Quaternary environmental and climate changes in the Central Andes

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ABSTRACT

The reconstruction of past climates is essential for our understanding of present global changes. The Central Andes are located at the transition zone between the tropical monsoon and the southern mid-latitude westerlies. They are therefore a particularly sensitive region for the detection of past climate and environmental changes. This chapter presents a review of recent studies conducted by the group of «Paleogeoecology and landscape evolution» (University of Bern, Switzerland) along the Central Andes and their adjacent forelands in Bolivia, Argentina and Chile.

The investigation of paleoenvironmental archives, including records from paleosols and glacial, fluvial-alluvial, aeolian and lacustrine sediments, has shown to contain manifold evidence for the highly dynamic climate and environmental history in the Central Andes and their forelands during the Quaternary. Marked changes have occurred in humidity and/or temperature conditions on timescales ranging from several hundreds to more than one million years. While the inferred changes in temperature generally coincide with global climatic phenomena such as the last glacial maximum (LGM), reconstructed changes in precipitation and humidity provide information on past intensities and/or shifts in latitudinal position of the monsoonal circulation and the mid-latitude westerlies.

Despite some remaining discrepancies and uncertainties, our results generally point to insolation forcing on orbital timescales as the primary control for variations in the atmospheric circulation patterns over the Central Andes. Ongoing research aims at complementing and refining these results by integrating further regional studies focussing on the investigation of new archives and proxies, as well as on the improvement of age control.

Keywords: Central Andes - paleoclimate - paleoenvironment - Quaternary - glacial - paleosol-sediment-sequences

RESUMEN

La reconstrucción de los paleoclimas es un conocimiento esencial para la comprensión de los cambios globales actuales. Situados en la zona de la transición entre el sistema del monzón tropical y los vientos meridionales del oeste, los Andes Centrales son una región particularmente sensible para la detección de cambios paleoclimáticos y ambientales. Esta contribución presenta un resumen de los recientes estudios realizados por el grupo de «Paleogeoecología y evolución del paisaje» (Universidad de Berna, Suiza) a lo largo de los Andes Centrales y los territorios adyacentes en Bolivia, Argentina y Chile.

La investigación de los paleoambientes incluye registros de paleosuelos y de sedimentos glaciales, fluvial-aluviales, eólicos y lacustres, y ha demostrado que posee evidencias de una historia paleoclimática y ambiental altamente dínámica en los Andes Centrales durante el Cuaternario. En ese tiempo ocurrieron marcados cambios de la humedad y/o temperatura durante lapsos que oscilan entre varios centenares de miles de años hasta más de un millón de años. Mientras que los cambios deducidos de temperatura generalmente coinciden con fenómenos climáticos globales tal como el último máximo glacial (LGM), los cambios reconstruidos de humedad y precipitación contienen informaciones sobre variaciones pasadas en intensidad y posición latitudinal de la circulación monzónica y de los vientos del oeste en las latitudes medias.

A pesar de las discrepancias e incertidumbres que restan por resolverse, por lo general nuestros resultados identifican a la insolación como el control primario de las variaciones de la circulación atmosférica a lo largo de los Andes Centrales. El objetivo de los trabajos en desarrollo es complementar y afinar estos resultados e integrar otros estudios regionales que procuren investigar nuevos archivos y proxies, así como perfeccionar el control cronológico de los fenómenos estudiados.

Palabras clave: Andes Centrales - paleoclima - paleoambientes - Cuaternario - glacial - secuencias paleosuelos-sedimentos

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INTRODUCTION

The understanding of climate and environmental dynamics is a major issue in the ongoing discussion of present global changes. In this context, documentation and interpretation of longer term dynamics in the past is a necessary precondition for any substantial prediction and simulation of future scenarios (Bradley 2000; Jansen et al. 2007). Major environmental changes, such as the repeated growth and decay of large continental ice shields, have occurred during the Quaternary – the last two million years of the Cenozoic. Quaternary research is a multi-disciplinary field concerned with i) the reconstruction of past environments throughout the last two million years, and ii) the investigation of mechanisms and forcings of past changes.

The reconstruction of paleoenvironments and paleoclimates is based on a variety of different proxy data contained in geological, glaciological, biological, and historical archives from around the globe. However, the number of relevant paleoenvironmental studies in the Southern Hemisphere is still comparatively scarce (Heine 1984; Markgraf 1998; Markgraf et al. 2000; Kershaw and Chappellaz 2007). Over the last two decades, our working group «*Paleogeoecology and landscape evolution*» at the Institute of Geography, University of Bern, has conducted multi-disciplinary geoscientific research and cooperation in several South American countries, mainly Chile, Argentina and Bolivia. Initially, these efforts had focussed on the analysis of lake sediments (Grosjean 1994; Grosjean et al. 1995; Grosjean et al. 1997; Grosjean et al. 2001) and glacial archives (Vuille and Ammann 1997; Messerli et al. 1998; Kull and Grosjean 2000; Ammann et al. 2001) along the Central Andes of Chile. This chapter aims at giving an overview over the more recent studies along the Central Andes and their forelands, summarizing results from glacier reconstruction and modelling, sedimentological and pedological investigations on fluvial and aeolian sediments, as well as from lake sediment analyses.

GEOGRAPHICAL SETTING

The Central Andes extend from approximately 15° to 40°S, and comprise several distinct geological and geomorphic units (Allmendinger et al. 1997) (Fig. 1). North of ~28°S, the Cordilleras Oriental and Occidental – both with summits of >6000 m asl – enclose a broad high-altitude plateau (~4000 m asl) known as the Altiplano (Peru and Chile) or Puna (NW-Argentina). South of ~28°S, the width of the Andes decreases substantially, although summit altitudes drop to ~3000 m asl only south of ~36°S. The causal link between Central Andean uplift and Late Cenozoic climate change has been discussed controversially, while on shorter Quaternary timescales there is generally agreement regarding the crucial role of topography exerting control on precipitation (Montgomery et al. 2001; Lamb and Davis 2003; Strecker et al. 2007; Bookhagen and Strecker 2008). The Central Andes act as a topographic barrier for the atmospheric circulation over the South American continent resulting in extremely arid conditions along the so-called «Arid Diagonal».

