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Climate change and mass movements in the NW Argentine Andes

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Abstract

The chronology of multiple landslide deposits and related lake sediments in the eastern Argentine Cordillera suggests that major mass movements cluster in two time periods during the Quaternary: between 35 000 and 25 000 ^{14}C yr BP and after 5000 ^{14}C yr BP. The older cluster may correspond to the Minchin wet period (40 000 and 25 000 ^{14}C yr BP) identified in tropical and subtropical South America, suggesting a causal relation between enhanced landslide activity and climate change. The younger cluster predates the Titicaca wet period that began at about 3900 ^{14}C yr BP which also affected other regions in the Andes and the Amazon Basin. No landslide and associated lake sediments are documented during the Tauca wet period (between 16 000 and 8000 ^{14}C yr BP). However, the two clusters correspond to periods where it assumed that the El Niño/Southern Oscillation (ENSO) and tropical Atlantic sea surface temperature dipole (TAD) were active. The analysis of the present-day precipitation patterns in NW Argentina indicates significant spatial and temporal differences between the intra-Andean part of the study area and the Andean foreland. Whereas the TAD seems to consistently increase rainfall, the intensity of precipitation during the El Niño phase of the ENSO is reduced to only 25% of the mean annual average in the intra-Andean basins, whereas the regions east of the Andes receive more than 125%. Similar results, but with an opposite sign, characterize La Niña events. The comparison of this pattern with paleo-precipitation data as inferred from varved lake sediments suggests that increased interannual climate variability and, therefore, increased fluctuations in rainfall and river discharge in narrow valleys may reduce landsliding thresholds.

Keywords: Argentina; Quaternary; landslides; lake sediments; El Nino; Southern Oscillation; paleoclimate

1. Introduction

Catastrophic landslide events associated with the damming of drainage systems are most commonly triggered by earthquakes, extreme periods of precipitation, and rapid snowmelt along mountain fronts predisposed to failure [1]. A study of landslide dams and the deposits of the resultant lakes provides proxy data on the climatic boundary conditions and trigger mechanisms of landslides, and thus offers valuable insights into the

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risk and possible spatial distribution of future mass movements in a region.

In semi-arid to arid NW Argentina, many large landslide deposits with volumes in excess of 10^6 m^3 cluster along mountain fronts affected by repeated tectonic movements during the Quaternary [2,3]. Several of these landslides are rock avalanches (sturzstroms) in narrow valleys with steep walls characterized by favorably oriented rock anisotropies and/or young thrust faults, thus suggesting a tectonic origin [3]. However, in this environment higher runoff in the course of climate change would have resulted in enhanced scouring, undercutting, and landsliding along the structurally pre-conditioned mountain fronts and valley walls. Two different climatic scenarios could substantially reduce thresholds for catastrophic mass movements in such environments: long-term changes toward increased humidity and shifts toward enhanced intra- and interannual fluctuations in rainfall. For example, higher frequency landsliding and lake development have been reported in the arid White Rock Canyon, New Mexico, for climates that were significantly wetter than today [4,5]. In a different setting, greater precipitation variability in the course of recurring El Niño events is viewed as the most likely cause for multiple mass movements in the Quebrada Tacahuay, Peru [6] and in the Atacama Desert, Northern Chile [7]. Many other examples exist for these separate landslide-conditioning mechanisms, which underscore their importance for processes modifying topography in mountainous regions.

In this paper we present new data from well preserved erosional remnants of landslide deposits and associated lacustrine sequences assessing the role of climate as an important factor in landslide generation in presently arid to semi-arid mountains. The parallel study of other lacustrine environments not associated with landslides in this region gives additional evidence for the climatic boundary conditions for mass movements during this time. In particular, this study helps constraining the importance of increased humidity and enhanced precipitation variability with respect to catastrophic mass movements in the Central Andes as well as other mountain belts with comparable climatic and topographic conditions.

2. Regional geologic setting and climate

The Argentine northwest is at the southern end of the central Andes tectonic domain. To the north of this region, the Puna plateau has an average elevation of 4000 m and is related to major Neogene contraction [8]. To the east are the meridionally trending western Sierras Pampeanas and the Cordillera Oriental, which reach altitudes between 3000 and 5500 m. The Cordillera Oriental is a fold and thrust belt [9,10] composed of Precambrian basement and overlying unmetamorphosed Cambrian to Tertiary sediments [11–13]; it is cut by deeply incised valleys. In contrast, the Sierras Pampeanas are late Cenozoic Laramide-type uplifts composed of late Proterozoic metamorphic basement rocks that contrast with highly erodible Tertiary clastic sediments in the adjacent intramontane basins [8,9,14]. The basins are further characterized by alluvial fan deposits and coarse gravel associated with multiple, gently inclined pediments that abut the steep mountain fronts [15]. In addition, along tectonically active mountain fronts and in areas where antecedent rivers cross the uplifting ranges of the Cordillera Oriental, there exist voluminous landslide deposits often associated with lacustrine and terrace deposits [2,3].

