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Multiple landslide clusters record Quaternary climate changes in the northwestern Argentine Andes

Martin H. Trauth[a,*], Bodo Bookhagen[a], Norbert Marwan[b], Manfred R. Strecker[a]

[a] *Institut für Geowissenschaften, Universität Potsdam, P.O.Box 601553, D-14415 Potsdam, Germany*
[b] *Institut für Physik, Universität Potsdam, P.O.Box 601553, D-14415 Potsdam, Germany*

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Abstract

The chronology of multiple landslide deposits and related lake sediments in the semi-arid eastern Argentine Cordillera suggests that major mass movements cluster in two time periods during the Quaternary, i.e. between 40 and 25 and after 5 ^{14}C kyr BP. These clusters may correspond to the Minchin (maximum at around 28–27 ^{14}C kyr BP) and Titicaca wet periods (after 3.9 ^{14}C kyr BP). The more humid conditions apparently caused enhanced landsliding in this environment. In contrast, no landslide-related damming and associated lake sediments occurred during the Coipasa (11.5–10 ^{14}C yr BP) and Tauca wet periods (14.5–11 ^{14}C yr BP). The two clusters at 40–25 and after 5 ^{14}C kyr BP may correspond to periods where the El Niño–Southern Oscillation (ENSO) and Tropical Atlantic Sea Surface Temperature Variability (TAV) were active. This, however, was not the case during the Coipasa and Tauca wet periods. Lake-balance modelling of a landslide-dammed lake suggests a 10–15% increase in precipitation and a 3–4°C decrease in temperature at $\sim$30 ^{14}C kyr BP as compared to the present. In addition, time-series analysis reveals a strong ENSO and TAV during that time. The landslide clusters in northwestern Argentina are therefore best explained by periods of more humid and more variable climates.

Keywords: Argentina; Quaternary; landslides; lake sediments; paleoclimate

1. Introduction

Quaternary paleoclimatic records of tropical and subtropical South America are contradictory with respect to magnitude and timing of wet and dry periods (e.g. Sylvestre et al., 1999; Baker et al., 2001). It is a matter of debate whether these differences are the results of complex and spatial heterogeneous forcing mechanisms or are caused by uncertainties in dating techniques and interpreting paleoclimatic records (Baker et al., 2001). For instance, whereas modern climate data show no influence of Atlantic Sea Surface Temperature (SST) on the rainfall variations on the Bolivian Altiplano, a lake record from the Salar de Uyuni suggests strong coupling between the SSTs and precipitation during the last 50 kyr

* Corresponding author. Tel.: +49-331-977-5254; Fax: +49-331-977-5060.
E-mail address: trauth@geo.uni-potsdam.de (M.H. Trauth).

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(Baker et al., 2001). Baker et al. (2001) also report significant differences in the timing of the established wet periods documented on the Altiplano. For the Minchin (at around 40–25 ^{14}C kyr BP; e.g. Servant and Fontes, 1978; van der Hammen and Absy, 1994; Ledru et al., 1996; Godfrey et al., 1997; Turcq et al., 1997) and Tauca wet periods (14.5–11 ^{14}C kyr BP; Servant et al., 1995; Sylvestre et al., 1999), Baker et al. (2001) found significantly older ages, > 34.5 ^{14}C kyr BP and 23–12.2 ^{14}C kyr BP, respectively. The age of the Coipasa wet period at around 10.5 ^{14}C kyr BP (Baker et al., 2001) is consistent with the chronology published by Servant et al. (1995) (11.5–10 ^{14}C kyr BP) and seems to be synchronous with the Younger Dryas cold event in the high northern latitudes, but does not match the Early Holocene age (9.5–8.5 ^{14}C kyr BP) suggested by Sylvestre et al. (1999).

In northwestern Argentina well-dated and detailed paleoclimate records are scarce. Numerous smaller lake basins contain deposits that lack datable material or environmental indicators such as diatoms, ostracods and pollen (Trauth and Strecker, 1999). It is therefore difficult to assess causal linkages between local climate and external climate-forcing factors such as insolation and ocean-surface temperatures. Here we present a record of landslide activity in the northwestern Argentine Andes that is interpreted to document periods of wetter and more seasonal climates (Fig. 1) (Hermanns et al., 2000; Trauth et al., 2000). More rainfall and discharge at higher elevations, or even more effective, higher fluctuations in precipitation, runoff and erosion cause significantly increased destabilization of mountain fronts by undercutting streams in this semi-arid region (Trauth et al., 2000). In addition to enhanced 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 (Hermanns et al., 2000). We therefore interpret landslide clusters in narrow valleys that are traversed by allogenic rivers as valuable paleoclimatic information for northwestern Argentina. This paper summarizes prior research on mass movements and climate change in northwestern Argentina (e.g. Hermanns et al., 2000; Trauth et al., 2000) and evaluates the importance of landslide clusters as paleoclimate proxy. The field-based quantification of number and volume of these mass movements (Trauth et al., in review) combined with an assessment of the climatic conditions during enhanced landsliding through hydrological modelling (Bookhagen et al., 2001) and time-series analysis (Trauth et al., 2000; Marwan et al., in review) provides detailed insights into the magnitude of the climate changes in this part of the Andes and the climatic thresholds that cause higher landslide risks.