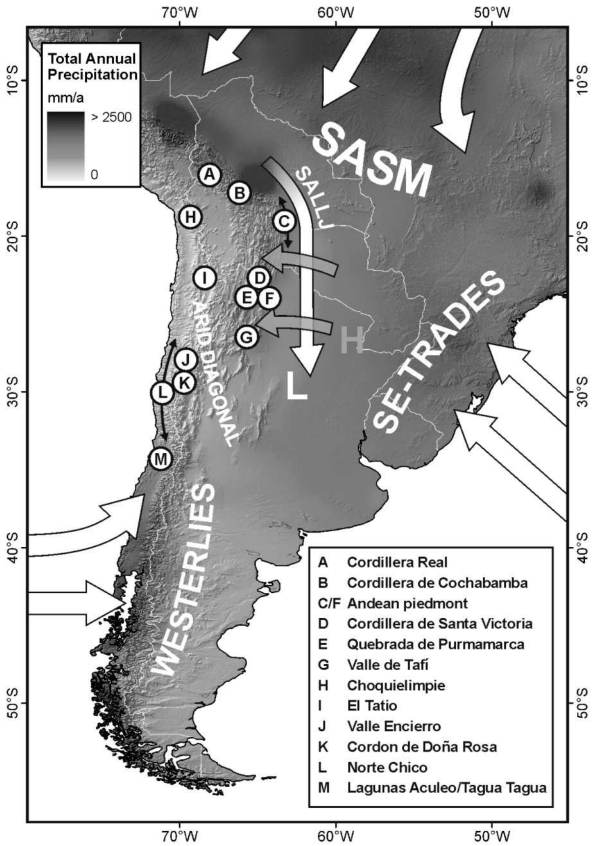

Figure 1. The main climatic components of the southern and central part of South America (SASM - South American Summer Monsoon, SALLJ - South American Low Level Jet, H - Bolivian High, L - Chaco Low, Precipitation data from New et al. 2002); letters mark the study locations discussed in the text.

North of the Arid Diagonal, the South American Summer Monsoon (SASM) system advects tropical moisture from the Atlantic and is responsible for precipitation maxima in austral summer along the northern ranges and foreland slopes of the Central Andes (Zhou and Lau 1998; Nogues-Paegle et al. 2002; Vera et al.

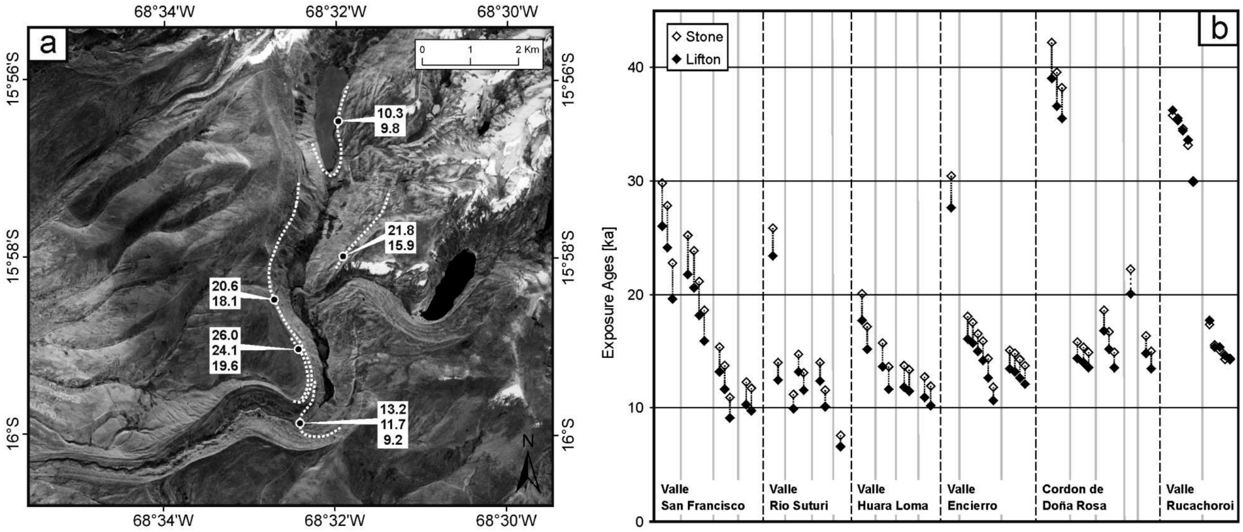

Figure 2. Glacial archives. a) Satellite image of Valle San Francisco, Cordillera Real (Bolivia), with white dotted lines depicting the sampled moraines and surface exposure ages shown (calculated following Lifton et al. 2005); b) Summary plot of all surface exposure ages along the N-S transect through the Central Andes.

2006). The strong northerly wind system of the South American Low Level Jet transfers tropical moist air masses further southward along the eastern flanks of the Central Andes (Berri and Inzunza 1993; Marengo et al. 2004). Here, the position and strength of the Bolivian High and the associated Chaco Low exert a dominant control on moisture advection and precipitation – both in the lowlands and on the southern Altiplano. Contrarily, increased precipitation on the northern Altiplano is mainly related to the strength of the upper-tropospheric easterlies, which in turn are influenced by Pacific sea surface temperatures (Lenters and Cook 1997; Garreaud et al. 2003; Vuille and Keimig 2004; Garreaud and Aceituno 2007). South of the Arid Diagonal, moisture is mainly derived from the Pacific and advected by the southern westerlies. The precipitation maximum occurs during austral winter due to the seasonal northward shift of the westerlies (Garreaud and Aceituno 2007). Additionally, on both sides of the Central Andes, frontal systems can periodically cause temperature drops and rainfall (Vuille and Ammann 1997; Garreaud 2000, Vera et al. 2002; Pezza and Ambrizzi 2005).

Due to their location at the transition zone between the SASM and the westerlies, the Central Andes are a particularly sensitive region for the reconstruction of past environmental changes and for the investigation of the associated shifts in the intensity and meridional position of the atmospheric circulation patterns. In the following, results from our various methodological approaches to deduce regional-scale Quaternary paleoenvironmental and climate changes are summarized. The integration of these studies across the Central Andes and along the adjacent lowlands can be considered a large-scale paleoenvironmental transect from the tropical northern to the subtropical and mid-latitude southern parts of the Central Andes.

RESULTS

Tropical Andes, Bolivia

The tropical Andes of Bolivia are characterized by a steep hygric gradient ranging from >1500 mm/a along the north-eastern Andean slopes and lowlands to <500 mm/a on the Altiplano and the eastern foreland. Most of the precipitation falls in austral summer. Our paleoenvironmental studies in Bolivia focus on i) establishing glacial chronologies using ^{10}Be Surface Exposure Dating (SED), ii) glacier-climate modelling, and iii) paleosol-sediment-sequences along the piedmont in the eastern Andean foreland.

Late Quaternary glaciation

Glacial reconstruction in the tropical Andes of Bolivia and Peru has long been limited to mapping, soil development on moraines, and very few basal radiocarbon ages. Recent reviews of the glaciation history therefore highlighted the lack of reliable age control and concluded that not even the timing of the maximum of the

Method Box 1: Surface Exposure Dating

Cosmic radiation constantly bombards the earth and produces in-situ cosmogenic nuclides (CN), for example ^{10}Be, in the upper few decimeters of the earth' surface (Gosse and Phillips 2001). The concentration of CNs depends on the exposure time, the local production rate, and – in case of radioactive nuclides – on the decay constant. The exposure ages of glacial erratics allow estimating the timing of deposition of moraines and thus establishing glacial chronologies. Two current methodological uncertainties, however, need to be considered: i) Exposure ages often scatter much more than one would expect from the analytical precision (~5%). Too old exposure ages can occur due to pre-exposition ('inheritance'), which is rather unlikely (~3%, e.g. Putkonen and Swanson 2003). Too young ages can be caused by common geomorphological processes, including post-depositional boulder exhumation, boulder spallation and erosion. The 'oldest age model' therefore suggests that the oldest of several boulder ages is generally the best available estimate for the deposition age of the respective moraine. ii) The local production rate mainly depends on latitude and altitude, because the cosmic radiation is deflected first by the geomagnetic field and then attenuated on its way through the atmosphere. Details about how exposure ages should be calculated remain ambiguous (Balco et al. 2008), and therefore here the ages are presented as 'x/y', with 'x' being the age based on the still most widely used but simplifying scaling system of Stone (2000), and 'y' the age based on the more recently developed scaling system of Lifton et al. (2005). For the exposure age calculations the now available CRONUS online calculator of Balco et al. (2008) was used, which explains minor deviations from previously published ages.