Atmospheric circulation of NW Argentina is mainly controlled by a seasonal low-pressure system east of the Andes (Fig. 1). During the austral summer, this low-pressure system attracts northeasterly and easterly moisture-bearing winds in the northern part of the region (e.g., Salta), whereas the southeastern parts are dominated by southerly and southwesterly winds (e.g., Tucuman) [16]. The low-pressure cell also attracts air masses from the Pacific anticyclone creating a dry and cold wind that gains intensity during the austral winter [16,17]. Precipitation within the study area is highly seasonal. Enhanced precipitation at the start of the summer rainy season is associated with convection within the intertropical convergence zone (ITCZ), while precipitation in winter is more closely linked to equatorward-moving polar frontal systems. Due to the orographic barriers to the east, the intra-Andean basins and valleys are arid and receive less than 200 mm yr^{-1} pre-

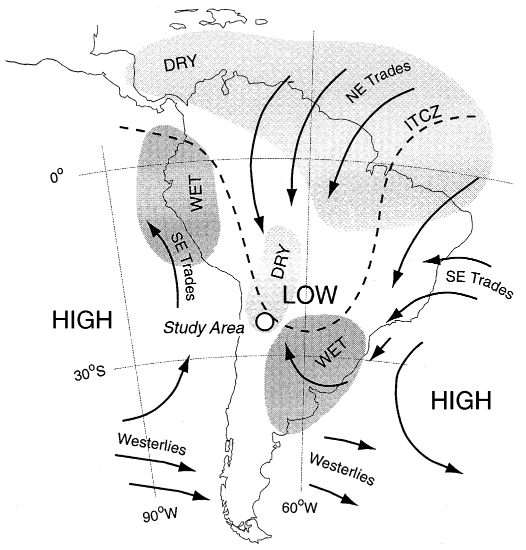

Fig. 1. Present-day airflow patterns during the summer rainy season and principal areas of rainfall anomalies during El Niño years in South America. Modified from [22,23].

cipitation [18]. These longitudinal and transverse geomorphological depressions develop their own wind systems [16]. Predominating winds from the mountains to the plains occur in the cool season and in the reverse direction in summer.

Interannual variation in the intensity of the summer rains appears to be controlled by the sea surface temperatures (SST) of the tropical Atlantic and Pacific Ocean. Of particular importance are decadal variations of the interhemispheric SST gradient across the Equator in the Atlantic, which is also called the tropical Atlantic SST dipole (TAD) [19,20]. When the cross-equatorial SST gradient is reduced, i.e., minimum TAD amplitude, the tropical North Atlantic is cool relative to the South Atlantic, resulting in increased surface pressure over the North Atlantic and a southward shift of the ITCZ. This leads to weakening of the SE trades and intensification of the NE trades, and hence to stronger moisture transport and precipitation in tropical and subtropical South America with mean periodicities of 10–14 years [19,20]. In addition, the amount and distribution of rainfall are influenced by the El Niño/Southern Oscillation (ENSO) [16,17,21]. The ENSO teleconnection results in a complex spatial pattern of rainfall anomalies in South America (Fig. 1). Instrumental records show decreased precipitation over northeastern Brazil, the Amazon Basin, and the Altiplano/Puna plateau at about 3500 m elevation during the El Niño phase of the ENSO. Increased rainfall occurs in northwestern (Ecuador, northern Peru) and southwestern (Chile) South America, and in southeastern Brazil (Fig. 1) [18,22,23]. La Niña events cause similar spatial rainfall anomalies but with opposite sign and lower amplitude than El Niño events [22,23]. In NW Argentina, information on the ENSO influence on local rainfall is limited. However, instrumental records of the last decades show a weak, but spatially and temporally highly variable tendency toward less rain during El Niño years [18].

3. Methods assessing climate character

3.1. Present-day climate

For the spatial and temporal analysis of the present-day climate we used monthly precipitation data from 380 weather stations in the study area collected between 1884 and 1991 by the Instituto Nacional de Tecnología Agropecuaria (INTA) encompassing Andean foreland regions between the towns of Tucuman, Salta, and Jujuy as well as intra-Andean valleys [18] (Fig. 2A). Annual data from these records were calculated by adding up monthly values between July and June of the following year. In order to evaluate the impact of ENSO and TAD on regional precipitation patterns, we computed the ratio between annual precipitation for extreme ENSO or TAD years and the long-term average for each station. Since the majority of the intra-Andean stations only provide rainfall measurements for the 1960s, the data for 1966 were taken as representative for an El Niño year, 1965 for typical La Niña conditions, and 1963 as a minimum strength TAD year. Comparisons with other extreme years during other decades corroborate the observed spatial patterns in rainfall distributions. The irregularly spaced data were interpolated onto an one-by-one degree regular grid applying the Matlab®

