spreading both upstream and downstream in the channel. Because the rockfall debris that filled the valley and went up the opposite slope also extended a short distance upstream and downstream, it resembles the type III landslide dam of their classification.

Most lakes produced by landslide dams fail soon, some within hours of blockage, but others have lasted for centuries (Costa and Schuster, 1988). To accumulate the thickness of lake sediments observed, the ancient lake south of Alemania surely lasted at least a few decades and could have endured for several hundred years. Failure of the dam, though, would have drained the lake rapidly and produced a catastrophic flood downstream.

Sandstone is permeable, and most rocks, when fractured, become more permeable. Water from the lake undoubtedly leaked through the landslide dam, causing springs to form along its downstream slopes. Loss of water through seepage could have kept the lake from overflowing the crest of the landslide dam unless unusually high precipitation upstream or perhaps large amounts of meltwater from glaciers in the mountains west of the Calchaquí valley, filled the lake beyond capacity. Piping has resulted in failure of human reservoirs, and could have been the manner by which this natural one failed. Alternatively, failure by overtopping, if water in the lake rose high enough, would have produced a similar result. Once an opening existed in the dam, rapid drainage would have accelerated erosion of the outlet, and the lake would have emptied within a few days. Downstream the result would have been an extremely high magnitude flood. An accumulation of large boulders, mostly sandstone, exposed in a road cut about 4 km downstream from the rockfall, may be a deposit left by the flood discharge when the dam broke. Most of the sediments carried by the torrent of water would have accumulated in the lowland east of the town of Coronel Moldes, however,

where the Río Juramento flows eastward to enter a rock gorge. This location now lies beneath the water of Cabral Corral Reservoir (Figure 3).

In addition to the large rockfall that blocked Río de las Conchas, two smaller mass movements occur high on the slopes of Cerro El Morro, 2 to 3 km west of Alemanía (Figure 4). One is a rock slide about 500 m wide and 200 m from scarp to toe that moved southwestward. The other is a shallow translational slide about 400 m wide and 800 m long (Figure 2) that covers a southeast-facing slope. Both may have taken place at the same time as the rockfall.

6. Summary

All regions of actively rising mountains are affected by seismic activity. Evaluation of the frequency and magnitude, hence damage potential of future earthquakes, generally is based on historic earthquake data. Rockfalls and other large mass movements generated by prehistoric earthquakes that can be recognized and dated provide an additional basis for seismic hazard evaluation. The Alemanía rockfall most probably was caused approximately 6000 years ago by a major (magnitude >5.0) seismic event that had its epicenter near the south end of the Guachipas Valley.

Río de las Conchas has incised its bed about 7 m deeper than it was at the time the rockfall dammed the stream. This incision resulted from uplift within the Cordillera Oriental and represents a mean rate of uplift of about 2 mm/year.

In a landscape of scenic and geologic interest like that along the spectacular valley of Río de las Conchas between Alemanía and Cafayate, recognition of the distinctive chaotic pile of sandstone south of Alemanía that dammed the river only a few thousand years ago serves as testimony to the potential for destructiveness of earthquakes in the Province of Salta. It also provides one more point of interest for those who tour this part of the province.

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