last glaciation was known (Heine 2004; Mark et al. 2004; Smith et al. 2005c). The local LGM could have occurred before, synchronous or after the global LGM (~18-24 ka). SED using in-situ cosmogenic ^{10}Be (Method Box 1) was applied in the San Francisco Valley, Cordillera Real, and in two valleys in the Cordillera de Cochabamba (Zech et al. 2007a; Zech et al. 2008) (Fig. 1). In the Valle San Francisco (Fig. 2a), the oldest dated glacial deposit is an outer lateral moraine at ~4670 m asl, for which a deposition age of 29.8/26.0 ka has been inferred. Exposure ages from the two inner lateral moraines (25.2/21.8 ka and 23.8/20.6 ka, respectively) suggest that the glacier remained very extensive for several millennia. The deglaciation history in the Valle San Francisco is constrained by exposure ages from the two innermost prominent terminal moraines. They indicate moraine deposition at 15.3/13.2 ka and 12.3/10.3 ka. The oldest moraine in Valle Río Suturi, Cordillera de Cochabamba, is tentatively assigned an age of ~25.9/23.4 ka (Fig. 2b). Recessional moraines are dated to 14.7/13.2 ka and 14.0/12.4 ka. In the Valle Huara Loma, inferred deposition ages for the moraines are 20.1/17.7 ka, 15.7/13.6 ka, 13.7/11.8 ka and 12.8/11.0 ka (Fig. 2b).

The relatively 'early local LGM' in Valle San Francisco is in good agreement with exposure data that have been published for the Cordillera Blanca, the Lake Junín area, both Peru, and the Milluni Valley, Bolivia (Farber et al. 2005; Smith et al. 2005a; Smith et al. 2005b). Provided that the new scaling system of Lifton et al. (2005) proves to be more accurate than the one of Stone (2000), the local LGM in these parts of Bolivia and Peru should have occurred roughly in-phase and can be explained with the temperature minimum during the global LGM. Increasing rain-shadow effects and aridity during the course of the glaciation probably explain the preservation of the relatively early LGM moraines (~25 ka). Rain-shadow effects are less in the Cordillera Cochabamba, where the local LGM seems to have occurred later than in the Cordillera Real and more in-phase with the global LGM *stricto sensu* (~20 ka). Further south and west, on the Bolivian Altiplano, radiocarbon ages suggest that glaciers reached their maximum even later, namely during the Lateglacial at ~16 ka (Clapperton et al. 1997; Clayton and Clapperton 1997). This 'late local LGM' can be explained with the strong NE-SW precipitation gradient: glaciers became more and more precipitation-sensitive and reached their maxima synchronous with the lake-transgression phases Tauca (18-14 ka) and Coipasa (13-11 ka, Placzek et al. 2006). Increased precipitation during these two phases can be attributed to an intensification and/or southward shift of the South American Summer Monsoon.

Overall, we conclude that the glaciation history in Bolivia varies regionally due to the strong precipitation gradients and the resultant specific sensitivity of glaciers to past temperature and precipitation changes. This is likely also true for the deglaciation history, although methodological uncertainties currently prevent addressing millennial-scale questions, like e.g. synchrony with the northern-hemispheric Younger Dryas event or the Antarctic Cold Reversal.

In order to quantitatively assess paleoclimatic conditions for the late Pleistocene glacial maximum advances along the north-eastern Andean slopes, glacier-climate modelling (Method Box 2) was conducted in the Cordillera de Cochabamba (Imhof et al. 2006; Kull et al. 2008). Based on detailed field work and remote sensing data, regional patterns and differences in glaciological parameters were mapped. Geomorphological and stratigraphical data reveal a NE to SW increase in paleo-ELAs of the maximum glaciation from ~4250 to 4450 m asl. This points to the Amazonian lowlands as a moisture source and precipitation gradients similar to today. Pleistocene maximum advances are generally characterized by long and narrow tongues indicating reduced ablation with dominance of sublimation, even at lower elevations. In addition, these paleoglaciers show relatively low AARs compared to the younger glacial advances with higher values. Most of these younger advances are restricted to high elevation mountain peaks (~4800 - 5000 m asl) and did probably not need a massive temperature depression to occur.

In combination, the younger advances in the Cordillera de Cochabamba are inferred to document intervals of moderately cold, but very humid climate conditions, probably during the Lateglacial, whereas the late Pleistocene maximum advances imply a substantial regional drop of the paleo-ELA and a massive temperature reduction of -6.4°C (+ 1.5/- 1.3°C) without essential changes in annual precipitation. These calculations are in good agreement with other reconstructed paleotemperatures during the global LGM throughout the Central Andes and the Amazonian lowlands (e.g. Colinvaux et al. 1996; Heine 2000).

The piedmont along the eastern Andes

Along the Eastern Cordillera of tropical Bolivia and the Andean foreland of the Chaco, the number of paleoenvironmental studies has been very scarce until recently (Markgraf 1998). Therefore, different types of remote sensing data were used in order to obtain a geomorphological overview over the landscape evolution, and to establish a framework for the investigation of the various geomorphic archives in eastern Bolivia (May 2006).

At Charagua (~20°S) the investigation of piedmont stratigraphy was combined with large-scale geomorphological mapping providing evidence for significant spatial and temporal variability of the fluvial processes during the last four decades (May et al. 2008a). The onset of recent regional landscape activity began between ~1 and 0.6 cal ka BP and has been inferred from the burial of a marker paleosol, which could be identified in all profiles exposed along the six investigated piedmont streams (Method Box 3). Substantial increase in sediment supplies, as well as the subsequent incision within the last two centuries might be related to climate changes during the Little Ice Age, e.g. frequency changes in the El Niño Southern Oscillation (Villalba et al. 1998; Maas et al. 2000; Rabatel et al. 2005). Additionally, historical and pre-Columbian human impact should be considered as a potential cause for local deforestation and land cover changes in the catchments (Thompson et al. 1988; Erickson 2000; Abbott and Wolfe 2003; Kulemeyer 2005).