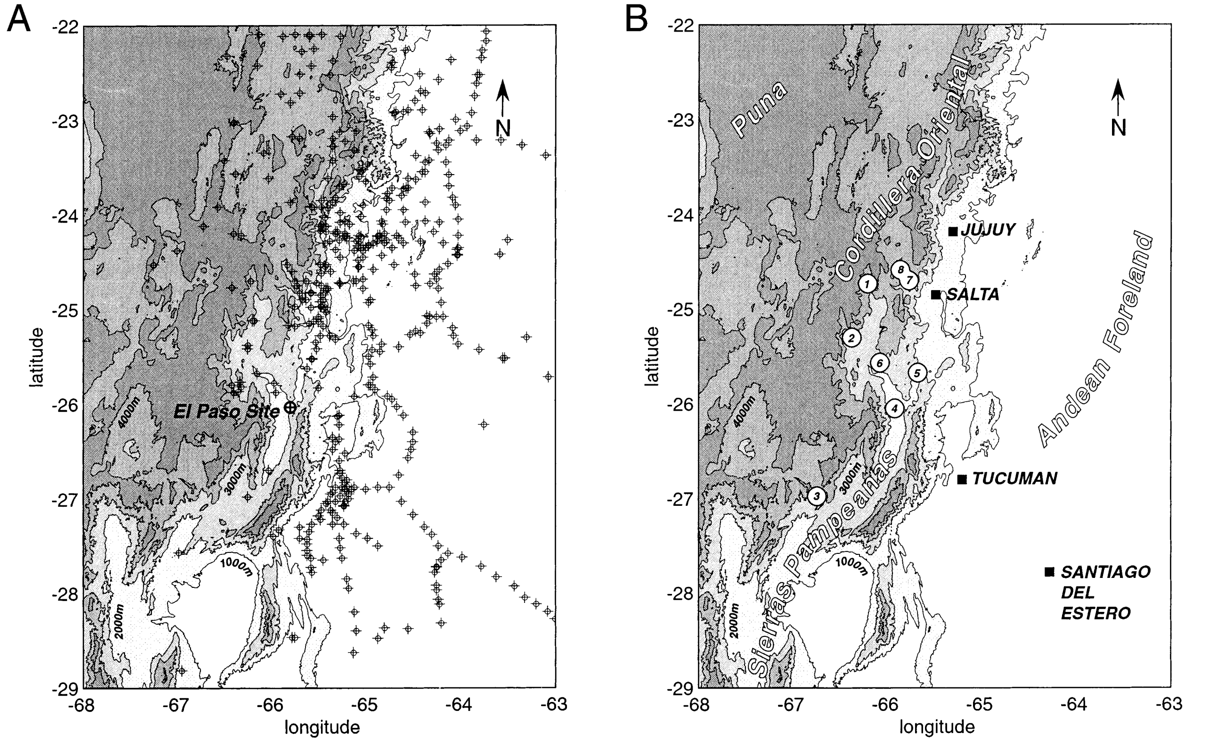

Fig. 2. Topographic map of the study area showing (A) distribution of rainfall stations [18] and (B) location of landslides and lake basins. (1) La Poma; (2) Lago Brealito; (3) Villa Vil; (4) Quebrada de Cafayate; (5) Alemania; (6) Quebrada del Tonco; (7) Golgota and (8) Arcas in the Quebrada del Toro.

routine *tspline* using Green's functions for splines in tension [24]. Contour maps were computed using the Matlab® routine *contourf* contained in the Mapping Toolbox provided by The Mathworks, Inc.

3.2. Paleoclimate

In order to assess the paleoclimatic history of the region, lake sediments from various basins were studied (Fig. 2B). Sedimentary sequences were collected from the La Poma paleo-lake dammed by a basaltic lava flow at the northern end of the Valles Calchaquies, from the landslide-dammed paleo-lakes in the vicinity of Alemania, in the Santa Maria Basin, and the Quebrada del Toro and sampled for AMS ^{14}C dates (Fig. 2B). AMS radiocarbon dates are reported as RCYBP (radiocarbon years before present, 'present' = 1950 AD) and are calculated using the Libby ^{14}C half-life of 5568 years. The ^{14}C ages were converted to calendar ages as published in Radiocarbon, Vol. 40, No. 3, 1998, using the cubic spline fit mathematics as published by Talma and Vogel [25]. An age estimate for Lago Brealito and the landslides in the Quebrada del Tonco was given by Hermanns et al. [26]. The Villa Vil paleo-lake was radiocarbon-dated by Fauque et al. [27].

In the Santa Maria Basin (26.0°S 65.8°W), a lake sediment section near the location El Paso in the Quebrada de Cafayate was analyzed using continuous sections of well-preserved varved sediments, 10–250 cm thick. The remaining parts of the section are either not varved or contain varves which are disturbed. About 350 cm above the base of the section, a continuous succession of 245 varves was analyzed for cyclicities in coloration, which are interpreted as a proxy for river discharge and thus precipitation changes in the proximal parts of the catchment area [28]. An exceptionally well-preserved section of 70 varves contained in the 245-varve interval was used for more detailed statistical analysis of the observed cyclicities. High-quality photographs from this section were scanned and subjected to standardized color and illumination corrections. Subsequently, one pixel wide representative red color intensity transects across these varves were extracted from the image. The resolution of these data series was of the order of 10 intensity values per varve. Color intensity measurements were made using routines contained in the Matlab® Image-Processing Toolbox. Welch power spectrum estimates of the red color intensity transects in the laminated sectors were calculated using the Matlab® routine *sptool.*

4. Results

4.1. Present-day climate

Using the complete data set provided by Bianchi and Yañez [18], we mapped spatial and temporal precipitation changes in NW Argentina and tried to link precipitation anomalies with global-scale changes in SSTs. The spatial distribution of mean annual precipitation shows the expected maxima along the eastern flank of the NW Argentine Andes. Rainfall in this region is mainly orographic and therefore restricted to the eastern slopes of the ranges near the towns of Tucuman, Salta, and Jujuy (Fig. 3); due to the high rainfall on the windward slopes, a tropical–subtropical forest vegetation extends in a narrow strip along these ranges [16]. West of these high ranges, the intra-Andean regions receive less than 20% of the precipitation east of the mountains and are characterized by sparse xerophytic vegetation.