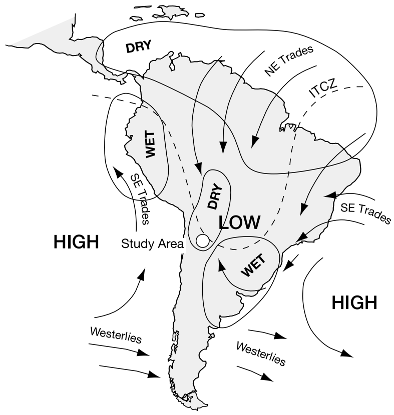

Fig. 1. Present-day airflow patterns during the summer rainy season and principal areas of rainfall anomalies during El Niño years in South America. Modified from Ropelewski and Halpert (1987) and Kiladis and Diaz (1989).

2. Setting

The Argentine northwest represents the southern end of the central Andes structural domain (Fig. 2). To the northwest, the Puna plateau has an average elevation of 3600 m above sea level. Its eastern margin is straddled by the meridionally-oriented western Sierras Pampeanas and the Cordillera Oriental, which reach altitudes between 3000 and 5500 m and constitute effective orographic barriers (Haselton et al., 2002). The Quaternary deposits in these intramontane basins east of the Puna and within these provinces are characterized by alluvial-fan deposits and coarse gravel, associated with multiple, gently inclined pediments that abut the steep fault-bounded mountain fronts (Strecker et al., 1989). In addition, along tectonically active mountain fronts and in areas where antecedent rivers cross the uplifting ranges of the Cordillera Oriental, voluminous landslide deposits are often associated with lacustrine and terrace deposits (Hermanns and Strecker, 1999; Strecker and Marrett, 1999; Trauth et al., 2000). Except for Lago Brealito, the landslide-dammed lakes studied in this paper do not hold water anymore due to headward erosion and are drained by streams integrated in the foreland drainage system (Fig. 2).

The atmospheric circulation in this region is mainly controlled by a seasonal low-pressure system east of the Andes (Fig. 1). During the austral summer rainy season, 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 receive southerly and southwesterly winds (e.g. Tucuman) (Prohaska, 1976). 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 (Prohaska, 1976; Hastenrath, 1991). Due to the orographic barriers to the east, the intra-Andean basins and valleys are arid and receive less than 200 mm yr^{-1} precipitation (Bianchi and Yañez, 1992). Interannual variations in the intensity of the summer rains appear to be controlled by the SSTs of the tropical Pacific and Atlantic oceans. Of particular importance are the El Niño–Southern Oscillation (ENSO) and the Tropical Atlantic Sea Surface Temperature Variability (TAV) (Philander, 1989; Hastenrath, 1991; Diaz and Kiladis, 1992; Enfield and Mayer, 1996; Chang et al., 1997). The ENSO teleconnection results in a complex spatial pattern of rainfall anomalies in South America (Fig. 1) (Ropelewski and Halpert, 1987; Kiladis and Diaz, 1989), whereas the TAV consistently increases precipitation in tropical and subtropical South America with periodicities of 10–14 years (Enfield and Mayer, 1996).

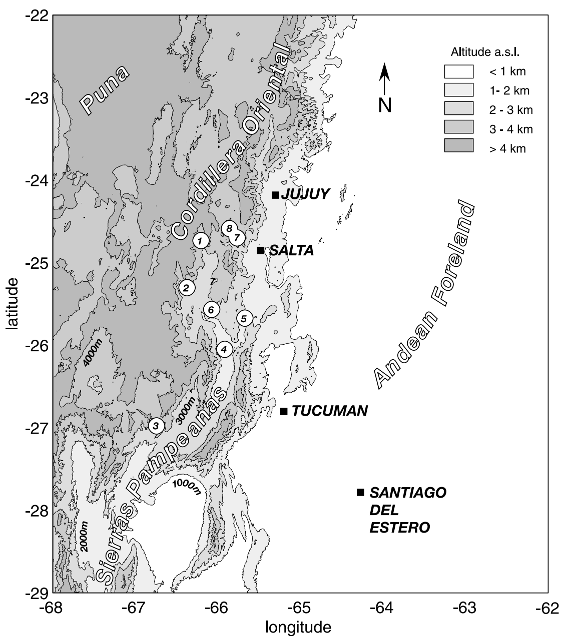

Fig. 2. Topographic map of the study area showing location of landslides and lake basins. Key: (1) La Poma; (2) Lago Brealito; (3) Villa Vil; (4) Quebrada de Cafayate; (5) Alemania; (6) Quebrada del Tonco; (7) the lower and (8) upper site in the Quebrada del Toro.

3. Methods

Several exposed sedimentary sequences from formerly landslide-dammed lakes were sampled for AMS ^{14}C dating. AMS radiocarbon dates are reported as ^{14}C kyr BP (radiocarbon years Before Present, i.e. AD 1950), calculated using the Libby ^{14}C half life of 5568 yr. Additional age data were obtained using tephrochronology (see Hermanns et al., 2000). In the Santa Maria Basin (26.0°S, 65.8°W), an approximately 30-^{14}C-kyr old lake-sediment section near the location El Paso in the Quebrada de Cafayate was investigated for detailed sedimentological and micropaleontological analysis (see Trauth and Strecker, 1999; Trauth et al., 2000). Continuous sections of well-preserved laminated sediments were taken from the lake-sediment succession in the Santa Maria Basin. Cyclicities in the coloration of individual layers were interpreted as a proxy for river discharge and thus precipitation changes in the