The investigated profiles at Santa Cruz (~18°S) and Cabezas (~19°S) provide stratigraphical records extending further back in time. Particularly at Santa Cruz, strong

Method Box 2: Glacier-climate modelling

Scenarios of past and present climatic conditions can be calculated with a glacier-climate model, which was developed for the Central Andes (Kull 1999; Kull and Grosjean 2000; Kull et al. 2002; Kull et al. 2003; Imhof et al. 2006; Kull et al. 2008). The model integrates i) topographic information regarding the detailed geometry of the glacier or paleoglacier (e.g. terminal and lateral moraines) as mapped in the field or derived from remote sensing data, ii) climatic information on modern diurnal and annual cycles, amplitudes and lapse rates, iii) empirical-statistical sublimation-, melt- and accumulation models developed for this area, and iv) dynamic ice flow calculations through known cross-sections. Based on these data, mass balances are derived for the individual altitudinal segments of the glacier, and glacial mass flow is calculated for given cross-sections. Steady-state conditions (i.e. glacial maximum advances) are fulfilled when i) the mass balance over the whole glacier is zero, and ii) the annual mass flux through a given cross-section in the ablation area equals the annual mass balance («mass loss») below. By iteration the model can then be tuned to a climate scenario which meets these criteria.

This glacier-climate model has been applied to climatically different test areas in the Central Andes. The discussion of these results in a paleoclimatic context has shown some constraints, which are crucial for an improved understanding of the model. As summarized by Kull et al. (2008), the correct calculation of glacial mass balances relies on an improved understanding of processes such as sublimation and redeposition of snow. In addition, seasonality plays an important role for the annual cycle of mass balance. Finally, the results are pointing to the relationship between glacial geometry (e.g. tongue length and the accumulation-area ratio AAR) and climate. This issue has to be considered when interpreting paleo-equilibrium line altitudes (ELA, Kaser and Georges 1999; Kull and Grosjean 2000; Kaser 2001; Kull et al. 2003).

Method Box 3: Paleosol-sediment-sequences

Along the Andean piedmont in eastern Bolivia and NW Argentina, outcrops are frequently exposed at cut banks of incised ephemeral streams or the larger foreland rivers, and show an alternation of paleosols and sediments. Unlike the large fluvial systems with their extensive drainage basins in the high Andes, the small piedmont streams and alluvial fans have their catchments and sediment source areas in the sub-Andean ranges. Climate is a primary factor in controlling the spatial and temporal variability of alluvial fan deposition and stratigraphy over late Quaternary timescales (Bull 1991; Harvey 1997; Harvey et al. 2005). The piedmont stratigraphy therefore sensitively records past regional geomorphic changes and thus contains information regarding hydrological and environmental changes. The interpretation of these paleosol-sediment-sequences requires adequate geomorphological concepts.

Well-developed paleosols of regional character (marker horizons) can be assumed to reflect «landscape stability» and to be indicative of a dense vegetation cover under sufficiently humid conditions (Rohdenburg 1970). On the contrary, widespread sedimentation or erosion/denudation reflects «landscape activity», which implies increased sediment transport by fluvial or aeolian agents, and is generally assumed to result from the degradation of vegetation cover under more arid conditions. Whereas this simplified concept offers the possibility of distinguishing between two general landscape modes – each of them with contrasting environmental conditions – it does not account for the constant dynamic changes within a geomorphic system (Chorley 1962). In this regard, the geomorphic effect of a given environmental change (i.e. the «landscape sensitivity») does not only depend on the direction of the change (e.g. from dry to wet conditions), but also on the amplitude and duration of environmental conditions before the change (Langbein and Schumm 1958; Wolman and Miller 1960; Thomas 2001).

spatial heterogeneity of the stratigraphy, the paleosols and the corresponding pedogenic processes has been documented (May and Veit 2009). The formation of well-developed Luvisols during the Lateglacial and most of the late Holocene can be attributed to humid conditions similar as today, whereas dry and highly seasonal conditions during the LGM and the mid-Holocene caused sedimentation pulses, brief intervals of soil formation dominated by strong seasonal evaporation and ascending soil water, and frequent forest fires. The most complete and laterally extensive profiles are situated at Cabezas (May et al. 2008b), where lateral bank erosion of the Río Grande has exposed a paleosol-sediment-sequence of the proximal piedmont (Fig. 3a).

The lowermost stratigraphical Unit I consists of very coarse fluvial gravels and sands, which were likely deposited in a braided river environment. Although based on a single radiocarbon date, these sediments probably indicate overall dry and seasonal conditions as well as a significant reduction of regional vegetation cover before ~22 cal ka BP. An extensive paleosol (Unit II) is interpreted to reflect increased moisture availability, probably due to the intensification and southward shift of the SASM during the lateglacial Tauca phase with highest lake levels on the Altiplano between ~18 and 11 ka (Argollo and Mourguiart 2000; Placzek et al. 2006). Fine-grained overbank sediments were deposited during the Pleistocene-Holocene transition between ~11.5 and 10 cal ka BP (Unit III). They might document a peak in winter precipitation intensities and a reduced seasonality during the early Holocene, which is in agreement with wetland studies from the Altiplano (Servant and Servant-Vildary 2003). Subsequent erosion, channel incision and accumulation of sands by laterally dynamic fluvial systems characterize the mid-Holocene (Unit IV), providing further evidence for geomorphic instability under semi-arid to arid conditions in eastern Bolivia and the adjacent regions (Servant et al. 1981; Kruck 1996; Mourguiart and Ledru 2003). The return to wetter conditions after ~4 cal ka BP is documented by well-developed modern soils at the surface (Unit V) and is in good agreement with results from southern tropical and subtropical South America (Pessenda et al. 1998; Mayle et al. 2000; de Freitas et al. 2001).

Overall, these results show significant environmental changes along the eastern Andes during the late Quaternary, pointing to intensity changes and latitudinal shifts in the SASM as a primary control on the paleoecological evolution in central South America. This is generally in good agreement with records in the Amazonian lowlands (van der Hammen and Absy 1994; Mayle et al. 2000; Behling 2002; Latrubesse 2003; Burbridge et al. 2004), speleothem studies in SE Brazil (Cruz et al. 2005; Wang et al. 2006) and paleolakes in the Andean Altiplano (Baker et al. 2001a; Baker et al. 2001b; Fritz et al. 2004; Placzek et al. 2006).

Subtropical Andes, Northwestern Argentina

NW-Argentina is located at the transition between the tropical and subtropical climate regimes (Fig. 1). Here, our paleoenvironmental and climate studies are again based on establishing glacial chronologies, glacier-