The pattern of rainfall distribution does not show significant spatial changes over the observed time period of instrumental records. However, the intensity of precipitation within a given area fluctuates by more than a factor of two. Potential sources for this variability are the ENSO and TAD precipitation teleconnections. Rainfall during an El Niño event is anomalously low in the intra-Andean part of the study area, whereas rainfall amounts are significantly higher in the Andean foreland (Fig. 4A). During El Niño years, most stations in the intramontane Santa Maria Basin receive less than 50% rainfall as compared to the mean annual value. Similar lower values are observed in the Quebrada del Toro and the area close to Alemania within the Eastern Cordillera. Lago Brealito receives only 25% of the normal rainfall during El Niño years. In contrast, several regions east of the Andes receive more than 125% of the normal value. Similar results, but with an opposite sign, characterize La Niña events (Fig. 4b). Whereas mountainous regions receive higher precipitation, the foreland experiences reduced rainfall. However, the amplitude of these spatial anomalies is smaller than the corresponding anomalies during an El Niño event. The major part of the study area shows only a

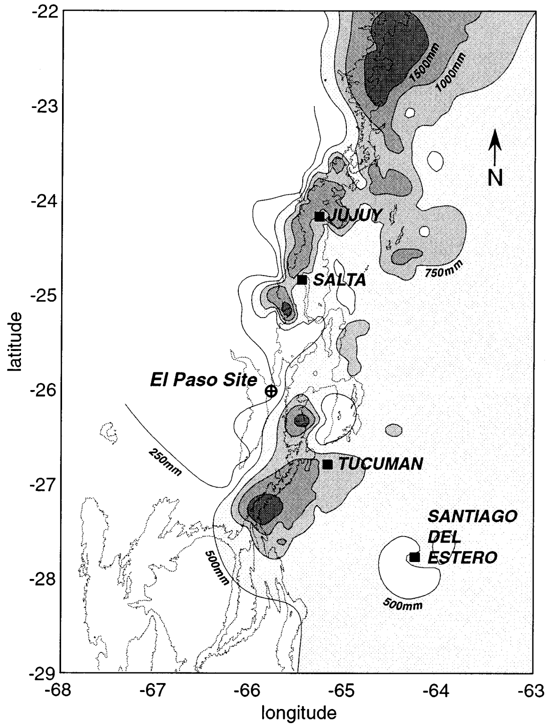

Fig. 3. Mean annual precipitation showing topography-controlled maxima along the eastern slopes of the Andes in the vicinity of Tucuman, Salta, and Jujuy. Due to the orographic rainshadow effects, the intra-Andean regions farther west receive less than 20% of the precipitation east of the mountains. Rainfall data from [18].

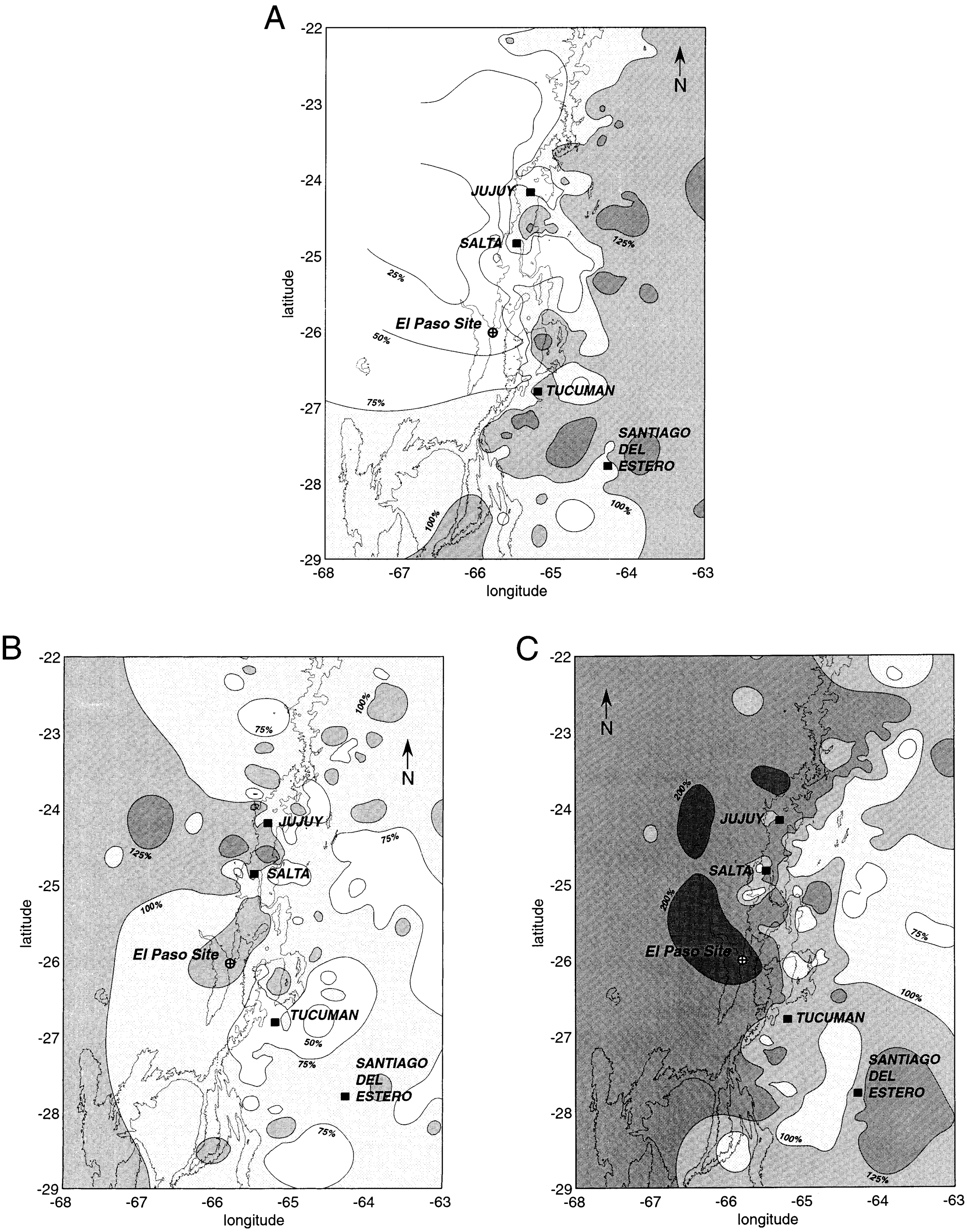

Fig. 4. Rainfall anomalies during (A) El Niño years, (B) La Niña years, and (C) minimum-TAD years expressed as percentage of annual rainfall as compared to mean annual precipitation. Rainfall data from [18].