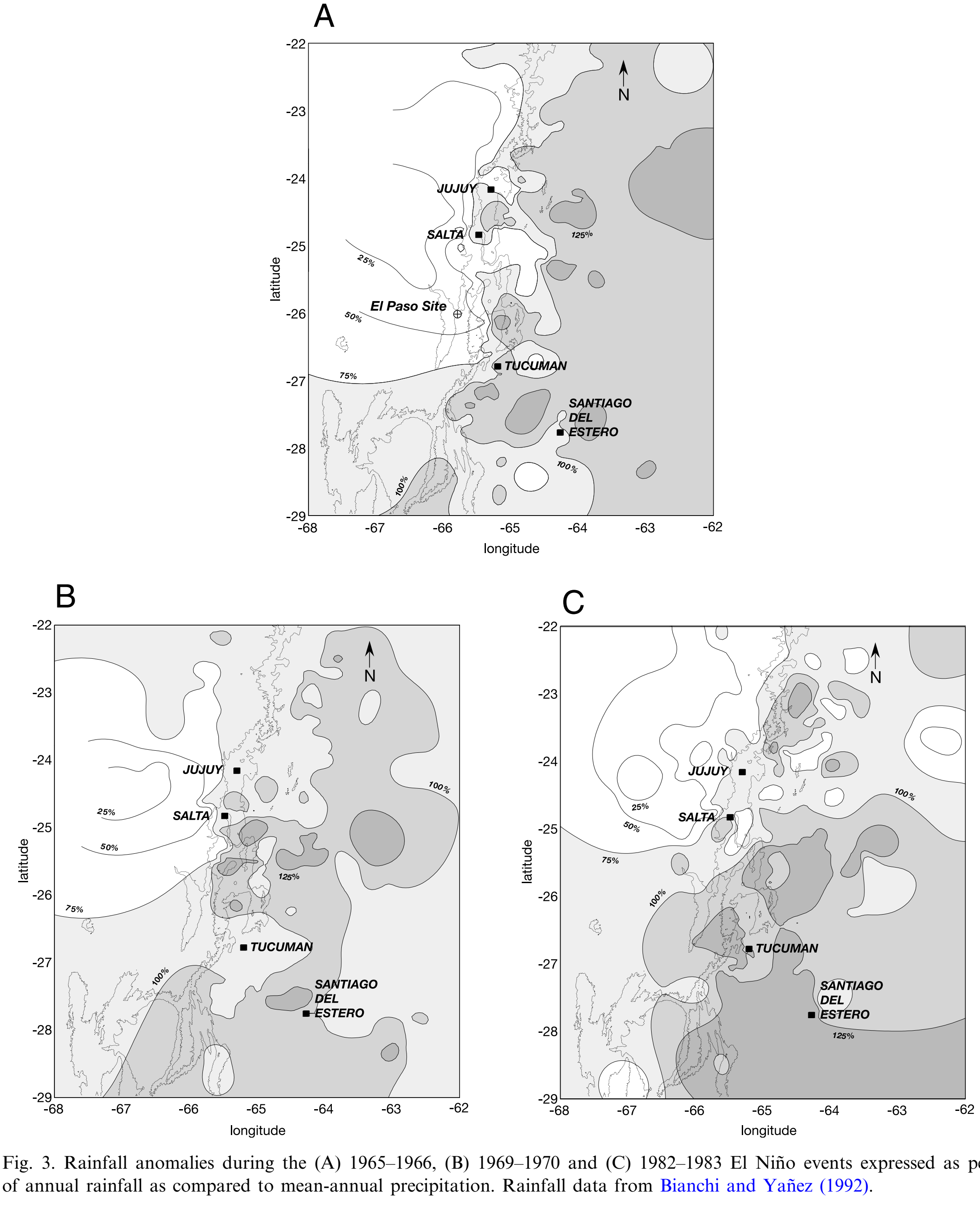

Fig. 3. Rainfall anomalies during the (A) 1965–1966, (B) 1969–1970 and (C) 1982–1983 El Niño events expressed as percentage of annual rainfall as compared to mean-annual precipitation. Rainfall data from Bianchi and Yañez (1992).

proximal parts of the catchment area (Trauth and Strecker, 1999; Trauth et al., 2000). These paleo-precipitation records were compared to the modern rainfall data published by Bianchi and Yañez (1992). Welch power-spectrum estimates were calculated using the Matlab® routine *sptool* for the linear behavior of the climatic conditions (Trauth et al., 2000). In order to study the higher-order causalities between climate indices such as ENSO, TAV and local precipitation, we used a technique of non-linear data analysis, the method of cross-recurrence plots (CRP; Zbilut et al., 1998; Marwan et al., in review). This method allows us to compare the dynamics of two processes (i.e. ENSO and local rainfall) represented in two time series. A CRP is a 2-D visualization tool for sequential data, which gives information about the temporal correlation between the two processes; high correlations correspond to black areas in the CRP. From the occurrence of lines parallel to the diagonal in the recurrence plot it can be seen how long similarities in the behavior of the systems persist in time or how fast they diverge. Therefore, the average length of these lines (L) and the effective recurrence rate (RR) of black areas in the CRP are valuable measures to quantify these similarities (Marwan et al., in review; Marwan and Kurths, in review). For the spatial analysis of the ENSO impact, we mapped the ratio between annual precipitation for three recent El Niño events (1965–1966, 1969–1970 and 1982–1983) and the long-term average for each station (Trauth et al., 2000). We estimated the absolute values for paleo-precipitation and temperature during enhanced landsliding using a hydrological model applied to the landslide-dammed lake in the Santa Maria Basin (Bookhagen et al., 2001).