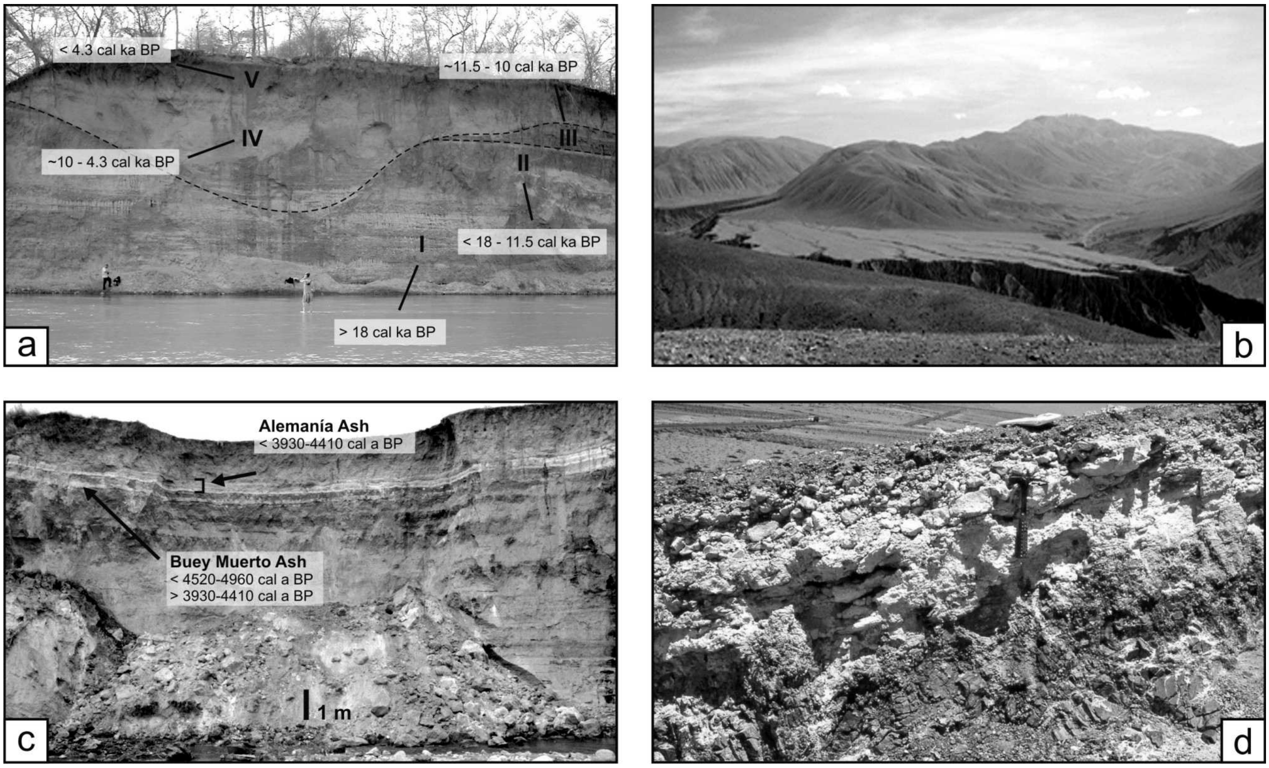

Figure 3. Sedimentary, paleopedological and geomorphic archives for the reconstruction of Quaternary paleoenvironments in the Central Andes and adjacent regions. a) The paleosol-sediment-sequences at Cabezas (E Bolivia) are divided into stratigraphical units (I-V), which represent distinct phases of late Quaternary landscape evolution along the Andean piedmont under changing paleoenvironmental conditions (note persons for scale); b) The terrace segment stands more than 100 meters above the present valley floor in the Quebrada de Purmamarca (NW Argentina) and represents the youngest of several major Quaternary cut-and-fill cycles in the Cordillera Oriental; c) The sedimentary record in this Tafí terrace section allows for the first time to separate two closely spaced ashes (known as Buey Muerto and Alemanía ashes), that are indistinguishable in geochemical composition, and to interpret them as two individual tephra layers; the ashes are important stratigraphic markers (note late Holocene ages) in the organic-poor sediments of the Central Andes; d) The Pleistocene paleosol (note the thick petrocalcic horizon) in «Norte Chico» south of Copiapó (Chile) has formed under more humid environmental conditions than today.

climate modelling and paleosol-sediment-sequences along the piedmont. Additionally, geomorphological results from the Cordillera Oriental and results from a detailed investigation of a 1.2 Ma loess-paleosol-sequence are summarized.

Late Quaternary glaciation

The only study providing numeric age control for the late Quaternary glaciation in NW-Argentina, so far, has been Zipprich et al. (2000). Radiocarbon ages of two fossil Ck-horizons on the Puna plateau (28.0 and 15.8 ^{14}C ka BP, i.e. 32.5 and 19.0 cal ka BP) were interpreted as evidence for humid conditions during the «pre-LGM» and «post-LGM», respectively, and tentatively correlated with moraines mapped in the Cordillera de Santa Victoria. However, neither the correlation, nor radiocarbon dating of pedogenic carbonates is trivial. As discussed in detail in Placzek et al. (2006) based on an extensive radiocarbon and U/Th dating campaign on shorelines on the Altiplano, earlier age estimates for the traditionally assumed humid phases Tauca (Lateglacial) and Minchin (pre-LGM: ~35 ka) are significantly affected by re-crystallization of the radiocarbon-dated carbonates.

First results from ^{10}Be SED near the Tres Lagunas in the Cordillera de Santa Victoria (21 ages, Zech et al. in prep.) suggest deposition of the most prominent moraines at ~130/115 ka, ~19/17 ka, and ~15/14 ka. Several recessional moraine stages were mapped and further ^{10}Be analyses are being carried out, but ice-free conditions even in the upper parts of the Laguna Grande Valley are dated to ~13/12 ka. The preliminary interpretation of the hitherto available exposure ages is that i) the oldest preserved moraines are much older than the global LGM, ii) moraines are preserved, which may document in-phase glaciation with the global LGM, and iii) the most prominent moraines are of lateglacial age (~15/14 ka) and probably coincide with the Tauca lake transgression phase on the Altiplano. The lateglacial moraines indicate the high precipitation-sensitivity of the glacier mass balances in NW-Argentina, similar as on the Bolivian Altiplano, but the preservation of the LGM moraines indicates that glaciers were temperature-sensitive as well. An important observation is that the lateglacial moraines are more prominent compared to the LGM moraines and that the LGM moraines seem to be preserved only as lateral moraines at high altitudes. This points to differences in glacier morphology and can probably be explained with significantly different climate conditions between the LGM and the Lateglacial – the LGM being cold and dry, and the Lateglacial moderately cold and very wet. Further investigations will have to focus on this issue in order to test this hypothesis.

The late Pleistocene maximum glaciations in the Cordillera de Santa Victoria were also subject to modelling studies (Kull et al. 2003). In order to explain the observed maximum glacier extension, a massive temperature drop of 4.5-8°C in combination with moderate precipitation increases was calculated. Glacial geometries characterized by long tongues and relatively low AARs corroborate these scenarios and point to sublimation as the dominant ablation processes. These model results indicate a temperature-driven maximum glaciation in the Cordillera de Santa Victoria in phase with the global temperature depression during the LGM. However, geomorphic evidence for significant lateglacial advances was also detected.

Geomorphic records in the Cordillera Oriental

The Cordillera Oriental is an actively deforming fold and thrust belt with uplift of N-S trending mountain ranges reaching >5000 m asl, and ongoing formation of intramontane valleys and deep gorges. In the Quebrada de Purmamarca three generations of fluvial terraces more than 100 m high above the valley bottom were mapped and investigated (May 2008) (Fig. 3b). Although their climatic vs. tectonic origin remains ambiguous, these terraces can be interpreted as evidence for repeated cut-and-fill cycles in the Cordillera Oriental during the Quaternary (Tchilinguiriani and Pereyra 2001; Hilley and Strecker 2005). Reliable age control is not yet available, but geomorphic evidence and preliminary age estimates date the major lowermost terrace deposits to the last glacial interval (Robinson et al. 2005; Spencer and Robinson 2008). Periglacial activity such as frost creep and cryoplanation might thus be responsible for a climatically-driven increase in sediment supply and the aggradation of the terrace deposits in the Quebrada de Purmamarca. These results suggest a significant temperature-driven depression of the periglacial altitudinal belt during the glacial cycles (May 2008), which corroborates previous estimates of up to ~1200 m (Garleff and Stingl 1985; Abraham de Vazquez et al. 2000). The onset of terrace incision and the evacuation of large quantities of sediment certainly required significantly increased precipitation and discharge amounts. Further age dates are required to test whether the intensification of the tropical circulation and the related increase in austral summer precipitation during the Lateglacial coincided with the observed geomorphic changes.