weak La Niña response, i.e., values are in the order of the mean annual precipitation. Only the northwestern mountain regions receive higher amounts of rainfall during La Niña events. The TAD seems to consistently increase rainfall in NW Argentina (Fig. 4C). Especially in the mountain regions, rainfall is locally significantly higher by a factor of two. A few areas east of the Andes receive slightly lower rainfall. Compared to the ENSO patterns, the TAD pattern seems to be relatively little influenced by the barrier of the easternmost Andean ranges.

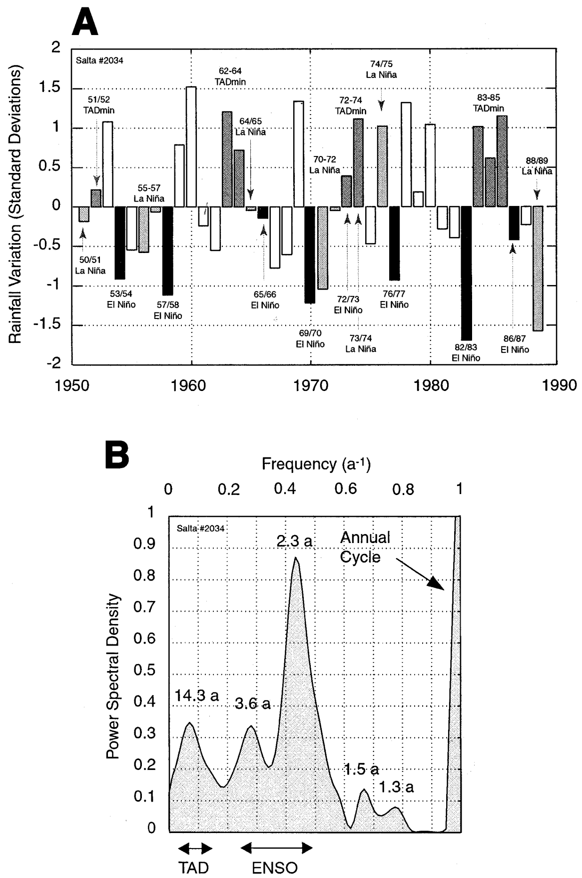

Fig. 5. Present-day rainfall variation in Salta. (A) 40-year record of normalized and detrended total annual (July to June +x) precipitation showing influence of El Niño and La Niña years and minimum-TAD phases on local rainfall. (B) Power spectrum estimate of monthly precipitation data showing a strong influence of the TAD, ENSO, and the seasonal cycle on local rainfall. Station #2034 from data published by Bianchi and Yañez [18].

Recent precipitation measurements from Salta as a representative station for the study area corroborate the observed controls on local rainfall variations (Fig. 5). Annual rainfall measurements in Salta consistently show low precipitation during El Niño years. However, the expected increase in rainfall during La Niña years is rather weak. In contrast, minimum TAD years generally correlate with increased rainfall amounts. The power spectrum estimate of monthly precipitation values in Salta shows significant peaks at 14.3 years, suggesting a significant TAD influence, and cyclicities of 3.6 and 2.3 years within the ENSO frequency band.

4.2. *Paleoclimate*

In the Santa Maria Basin (26.0°S 65.8°W), partly laminated and buff-colored lake sediments up to 40 m thick unconformably overlie multiple landslide deposits. The landslide debris once formed a complete drainage barrier resulting in a lake that occupied the valley up to the 1700 m contour and covered an area of about 630 km^2 [28]. The damming event is dated at 28 990 ± 150 ^{14}C yr BP (Table 1). The internal structure of the laminae and the cyclic recurrence of paired diatomite and clastic layers suggest that these laminations are varves [28] (Fig. 6). The power spectrum estimate of a red color intensity transect over 70 varves reveals significant peaks at 13.1, 3.2, 2.2, and around 1.0 yr, whereas the full record of 245 varves shows peaks at 16.6, 5.5, 3.5, 2.3 and 1.0 yr. This suggests a strong influence of both the ENSO and the TAD besides the seasonal precipitation changes (Fig. 7). Comparable varved sections in the higher parts of the profile show similar, but less regular cyclicities.

In the Quebrada del Toro (24.7°S 65.8°W), erosional remains of lacustrine sediments are related to two successive landslide-damming events [2,28]. AMS ^{14}C dates on scarce freshwater snails sampled from the upper portions of the deposits of both paleo-lakes provide an age of 30 050 ± 190 ^{14}C yr BP for the lower lake at 1950 m, and 26 080 ± 130 ^{14}C yr BP for the upper lake at 2220 m, defining a maximum age for the two landslide events (Table 1). The lake sediments in

Table 1
Accelerator mass spectrometry ^{14}C dates and 1σ errors[a]