4. Results

Using the complete precipitation time series of Bianchi and Yañez (1992), we mapped modern spatial and temporal precipitation changes in northwestern Argentina during the El Niño events 1965–1966, 1969–1970 and 1982–1983 and tried to link precipitation anomalies with ENSO. The amount of rainfall compared to the long-term annual mean during three representative El Niño events suggests anomalously low precipitation in the intra-Andean part of the study area, whereas rainfall amounts are significantly higher in the Andean foreland (Fig. 3A–C). During La Niña events, this pattern is reversed but with lower amplitude (Trauth et al., 2000). In addition to this

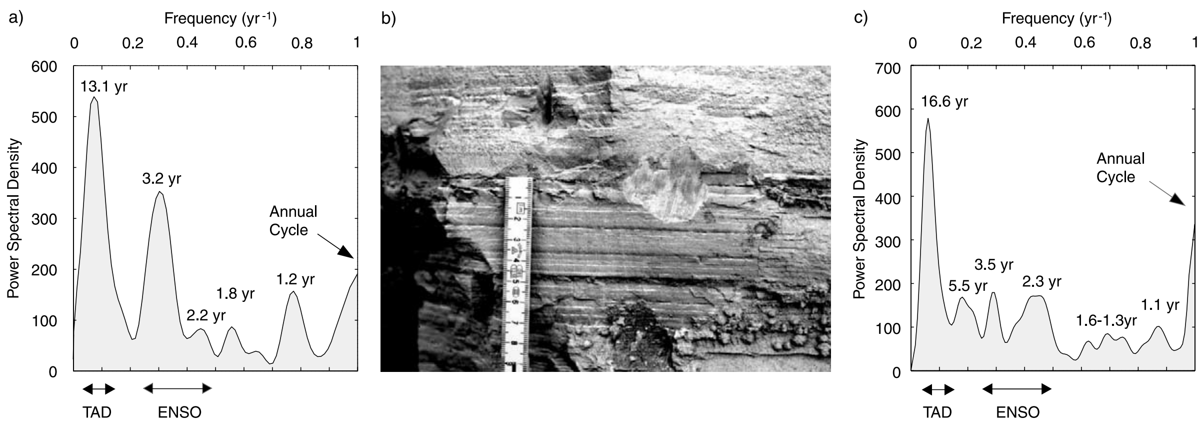

Fig. 4. (a) Power-spectrum estimate of monthly precipitation data showing a strong influence of the TAV, ENSO, and the seasonal cycle on local rainfall (data from Bianchi and Yañez, 1992). (b) Photograph of varved lake sediments from the Quebrada de Cafayate in the Santa Maria Basin with cyclic occurrence of intense dark-red coloration reflecting enhanced precipitation and sediment input during ENSO- and TAV-type periodicities (El Paso section). (c) Power-spectrum estimate of a red-color intensity transect across 245 varves. Dominant frequency bands suggest a strong influence of the TAV, ENSO, and the seasonal cycle on local rainfall.

bipolar ENSO influence in northwestern Argentina, the decadal variation of the transequatorial SST variations also influences precipitation in the study area (Trauth et al., 2000). The power-spectrum estimate of monthly precipitation values in Salta shows significant peaks at 13.1 yr, suggesting a significant TAV influence, and cyclicities of 3.2 and 2.2 yr within the ENSO frequency band (Fig. 4a).

A floating 6700-year chronology developed from laminated sediments deposited in the paleolake Santa Maria dating back ∼30 ^{14}C kyr BP allows us to compare the modern ENSO and TAV impact with the influence of paleo-SST variations on local rainfall (Fig. 4b) (Trauth et al., 2000; Trauth et al., in review). The internal structure of the laminae, the cyclic recurrence of paired diatomite and clastic layers, sediment coloration, and provenance provide strong evidence that rhythmic sedimentation in this region is controlled by the strong annual cycle in precipitation (Anderson, 1996; Trauth and Strecker, 1999; Trauth et al., 2000; Trauth et al., in review). This conclusion is also supported by the results from non-linear time-series analysis showing significant similarities in the dynamics of modern rainfall data and paleo-precipitation records extracted from the lake sediments (Marwan et al., 2000, in review).