Loess-paleosol-sequences and tephra layers in Valle de Tafí

Thick accumulations of loess are exposed in Valle de Tafí, Tucumán (Fig. 1) and are generally interpreted as evidence for deflation of dust from the Argentine and Bolivian lowlands during dry climatic intervals (Iriondo 1997). The trapping of aeolian dust in the intramontane basin of Tafí is facilitated by its favourable geomorphic setting at ~2000 m asl. Within the more than 50 m of loess sediment at the Las Carreras site, 32 paleosols have formed and have been interpreted to reflect stable landscapes under wetter paleoenvironmental conditions (Schellenberger 2006; Schellenberger and Veit 2006). In the profile, carbonate leaching and reprecipitation, ped formation, and translocation of clay and organic matter were identified as the main pedogenic processes. However, the boundaries between the individual paleosols are not always clearly defined due to indistinct transitional zones. Based on both pedological and sedimentological characteristics the sequence was subdivided into three units, with paleosols in Units I and III designated as well-developed Luvisols and paleosols in Unit II tentatively classified as (Luvic) Kastanozems with only minor clay illuviation (Fig. 4).

Previous interpretation of the Las Carreras loess deposit was based on radiocarbon dating, and placed the entire sequence in the late Pleistocene resulting in high loess deposition rates (Zinck and Sayago 2001). Using a paleomagnetic approach, a minimum age of 1.15 Ma could be established for the onset of loess deposition in Valle de Tafí, making the Las Carreras sequence one of the longest Quaternary terrestrial paleoenvironmental records available in South America (Schellenberger et al. 2003). OSL ages independently confirmed the antiquity of Tafí loess (Kemp et al. 2003; Kemp et al. 2004).

The pedosedimentary record at Las Carreras has been interpreted to indicate two major shifts in climate modes at ~1.01 Ma and at ~0.72 Ma (Schellenberger 2004). These shifts in the south-eastern Central Andes probably correspond to global climatic changes associated with the mid-Pleistocene transition. The alternation between loess deposition and soil formation in the Tafí loess since the early Pleistocene implies cyclic changes of paleoenvironmental conditions (effective moisture) in the eastern Cordillera, which are ultimately controlled by larger-scale variations of the SASM system. The sequences thereby reveal the first long-term history of South American monsoonal climate and enable a preliminary evaluation of orbital forcing mechanisms.

On much shorter timescales, terrace deposits in Valle de Tafí contain evidence for Holocene climate and environmental changes. Fluvial sedimentation was dominant during the late Pleistocene and early to mid-Holocene pointing to increased sediment supplies and an overall aggrading fluvial system under more arid environmental conditions than today. The onset of terrace incision after ~4 cal ka BP reflects a shift to wetter conditions with enhanced stream flow as reported from different parts throughout subtropical South America (Marchant and Hooghiemstra 2004). Up to three different tephra layers (volcanic ash deposits) are sporadically intercalated with the fluvial sediments and have been integrated to regional-scale tephrochronological studies (Hermanns et al. 2006; Hermanns and Schellenberger 2008) (Fig. 3c). In combination with thorough stratigraphical documentation, tephrochronology has proved to be an important tool for the dating, correlation and interpretation of sedimentary sequences, particularly in dry regions like the Central Andes.

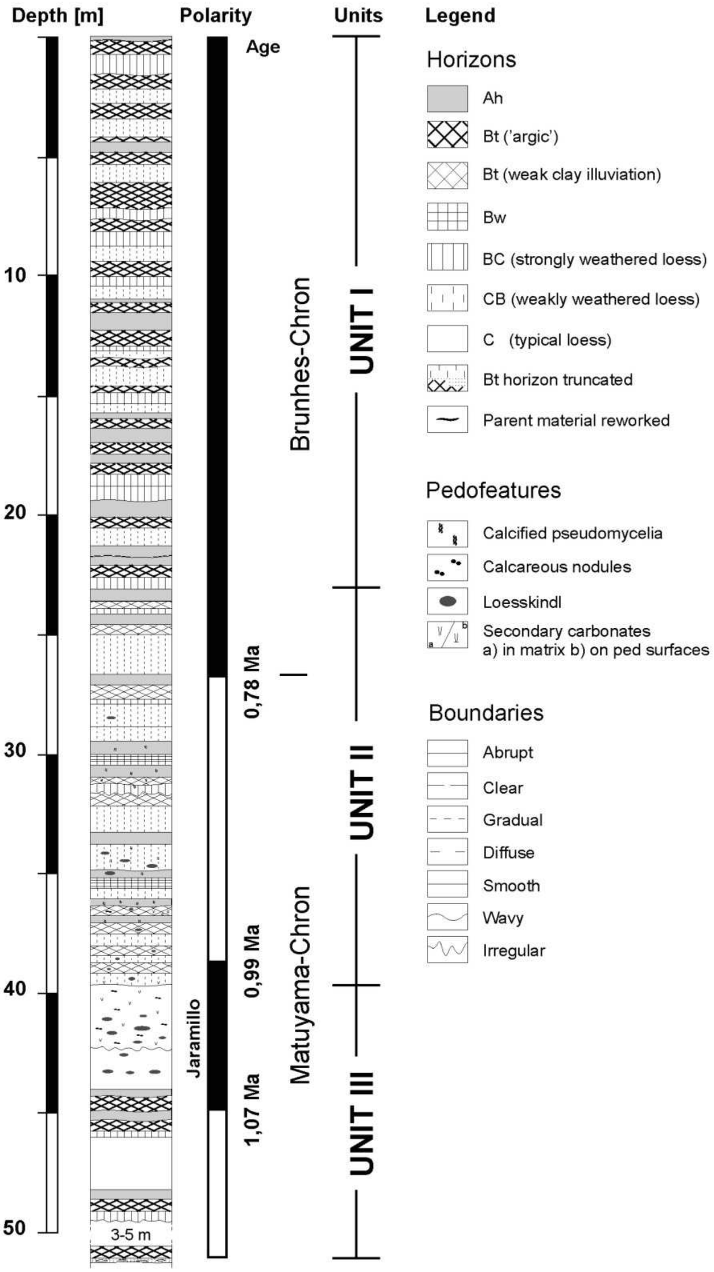

Figure 4. Paleopedology and magnetostratigraphy of the loess-paleosol-sequence at «Las Carreras» in Valle de Tafí, NW Argentina (for details see Schellenberger and Veit 2006).