Lab number	Material	Measured ^{14}C age (^{14}C yr BP)	$\delta^{13}C$ (‰)	$\delta^{13}C$-adjusted age (^{14}C yr BP)	Calibrated age (cal yr BP)
Santa Maria Basin					
Beta-116782	Bivalve shells	28 690 ± 150	−6.7	28 990 ± 150	–
Quebrada del Toro					
Beta-105340	Snail shells	29 790 ± 190	−9.0	30 050 ± 190	–
Beta-105341	Snail shells	25 820 ± 130	−9.1	26 080 ± 130	–
La Poma					
Beta-129763	Organic sediment	32 750 ± 280	−23.0	32 780 ± 280	–
Alemania					
Beta-129764	Charcoal	4 910 ± 40	−25.2	4 910 ± 40	5 655–5 600
Beta-129762	Bivalve shells	4 900 ± 40	−10.0	5 140 ± 40	5 925–5 895
Beta-132273	Charcoal	4 820 ± 40	−23.8	4 840 ± 40	5 605–5 585
Beta-129760	Charcoal	3 840 ± 40	−10.7	4 080 ± 40	4 785–4 780 and 4 595–4 520

[a]Measurements were made by Beta Analytic Inc., Miami, FL. Dates are reported as RCYBP (radiocarbon years before present, 'present' = 1950 AD). Conversion of ^{14}C years into calendar years as published in Radiocarbon, Vol. 40, No. 3, 1998.

the Quebrada del Toro are not varved, nor were diatom-bearing strata identified. At the northern end of the Valles Calchaquies close to the village of La Poma (24.7°S 66.2°W), an undated basaltic lava flow dammed the Rio Calchaqui, resulting in a lake. Organic material sampled in the lowermost layers of the lake basin infill which overlies the lava flow has an age of 32 780 ± 280 ^{14}C yr BP (Table 1). Tephrochronology, radiocarbon dating, and geomorphological analyses suggest that the older of two landslides near Villa Vil (27.0°S 66.8°W), and a large landslide in the Quebrada del Tonco (25.7°S 66.0°W) may also have occurred at that time [26].

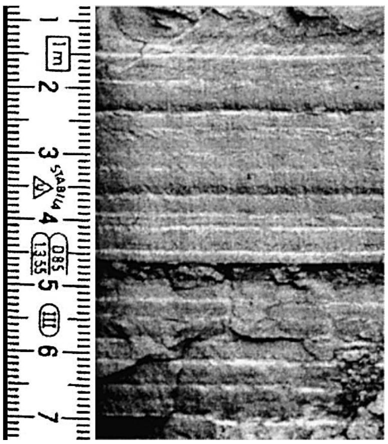

Fig. 6. Photograph of varved lake sediments from the Quebrada de Cafayate in the Santa Maria Basin with cyclic occurrence of intense dark-red coloration reflecting enhanced precipitation and sediment input during ENSO- and TAD-type periodicities (350 cm above the base of the El Paso section).

Lacustrine sediments associated with a rockfall at Alemania (25.7°S 65.7°W) previously studied by Wayne [29] and Hermanns et al. [26] are of Holocene age. The lower horizons (47 cm above the base) of the approximately 15 m thick fluvio-lacustrine basin infill upstream from the natural dam was dated at 4910 ± 40 ^{14}C yr BP (Table 1). At 720 cm above the base, bivalve shells yield an age of 5140 ± 40 ^{14}C yr BP and at 880 cm charcoal is dated 4840 ± 40 ^{14}C yr BP, both sampled from fine-grained lake sediments. At about 250 cm below the top of the fill, a sample from a continuous layer of charcoal was dated at 4080 ± 40 ^{14}C yr BP. The Alemania rockfall must therefore have occurred at around 5000 ^{14}C yr BP assuming a short time delay between the damming event and subsequent basin infill. It can thus be inferred that this basin existed for 1400–800 calendar years.

The landslide-dammed lake at Brealito (25.3°S 66.4°W) is interpreted to be of Holocene age based on the pristine morphology of the landslide deposits, breakaway scarps, intact sliding surfaces, and cosmogenic nuclide dating documenting an age below the limit of the method (< 27 000 yr BP) [26]. To this age group may also belong a

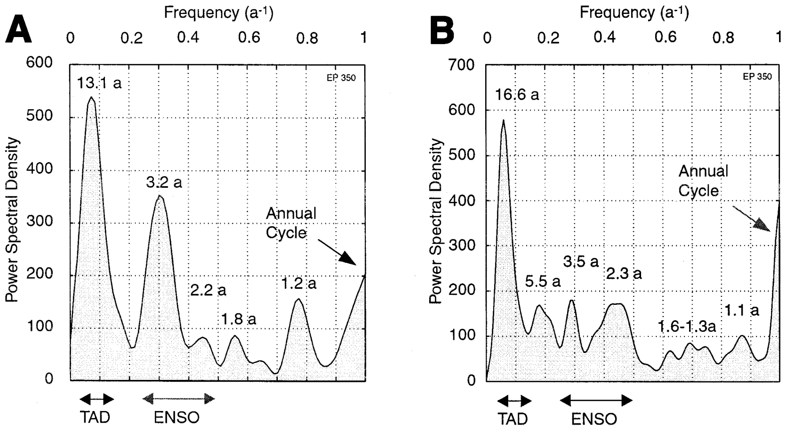

Fig. 7. Power spectrum estimate of a red color intensity transect across (A) 70 and (B) 245 varves. Dominant frequency bands suggest a strong influence of the TAD, ENSO, and the seasonal cycle on local rainfall.

giant granitic rockfall deposit 14 km northwest of Brealito, as well as rock avalanche deposits near Villa Vil (27.0°S 66.8°W), which are older than 3630 ^{14}C yr BP based on tephrochronology [26].