The power-spectrum estimate of a red-color intensity transect over these varved lake sediments shows similar cyclicities as the spectrum of modern data suggesting a strong influence of both the ENSO and the TAV (Fig. 4a,c). Cross recurrence plots tracing similarities and differences in several measures of complexity in both modern and past rainfall data support this interpretation (Marwan et al., in review) (Fig. 5). The first important result from this analysis is that the red-color intensity record from the varved lake sediments shows similar non-linear dynamics as the modern rainfall data (Marwan et al., in review). The distances between longer diagonal lines in the CRP of both records are about 2–4 years, the approximate time of recurrence of extreme ENSO phases today (Fig. 5). The first implication of this result is that the red-color intensity of the sediments is indeed a good proxy for the rainfall intensity at ∼30 ^{14}C kyr BP. The second major result is the significant similarity between the non-linear dynamics of present-day precipitation in the cities of Jujuy and Salta and the paleo-precipitation as recorded in the lake sediments in the location El Paso. Since our analysis of modern data reveals a strong relationship between local rainfall in the northern part of the study area and ENSO (Fig. 3A–C), we interpret this similarity as an indication of a strong ENSO-like influence in the Santa Maria Basin at around 30 000 years. The analysis of CRP also reveals that this ENSO impact in the northern part of the study area was even stronger than today causing stronger La Niña events in wide areas of northwestern Argentina including the location El Paso. In contrast, there is no significant linkage between modern rainfall in Tucuman and ENSO. This could indicate that ENSO does not influence precipitation in the southern part of the study area or this influence is rather diffuse or changing in time (Marwan et al., in review). The third important finding from the analysis of the parameters diagonal length (L) and the RR is a longer rainy season at ∼30 ^{14}C kyr BP.

Lake-balance modelling of the landslide-dammed paleolake Santa Maria helps to assess the differences in the precipitation/evaporation balance between today and at ∼30 ^{14}C kyr BP (Fig. 6) (Bookhagen et al., 2001). This model reveals that a hypothetical present-day lake would stabilize around 70 m below the reconstructed paleolake level at 1700 m. This hypothetical lake would have an area of 380 km^2 and a volume of 23 km^3, whereas the reconstructed paleolake covered an area of 660 km^2 with a volume of 62 km^3. In order to reach the paleolake level at 1700 m, two end-member scenarios illustrate the range of potential changes in the most critical input parameters mean-annual precipitation and air temperature. Assuming no change in precipitation, a temperature reduction of 6°C would be necessary. Alternatively, 30% more precipitation results in a similar water budget if the temperature would be at the modern value. In both cases, the equilibrium lake level would reach the 1700-m contour ∼400 years after the closure of the basin by the rock avalanche. The most likely climate scenario is a combined precipitation increase and temper-

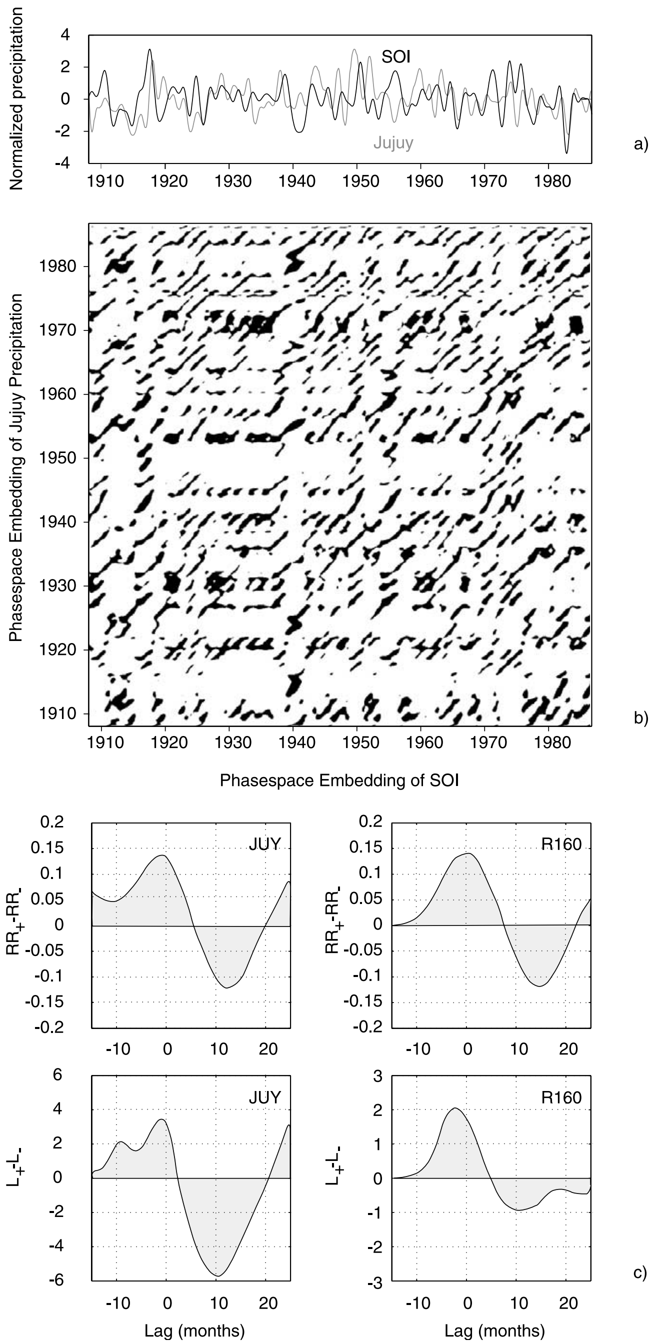

Fig. 5. (a) Comparison of normalized precipitation values in Jujuy and the Southern Oscillation Index (SOI). (b) Cross recurrence plot of SOI vs. precipitation in Jujuy (JUY) (dimension = 3, delay = 7 months, threshold = 15%, fixed neighbors amount, see Marwan et al., in review for details). The x-axis depicts time along the phase space trajectory of the SOI and the y-axis that of JUY. Black points represent the occurrence of similar states in both systems. SOI from the Bureau of Meteorology Australia Data Server (www.bom.gov.au), precipitation data from Bianchi and Yañez (1992). (c) RR and L (difference between the complexity measures of the correlated and anti-correlated states) vs. lag (in months) in a cross-recurrence plot of modern precipitation in Jujuy (JUY) and 160-yr long paleo-precipitation record from ~30 000-^{14}C-yr-old varved lake sediments (R160) sampled in the Santa Maria Basin vs. SOI, suggesting similar ENSO influences today and ~30 000 ^{14}C yr ago.