Paleosol-sediment-sequences along the piedmont

The late Quaternary foreland of the Central Andes in NW Argentina has attracted little attention so far. In order to close this gap, paleosol-sediment-sequences along the incised «Riacho Seco» piedmont stream, first described by Iriondo (1990), have been investigated (May et al. 2007). Documentation and radiocarbon dating of 14 profiles enable the correlation between the individual sites, thereby allowing the establishment of a regional piedmont stratigraphy. In summary, the Riacho Seco sequence consists of fluvial deposits with intercalated paleosols of varying degrees of soil development. Near the base of the sequences, particularly well-developed paleosols reflect a stable landscape before the LGM, probably characterized by dense vegetation cover. Widespread accumulation of sands during and after the LGM points to drier overall conditions. Aggradation alternated with paleosol formation, likely indicating wetter climatic conditions between ~18 and 12 cal ka BP. At the Pleistocene-Holocene transition between ~10.5 and 9.5 cal ka BP, a marked and extensive black paleosol reflects a stable surface. The detailed analysis of soil organic matter points to significantly reduced forest cover during the formation of this paleosol. The onset of the subsequent interval of sedimentation commenced in the early Holocene at ~10 cal ka BP downstream, successively progressing up the piedmont during a dry mid-Holocene. As suggested by the radiocarbon dates, incision – and therefore the end of piedmont deposition at Riacho Seco – started some time after 4 cal ka BP. This incision event probably reflects a large-scale geomorphic and climatic signal (Marchant and Hooghiemstra 2004), but could also be interpreted as the result of local to regional base-level changes.

Northern and Central Chile (~18-35°S)

The Andes in northernmost Chile are characterized by semi-arid to arid conditions. Precipitation shows large inter-annual variability, but generally falls as tropical summer rain due to the seasonal southward shift of the SASM. Towards the Arid Diagonal, which crosses the Andes at ~25°S (Fig. 1), mean annual precipitation drops from ~450 mm/a at 18°S to <100 mm/a at ~25°S (Ammann 1996). South of ~30°S, mean annual precipitation in the Andes and the Chilean piedmont increases again due to the influence of the westerlies. The paleoenvironmental studies presented here focus on i) ^{10}Be SED and derived glacial chronologies, ii) glacier-climate modelling, iii) paleosols along the Chilean piedmont, and iv) lake sediment analyses in Central Chile.

Late Quaternary glaciation

As on the Puna, direct dating control for the late Quaternary glaciation in northern Chile has virtually been absent until the advent of SED (Harrison 2004). Ammann et al. (2001) observed that no glacial deposits exist between ~25° and 27°S in the centre of the Arid Diagonal. It was proposed that the timing of the glacial advances north and south of the Arid Diagonal might have been asynchronous, with the glaciation south of ~27° being influenced by past variations of the westerlies. Application of SED in Valle Encierro at ~29°S, however, suggests that the prominent moraines there were deposited at ~18/16 ka and at ~15/13 ka (Zech et al. 2006; Zech et al. 2008) (Fig. 2b). This roughly coincides with the lateglacial advances and the lake transgression phases on the Bolivian Altiplano, and has therefore been interpreted to reflect the intensification and/or southward shift of the tropical circulation, although today most of the precipitation falls in austral winter and is related to the seasonal northward shift of the westerlies. Evidence for increased summer precipitation from 17-11 ka BP also comes from pollen records in rodent middens at ~25°S (Maldonado et al. 2005), and more humid conditions on the Chilean Altiplano have caused lake level highstands as far south as ~28°S (e.g. Geyh et al. 1999; Grosjean et al. 2001).

Exposure ages from Cordon de Doña Rosa at ~30°S corroborate the lateglacial chronology from Valle Encierro (Zech et al. 2007b; Zech et al. 2008) (Fig. 2b). Additionally, a more extensive earlier glacial advance could be dated to ~42/39 ka. This is much earlier than the global LGM and points to increased precipitation at that time. The likely source of precipitation was the Pacific, related to an intensification and/or northward shift of the westerlies, because evidence for a humid phase disappears further north, but there is more evidence for an 'early local LGM' further south. Preliminary ^{10}Be surface exposure ages from the Valle Rucachoroi in Argentina at ~40°S, for example, show that the local LGM there occurred at 35/35 ka (Fig. 2b), and glacial advances in the Chilean Lake District (~40°S) are radiocarbon-dated to ~35, 31, 28, 25, 18 and 17 cal ka BP, with the earlier advances being more extensive in the northern parts (Lowell et al. 1995; Denton et al. 1999; Heusser 2003). Our interpretation is corroborated by pollen analysis in rodent middens, which indicate increased winter precipitation between ~40 and 33 ka as far north as ~25°S (Maldonado et al. 2005).

In conclusion, glaciation in northern and central Chile was controlled by changes in the tropical monsoonal circulation during the Lateglacial, and the southern westerlies during pre-LGM times, respectively. Climate conditions during the global LGM are inferred to have been too dry to allow for significant glacial advances, although pollen data as well as lake and marine sediments have been interpreted to document a northward shift of the westerlies during the LGM (Heusser 1989; Lamy et al. 1999; Heusser 2003; Stuut and Lamy 2004; Valero-Garcés et al. 2005).

Along the Western Cordillera in northernmost Chile, glacier-climate-modelling was applied in two formerly glaciated test areas, at Choquielimpie at ~18°S and El Tatio at ~22°S (Kull and Grosjean 2000). Glacial morphology and extensive moraines provide evidence for a significant depression of the paleo-ELA down to ~4600-4900 m asl where modern glaciers are absent or restricted to elevations above 5800 m asl (Jenny and Kammer 1996; Klein et al. 1999). The model calculations suggest a massive increase in accumulation (precipitation) of about 900 to 1000 mm at Choquielimpie and El Tatio, but only moderate temperature depressions of 4.4 to 3.2°C compared to present mean annual temperatures. Additionally, the reconstructed glacier geometries show that the increase in precipitation mainly occurred during austral summer. Thus, the late Pleistocene glacial maximum advances in northernmost Chile probably coincided and can be explained with the intensification and southward displacement of the SASM during the Lateglacial.

South of the Arid Diagonal, glacier-climate modelling studies were conducted in the Western Cordillera at Las Palas, Encierro ~29° and Cerro Tapado at ~30°S (Kull et al. 2002). Here, paleo-ELAs were mapped at ~4300 m asl Model results for these sites suggest a much more moderate increase in mean annual precipitation (580 ± 150 mm) than in northernmost Chile, but point to a marked temperature reduction of ~5.7°C. This difference compared to north of the Arid Diagonal points to a different timing of the modelled glacier advances within an overall wet Lateglacial.

Paleosols along the Chilean piedmont

Well-developed soils, mainly Chromic to Calcic Luvisols, are widespread along the Chilean piedmont (Fig. 3d). At elevations below 2000-3000 m asl, they have a relatively sharp northern limit at 27°S. North of the Río Copiapó, conditions have been too dry for advanced soil development. At high elevations in the Andes there is a mixed influence of rainfall from the westerlies and easterly summer rains, allowing for Luvisols to occur mainly above 3000 m asl and further north. The soil types itself (Luvisols) and frequently existing cover sediments clearly indicate that at least the Luvisols of the semi-arid Norte Chico (33°-27°S) are relict soils, reflecting more humid conditions during past periods (Veit 1996).