5. Discussion and conclusion

Our chronology of large landslides in narrow valleys and accompanying lacustrine phases in NW Argentina suggests that these events were concentrated in two time periods during late Quaternary time (Fig. 8). The earlier cluster is dated between 35 000 and 25 000 ^{14}C yr BP, while the younger cluster is dated after 5000 ^{14}C yr BP, assuming that the lacustrine depositional systems were initiated immediately after the landslide event. The late Pleistocene cluster includes a series of landslides that occurred in the Quebrada del Toro, as well as multiple landslides at the outlet of the Santa Maria Basin. In addition, multiple landslides near Villa Vil and the Quebrada del Tonco, as well as a paleo-lake near La Poma, may also have occurred during this time period. In addition to these late Pleistocene landsliding events and lacustrine sedimentation, a suite of similar Holocene sedimentary systems at Brealito, Alemania, and Villa Vil occur in the same region.

The timing of landslide activity, the paleoclimatic information contained in the lacustrine sections behind the landslide barriers, and paleoclimate data from neighboring regions indicate that climate change may have had an important influence on conditioning already weakened bedrock for failure along predisposed mountain fronts (Fig. 8). In fact, the older landslide cluster corresponds to the Minchin wet period between 40 000 and 25 000 ^{14}C yr BP reported for other places in tropical and subtropical South America during interstadial 3 [30–34]. In the Central Andes, lake levels were generally high during this interval and glacier extension was at its maximum. Although the paleoclimatic database for this period is still scarce for arid NW Argentina, we hypothesize that effective precipitation in this region must also have been higher during that time. Support for this inference comes from a lake balance model of a landslide-dammed lake that occurred at about 28 990 ± 150 ^{14}C yr BP in the Santa Maria Basin [35]. Under the present climatic conditions, a hypothetical barrier in the Santa Maria Basin similar to the landslide would create a lake level that would stabilize well below the paleo-lake level, which can be reconstructed from the highest Pleistocene lake sediment outcrops. An increase in precipitation by 10–15% in the catchment would cause a water body similar to the reconstructed paleo-lake [35]. In addition, a regional snowline study for modern and Pleistocene glaciations in the southern arid Central Andes suggests high amounts of effective precipitation during the formation of cirque and valley glaciers [36].

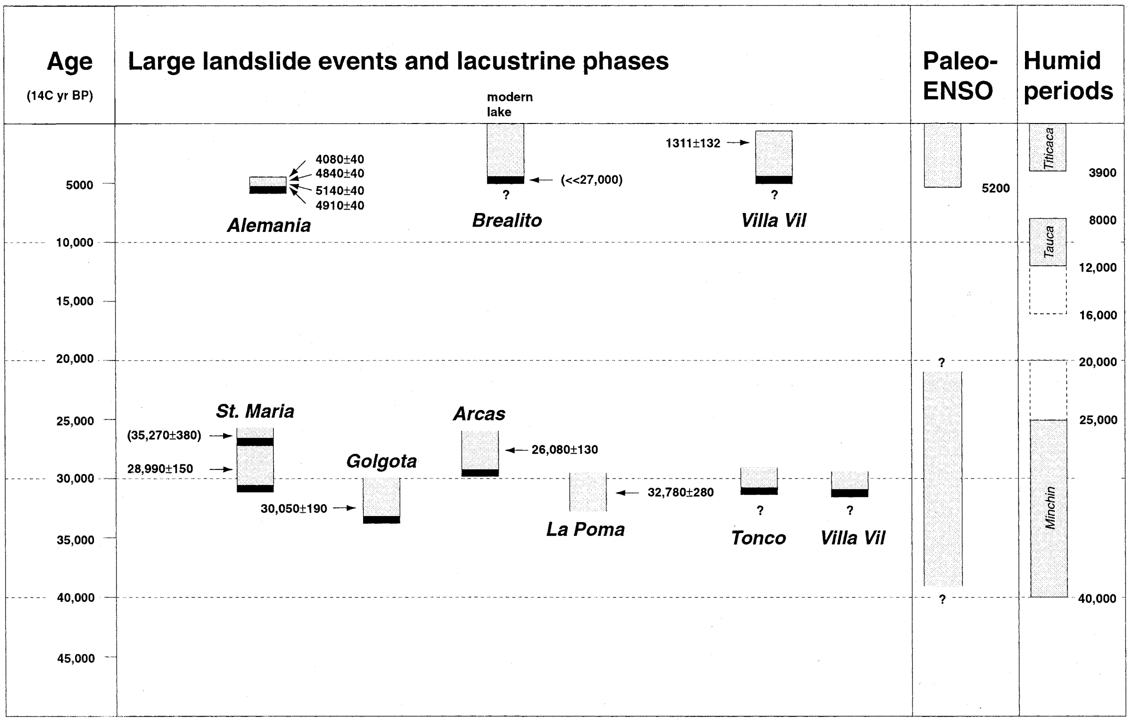

Fig. 8. Correlation of landslide and lacustrine events in NW Argentina with tropical and subtropical South American wet episodes; data from [26] and this work. Black horizontal bars denote landslide events. Lacustrine phases are indicated by gray rectangles. Radiocarbon age at Villa Vil from [27]; compilation of paleo-ENSO history based on [26,42]; chronology of humid periods in tropical and subtropical South America based on [30–34,37–41].