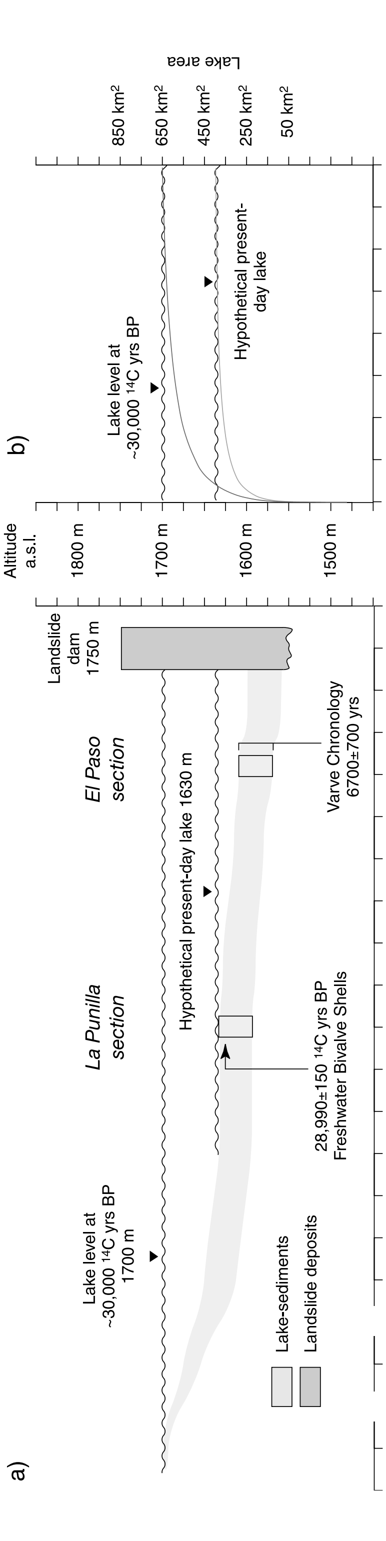

Fig. 6. (a) Cross section through the ∼30-^{14}C-kyr-old paleolake in the Santa Maria Basin as compared to a hypothetical present-day lake that would stabilize around 70 m below the reconstructed paleolake level at 1700 m. (b) Modelled lake-fill curves for both lakes applying modern climate parameters for the modern lake and +10–15% precipitation and −3–4°C air temperature for the paleolake Santa Maria.

ature reduction. For the Minchin wet period, no temperature reconstructions are available for northwestern Argentina. However, extrapolating paleo-temperature estimates based on pollen assemblages, the most likely temperature change for the Minchin period is a −3–4°C temperature reduction for northwestern Argentina (Markgraf et al., 1986; Markgraf, 1989). The corresponding best estimate for a precipitation change in order to reach the reconstructed paleolake level in the Santa Maria Basin would be +10–15%. These results imply slightly wetter and cooler conditions at ∼30 ^{14}C kyr BP as compared to the present.

The chronology of landslide events in northwestern Argentina was determined using ^{14}C ages of associated lake sediments and tephrochronologic correlations of intercalated ash layers (Fig. 7) (Hermanns et al., 2000; Trauth et al., 2000). Near the El Paso locality in the Quebrada de Cafayate, an older rock avalanche is overlain by the varved lake-sediment sequences documenting a 6700-year lacustrine period after landsliding (Trauth et al., in review). These sediments are in turn overlain by a younger and less voluminous rock-avalanche deposit. On top of this younger landslide are erosional remnants of carbonate-rich swamp deposits up to 10 m in thickness that contain abundant shells of amphibious freshwater snails (*Lymnaea viator*), dated at 35 650 ± 380 ^{14}C yr (Trauth and Strecker, 1999). AMS ^{14}C dating of carbonate bivalves (*Sphaerium* sp.) sampled from stratigraphically higher parts of an equivalent deposit 5 km west of El Paso provides an age of 28 990 ± 150 ^{14}C yr BP (Trauth and Strecker, 1999). The age of the sediment containing the bivalve shells was also estimated using infra-red stimulated luminescence dating yielding a preliminary Late Pleistocene age (Glenn Berger, pers. commun., 2001). During the second landslide event, the lake sediments must have been water-saturated because they were folded and injected into the landslide mass (Hermanns and Strecker, 1999). Situated in the Cordillera Oriental, the Quebrada del Toro farther north (24.7°S, 65.8°W), erosional remains of lacustrine sediments are related to two successive landslide-damming events. AMS ^{14}C dates on freshwater snails provide an age of 30 050 ± 190 ^{14}C yr BP for the