Age estimations of the soils have been realized by ^{14}C-dating of the corresponding carbonate crusts (calcretes or petrocalcic horizons) and luminescence dating (OSL) of overlying and underlying eolian sands. Both physically independent methods indicate that soil formation occurred prior to 27 ka, most probably between 44-27 cal ka BP. After that, climatic conditions at the piedmont never again reached the pre-LGM level of humidity and soil development. Cambisols, Regosols and Arenosols reflect the modern semi-arid conditions, instead. The amount of rainfall cannot be deduced exactly from the soil data, but given the existence of petrocalcic horizons, conditions were still arid, as indicated by high d^{13}C and d^{18}O values. As an estimate, rainfall might have increased to around 500 mm/a, reflecting more or less the modern conditions at 35°S, but resulting in a more than tenfold increase in the northern parts of Norte Chico.

In the coastal dunes of Norte Chico an even older period of increased humidity is reflected in a well-developed fossil B_t-horizon, appearing frequently some meters beneath the mentioned pre-LGM Luvisol (Veit 1996). Preliminary OSL-ages of the different dune generations indicate soil development between 80-70 ka. These periods with increased influence of the westerlies roughly coincide with reconstructions based on marine cores off the Chilean coast (e.g. Lamy et al. 1999; Stuut and Lamy 2004), probably pointing to precessional influence on the humidity in Norte Chico.

Lakes in Central Chile

Like soils, lakes in the Chilean Central Valley are sensitive to humidity changes in the westerlies. The late Quaternary sedimentological, geochemical and palynological records of Laguna Aculeo (33°50'S; 350 m asl) and Laguna Tagua Tagua (34°30' S; 200 m asl) were studied (Jenny et al. 2002a; Jenny et al. 2002b; Jenny et al.

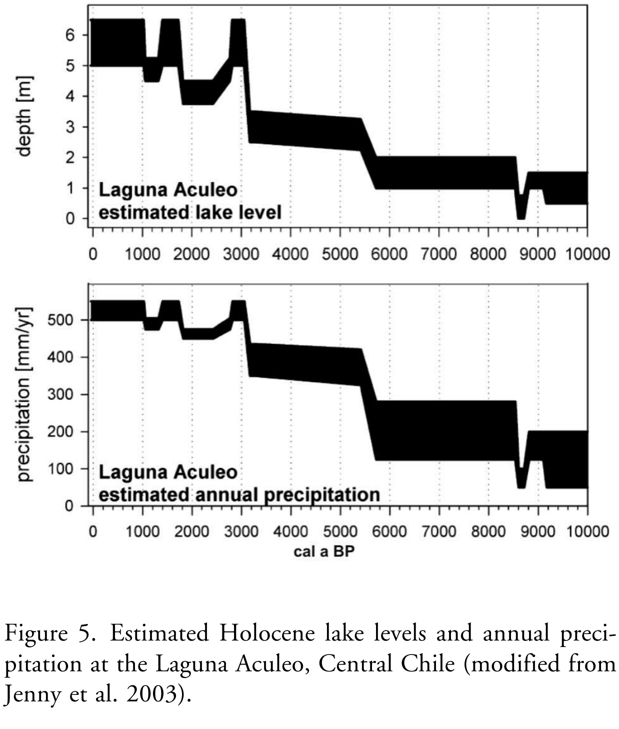

Figure 5. Estimated Holocene lake levels and annual precipitation at the Laguna Aculeo, Central Chile (modified from Jenny et al. 2003).

2003; Villa-Martinez et al. 2004; Valero-Garcés et al. 2005).

Laguna Aculeo is one of the largest natural lakes in the lowlands of central Chile. Average annual precipitation at Laguna Aculeo is 545 mm/a (72-yr average) but may reach >1000 mm/a during El Niño events, falling mostly during austral winter. The cores cover the entire Holocene (Fig. 5). Results indicate an arid early to mid-Holocene period (about 9.5-5.7 cal ka BP). After 5.7 cal ka BP effective moisture increased progressively and, around 3.2 cal ka BP, modern humid conditions were established. During the early and mid-Holocene, the westerlies were probably blocked and hence deflected southward by the subtropical high-pressure cell. Based on a simple water balance model, lake level changes have been simulated and hence precipitation estimated (Fig. 5). The results suggest that during the beginning of the Holocene, when the lake level (<1.5 m) was low, precipitation averaged <200 mm/a. Before 8 cal ka BP, the lake frequently dried out. Between 8 and 6 cal ka BP, precipitation appeared to be higher (150-300 mm/a) and after about 6 cal ka BP, precipitation increased dramatically (350-450 mm/a). Around 3 cal ka BP, modern lake level and precipitation (450-550 mm/a) were generally established, indicating a weakened subtropical high-pressure cell with intensified westerlies.

Laguna Tagua Tagua is dry today and has been drained for agricultural purposes since the 19th century. Prior to that, natural scientists like Darwin described the original lake with a surface area of about 30 km^2 and a maximum depth of 5 m. The modern annual precipitation is about 800 mm/a. The analysis of a core, which covers the last > 46 ka, revealed that relatively humid conditions occurred during glacial times before 43.5 cal ka BP and from 40 to 21.5 cal ka BP. Reduced moisture conditions and likely lower temperatures occurred from 42.4 to 40.1 cal ka BP. Higher lake levels, and pollen assemblages with Valdivian rainforest taxa, imply much higher precipitation during glacial times (40.1 to 21 cal ka BP) compared to today and, therefore, enhanced westerly activity in northern Central Chile. Afterwards, the general decrease in moisture was punctuated by two abrupt arid periods at 21 to 19.5 cal ka BP and 17 to 15 cal ka BP, and two more humid intervals from 19.5 to 17 cal ka BP, and from 13.5 to 11.5 cal ka BP.

SYNTHESIS AND CONCLUSIONS

The presented results from two decades of paleoenvironmental research in Bolivia, Argentina and Chile have shown to provide manifold evidence for a very dynamic Quaternary climate and environmental history in the Central Andes and their forelands. The multidisciplinary investigation of various archives has provided new data on various timescales ranging from several hundreds to more than a million of years.

The detailed analysis of paleosols as well as glacial, fluvial-alluvial, aeolian and lacustrine sediments has revealed marked spatial and temporal variations in humidity and/or temperature conditions. Changes in temperature, as can be inferred from glacial and periglacial archives, are in-phase and in agreement with the global LGM. Precipitation changes were deduced from several sedimentological and paleopedological archives and document major shifts in latitudinal position and/or intensity of the monsoonal circulation and the mid-latitude westerlies during the Quaternary.

Despite some remaining discrepancies and uncertainties, our results are an important contribution to ongoing discussions regarding the timing of past climate changes, their driving forces, and their environmental impact on different spatial scales. Particularly our results from glacial archives and paleosol-sediment-sequences point to insolation forcing as the primary control for regional variations in the atmospheric circulation patterns on longer, orbital timescales. Ongoing cooperation and research aims at complementing and refining these results by integrating further regional studies throughout the Central Andes focussing on the investigation of new archives and proxies as well as on the improvement of age control.

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