The younger cluster of landslides and dammed lakes may correspond to the Titicaca wet period (after 3900 ^{14}C yr BP), unless the well-dated Alemania landslide-dammed lake occurred slightly before this interval also reported from other Andean regions and the Amazon basin [32,37–39]. These two temporal landslide clusters are separated by a gap between around 25 000 and 5000 ^{14}C yr BP. It is interesting to note that although a large number of landslides and lakes were studied in NW Argentina, no landslides and accompanying lake sedimentation seem to occur during the Tauca wet period between 16 000 and 8000 ^{14}C yr BP [40,41]. Assuming that this period also affected NW Argentina, the relation between prevailing humid periods and increased landsliding activity is ambiguous. Thus, an alternative cause for more frequent mass movements in NW Argentina should be considered (Fig. 8). Instead of longer-lasting wet periods and resulting slope destabilization, increased intra- and interannual fluctuations in precipitation should be assessed as a possible trigger mechanism for landslides and other mass movements. Grosjean et al. [7], for example, report more than 30 debris flow events triggered by heavy rainfall in the Atacama Desert (Northern Chile) between 6200 and 3100 ^{14}C yr BP, i.e., during the generally arid mid-Holocene period. These authors suggest that this record documents extreme, short-lived precipitation climate events, potentially linked to ENSO. In addition, Keefer et al. [6] identify paleo-El Niño events after 5300 ^{14}C yr BP as the most likely cause for multiple landslide events in the Quebrada Tacahuay of Peru.

Our analysis of modern climate data shows that the main sources for interannual precipitation variability in NW Argentina are the TAD and the ENSO. The spatially concentrated multiple landslide deposits in the study area coincide with the boundary between two ENSO-related rainfall anomalies with opposite sign whereas the TAD influence does not show important spatial variations. The difference in the climatic overprint by the ENSO influence may reflect the effects of the NE trade winds in the northern and northwestern mountain regions, and of the SE trade winds in the southern and southeastern lowlands separated by the ITCZ. This is suggested by the predominant wind direction in the Salta and Tucuman regions, respectively. The NE trades and moisture transport tend to be reduced during El Niño years, whereas the SE trades result in enhanced precipitation (Fig. 1). The boundary between these wind systems and rainfall anomalies could react in a sensitive way to large-scale changes in the climatic boundary conditions.

The history and causes for the recurrence and intensity of ENSO are still not well understood. Evidence for the long-term history of ENSO comes from marine sediments offshore Peru. According to productivity and coastal upwelling records for the last 400 000 years on decadal and centennial time scales, the ENSO system probably operated during Pleistocene interglacial stages 1, (late) 5 and 7 and the warm interstadial 3, whereas it was largely reduced or absent during the glacial maxima [42]. For the Holocene, the ENSO history is more detailed. Various geoarcheological and paleoclimatic data point to a more weakened, perhaps entirely absent ENSO between 12 000 and 5000 ^{14}C yr BP [43–47]. The greater precipitation variability and overall greater moisture at low latitudes during the last 5000–3000 ^{14}C years suggest that ENSO events became far more common during the late Holocene than previously. In contrast, paleoclimate studies on TAD history are very limited. However, from the sediments of an Ecuadorian lake, Rodbell et al. [48] report clastic sedimentation events spaced 10–20 years during the last 6500 ^{14}C yr BP, which may document minimum-TAD events.

The rainfall variability in NW Argentina during the time of enhanced landsliding and lake development can be assessed with ultra-high resolution analysis of the laminated deposits sampled in the Santa Maria Basin [28]. The 10–20 year cycle reflected in the lake sediments suggests a strong influence of the TAD, which also accounts for a cyclic intensification of the rainy season in this region today. Whereas the present and past link between local rainfall anomalies and the TAD seems to be identical, we observe a significant change in the relation between precipitation and ENSO. Modern precipitation in this part of the Andes seems to be influenced by ENSO with a tendency toward less rain during El Niño years. La Niña events result in slightly increased rainfall in the northern parts of the study area. Contrary to the present ENSO manifestations with only slightly increased precipitation during La Niña events, the Pleistocene sedimentary record in the Santa Maria Basin reveals strong effects of higher precipitation and river discharge with ENSO-type periodicities. The discrepancy between present and past ENSO signals may be explained by significant shifts and intensity changes of ENSO-related spatial rainfall anomalies. Therefore, in such a setting, shifting rainfall anomalies could have caused intensified summer rains during La Niña years. Alternatively, in an extreme case, the ENSO influence could have been reversed, resulting in increased precipitation during El Niño years.

The more intense summer rains documented here most likely enhanced the intensity of erosion in the surrounding catchment areas. The described rock avalanche deposits occur in narrow valleys and are flanked by tectonically active mountain fronts with high relief. Higher runoff in the course of climate change would have resulted in enhanced scouring, undercutting, and landsliding along the structurally pre-conditioned mountain fronts and valley walls. Similar relations between increased climate-related scouring and enhanced landsliding activity were demonstrated along the Rio Grande in New Mexico [5]. In addition to scouring, greater humidity and more pronounced seasonality may have increased pore water pressures and lowered critical thresholds in rocks susceptible to failure. Under such circumstances, small earthquakes with lower levels of ground motion could have triggered large rock avalanches in these environments [3]. Therefore, climate could have played an important role in conditioning mountain fronts for failure that ultimately collapsed due to seismic activity.

In conclusion, we suggest that despite the structural, seismic, and lithologic parameters that control spatial clustering of rock avalanches in NW Argentina, a higher frequency of such events in the past may have been caused by different climatic setting. Although more paleoclimate data are needed, we infer that climatic shifts toward increased interannual variability can substantially reduce thresholds for catastrophic mass movements in the arid to semi-arid Central Andes and other regions with comparable climatic and topographic conditions. Future behavior of ENSO is still subject to discussion; different modeling results and paleoclimate data are contradictory in terms of intensity and variability of ENSO in scenarios with higher global temperatures [49]. In NW Argentina, however, increases in the intensity and the spatial distribution of ENSO-related precipitation anomalies would dramatically increase the risk of rock avalanching and other types of mass movements.

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