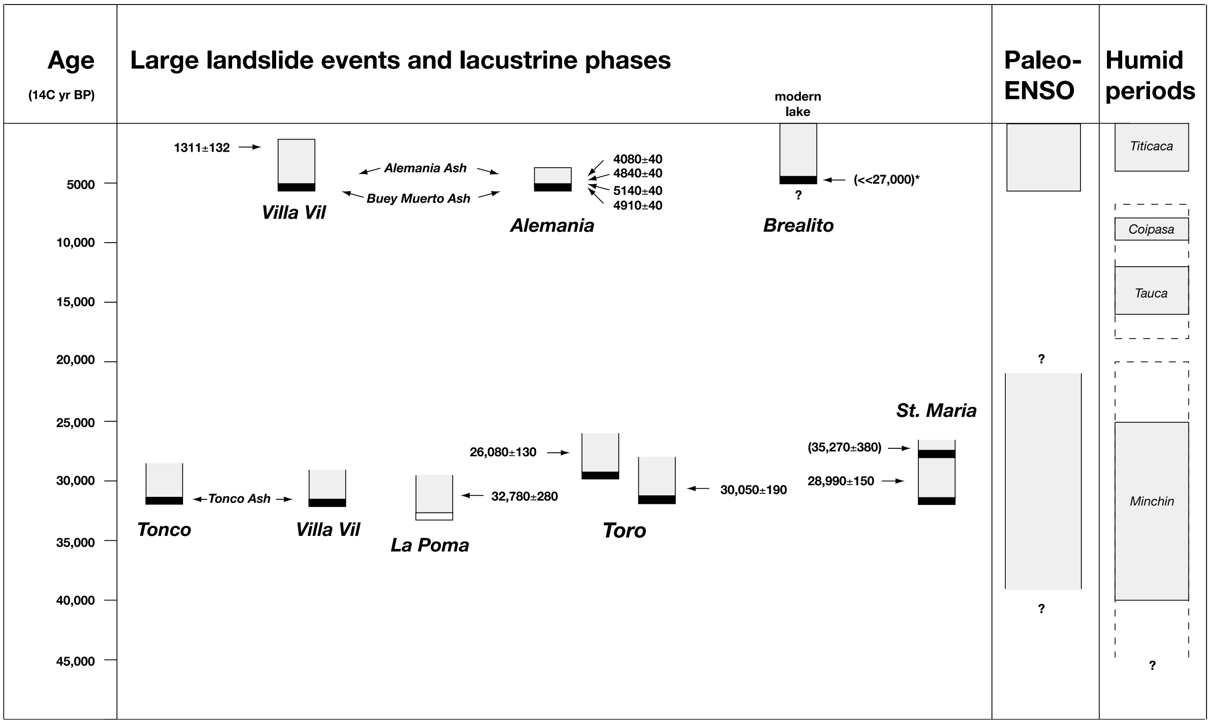

Fig. 7. Correlation of landslide and lacustrine events in northwestern Argentina with tropical and subtropical South American wet episodes; data from Hermanns et al. (2000), Trauth et al. (2000) and this work. Black horizontal bars denote landslide events; lacustrine phases are indicated by gray rectangles; a basaltic lava flow is indicated by a white rectangle. All ages are AMS ^{14}C ages except for those marked by an asterisk which are cosmogenic-nuclide exposure ages. The radiocarbon age at Villa Vil is from Fauque and Tchilinguirian (2002); the compilation of paleo-ENSO history is based on Oberhänsli et al. (1990) and Sandweiss et al. (2001, 1999); the chronology of humid periods in tropical and subtropical South America is based on Servant and Fontes (1978), van der Hammen and Absy (1994), Servant et al. (1995), Ledru et al. (1996), Godfrey et al. (1997), Turcq et al. (1997), Sylvestre et al. (1999), and Baker et al. (2001).

lower lake at 1950 m, and 26 080 ± 130 ^{14}C yr BP for the upper lake at 2220 m (Trauth and Strecker, 1999; Trauth et al., 2000). At the northern end of the Valles Calchaquies close to the village of La Poma (24.7°S, 66.2°W), a yet undated basaltic lava flow dammed the Rio Calchaqui, resulting in a lake at around 32 780 ± 280 ^{14}C yr BP (Trauth et al., 2000). Tephrochronology, radiocarbon dating, and geomorphologic analyses suggest that the older of two landslides near Villa Vil (27.0°S, 66.8°W) and several landslides in the Quebrada del Tonco (25.7°S, 66.0°W) may also have occurred at that time (Hermanns et al., 2000).

Lacustrine sediments associated with a rockfall at Alemania (25.7°S, 65.7°W), previously studied by Wayne (1999) and Hermanns et al. (2000), are of Holocene age. Several ^{14}C ages measured on charcoal and bivalve shells suggest that the Alemania rockfall must have occurred at ~5 ^{14}C kyr BP, assuming a short delay between the damming event and subsequent basin infill. 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 within the error bar of the method for this sample which was probably contaminated by nucleogenic reactions (≪27 kyr BP; Hermanns et al., 2000). To this age group may also belong a 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 (Hermanns et al., 2000).

5. Discussion

Terrestrial records from tropical and subtropical South America such as lake level and vegetation records document rather abrupt shifts in temperatures and precipitation during the Late Pleistocene and Holocene (e.g. Markgraf, 1989). The timing and spatial significance of wetter/drier or cooler/warmer periods varies regionally (Markgraf and Seltzer, 2001). However, many proposed causal linkages and teleconnections based on observed leads and lags between different climate records from various regions were identified as artefacts of dating uncertainties or ambiguous environmental proxies. These problems can be overcome by a higher spatial coverage of climate records, more precise and high-resolution age determinations, a better understanding of the processes behind environmental indicators and the establishment of new proxies, especially for paleo-precipitation. The landslide clusters in northwestern Argentina are a useful alternative to other climate proxies in high-altitude mountains (Trauth et al., 2000). Precise age determinations of the rock-avalanche deposits using various independent techniques (Hermanns et al., 2000) and the investigation of the sediments of associated landslide-dammed lakes (Trauth and Strecker, 1999; Trauth et al., in review) provide valuable information on Late Pleistocene and Holocene climate change in this region.

Our chronology of large landslides and accompanying lacustrine phases with allogenic, through-flowing rivers in narrow valleys in northwestern Argentina suggests that these events were concentrated in two time periods during Late Quaternary time (Fig. 7). The earlier cluster is dated at ~30 ^{14}C kyr BP, while the younger cluster is ~5 ^{14}C kyr old, assuming that the lacustrine depositional systems were initiated immediately following the landslide event. Lake-balance modelling suggests more humid conditions in northwestern Argentina at around ~30 ^{14}C kyr BP. The landslide cluster at ~30 ^{14}C kyr correlates with the well-established Minchin wet period of the central Andes (40–25 ^{14}C kyr, e.g. Servant and Fontes, 1978; van der Hammen and Absy, 1994; Ledru et al., 1996; Godfrey et al., 1997; Turcq et al., 1997). This period of higher landslide activity is also consistent with the new ages for the Minchin period as reported from the Salar de Uyuni, Bolivian Altiplano (>32.3 ^{14}C kyr BP; Baker et al., 2001), taking into account the potential uncertainties in the radiocarbon ages at both sites. 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 may have occurred slightly before the onset of this wet period also reported from other Andean regions and the Amazon basin (Ledru et al., 1996; Abbott et al., 1997; Mourguiart et al., 1998; Baucom and Rigsby, 1999). These two temporal landslide clusters are separated by a gap between of ~20 kyr. It is interesting to note that although a large number of landslides and lakes were studied in northwestern Argentina, no landslides and accompanying lake sedimentation seem to occur during the Tauca and Coipasa wet periods (Servant et al., 1995; Sylvestre et al., 1999).

Assuming that these periods also affected northwestern Argentina, the relationship between the prevailing humid periods and increased landsliding activity is ambiguous. In fact, new pollen data from lake-sediment cores obtained in the Laguna Hervidero (Müller, 2001; Müller et al., in preparation) and in the Jujuy province (Schäbitz, 2000) suggest that both the Tauca and Coipasa wet periods are recorded in northwestern Argentina. Thus, an alternative cause for more frequent mass movements in northwestern Argentina should be considered (Fig. 7). Instead of longer-lasting wet periods and resulting slope destabilization, increased intra- and interannual fluctuations in precipitation may represent possible trigger mechanisms for landslides and other mass movements. The similarities between the statistics in the modern rainfall data and the paleo-precipitation record from the lake sediments suggests that an ENSO-like oscillation was also active at around 30 ^{14}C kyr BP. We suggest that these events correspond to the periods of a strong ENSO as reported from deep-sea sediments offshore Peru (e.g. Oberhänsli et al., 1990), in the Indo-Pacific Ocean (Beaufort et al., 2001), and New Guinea corals (Tudhope et al., 2001). Grosjean et al. (1997) and Keefer et al. (1998) reported ENSO-triggered enhanced landsliding from Chile and Peru after around ~5 ^{14}C kyr BP, which coincides with the younger landslide cluster. The Holocene history of ENSO was intensively studied on both marine and terrestrial archives suggesting a more weakened, perhaps entirely absent, ENSO between 12 and 5 ^{14}C kyr BP, but a greater ENSO-related precipitation variability and overall greater moisture at low latitudes during the last 5–3 ^{14}C kyr (e.g. Rodbell et al., 1999; Keefer et al., 1998; Sandweiss et al., 2001; Haug et al., 2001). In contrast to the paleo-ENSO evidence, paleoclimate studies on TAV history are very limited. However, from the sediments of an Ecuadorian lake, Rodbell et al. (1999) reported clastic sedimentation events spaced 10–20 years during the last 6.5 ^{14}C kyr BP, which may document minimum-TAV events. However, these signals were not interpreted to be related to Atlantic SST changes by these authors.

Our analysis of modern climatic data shows that the main sources for interannual precipitation variability in northwestern Argentina are the ENSO and the TAV. The spatially concentrated multiple landslide deposits in the study area coincide with the boundary between two ENSO-related rainfall anomalies with opposite signs whereas the TAV influence does not show important spatial variations. The difference in the climatic overprint by the ENSO-influence may reflect differences in the importance of the northeasterly winds in the study region. Whereas the northern and northwestern mountain regions are mainly influenced by northeastern winds with less effective moisture transport during El Niño years, the southern part of the study area shows some influence from southern and southeastern winds with a weak tendency towards more rain during El Niño years (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.

6. Conclusions

Despite the structural, seismic, and lithologic parameters that control spatial clustering of rock avalanches in northwestern Argentina, a higher frequency of such events in the past may have been caused by a 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. On the other hand, we believe that since climate change is the most likely trigger for enhanced mass movements in narrow valleys in mountainous regions, landslide clusters can be used to infer important climate shifts towards more humid, but even more importantly towards more variable conditions due to stronger influences of decadal and interannual SST fluctuations.

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