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Late Miocene climate variability and surface elevation in the central Andes

Andreas Mulch [a,*], Cornelius E. Uba [b], Manfred R. Strecker [b], R. Schoenberg [c,d], C. Page Chamberlain [e]

[a] Institut für Geologie, Leibniz Universität Hannover, 30167 Hannover, Germany
[b] Institut für Geowissenschaften, Universität Potsdam, 14476 Potsdam, Germany
[c] Institut für Mineralogie, Leibniz Universität Hannover, 30167 Hannover, Germany
[d] Centre for Geobiology and Department of Earth Science, University of Bergen, 5007 Bergen, Norway
[e] Earth and Environmental Systems Science, Stanford University, Stanford, CA 94305, USA

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ABSTRACT

Temporal and spatial variations in topography and oxygen stable isotope ratios in precipitation in the central Andes have stimulated widespread discussion about the competing roles of mantle and crustal processes and their feedbacks with global-scale climatic change in uplifting and shaping the central Andes. In general, one of the major obstacles in assessing the relative contributions of long-term (10^5–10^6a) tectonic processes and precipitation (as a proxy for climate) to the uplift history of the Andean orogen is the lack of integrated data sets that record late Miocene patterns of uplift and climate. Radiogenic ($^{87}Sr/^{86}Sr$), sedimentologic, and stable isotope ($\delta^{18}O$) data from Subandean foreland deposits of the Chaco Basin (Bolivia) show a rapid (<200 ka) transition towards higher $\delta^{18}O$ and $^{87}Sr/^{86}Sr$ values at ~8.5 Ma that we interpret to reflect a change in precipitation patterns along the Eastern Cordillera and the Subandean fold-thrust belt. In agreement with $\delta^{13}C$ studies on paleosol carbonates we attribute this change to a southward deflection of the South American low-level jet (LLJ) that currently exerts the dominant control over the seasonality and amount of precipitation along the Eastern flanks of the Andes. Deflection of the LLJ occurred most likely as the combined effects of readjustment of relief and topography within the Eastern Cordillera at 20–22°S and possibly associated surface uplift of the Altiplano. Contemporaneous rapid positive shifts in $\delta^{18}O$ and $^{87}Sr/^{86}Sr$ of pedogenic carbonate in fluvial foreland deposits are consistent with a transition to more seasonal precipitation conditions and critical threshold elevations being attained that affected South American atmospheric circulation patterns. A four-fold increase in sedimentation rates in the foreland together with a shift to strongly radiogenic $^{87}Sr/^{86}Sr$ ratios in paleo-river water and sediment load as well as river incision into the well preserved San Juán del Oro paleo-surface directly reflects a rapid change in moisture distribution along the eastern flank of the central Andes at ~8.5 Ma and associated rearrangement of the drainage systems. Collectively, the data presented here strongly suggest that between 12 and 8 Ma the amount, oxygen isotopic composition, spatial distribution and seasonality of precipitation along the eastern flank of the Bolivian Andes changed dramatically which in turn require changes in trans-Andean moisture flux and isotopic composition of precipitation on the uplifting plateau region.

1. Introduction

The pursuit of paleoaltimetry data from the world's highest plateau regions is generally motivated by the desire to quantify the internal density structure of orogens and the resulting driving forces of orogenic processes. Furthermore, surface elevation histories are key elements of lithospheric-scale tectonic models that aim at integrating tectonic and atmospheric processes including the feedbacks of erosion, weathering and uplift of the Earth's surface. Stable isotope paleoaltimetry exploits systematic correlations between the oxygen ($\delta^{18}O$) and hydrogen (δD) isotopic compositions of meteoric water and elevation and hence represents a tool to elucidate coupled climatic and topographic changes during uplift of mountain ranges (e.g. Chamberlain et al., 1999; Mulch et al., 2006; Rowley and Garzione, 2007). As such, changes in the isotopic ($\delta^{18}O$ and δD) fingerprints of paleo-meteoric waters as deduced from authigenic, pedogenic or recrystallized minerals, ultimately permit the reconstruction of elevation histories. The main difficulty in understanding the individual roles of global and regional precipitation (climate) change and mountain building, however, is the lack of detailed surface uplift histories (e.g. Molnar and England, 1990).

Stable isotope paleoaltimetry bears enormous potential to unravel some of the most prominent research challenges in the Andes by documenting the combined effects of precipitation and elevation change in terrestrial stable isotopic archives (e.g. Chamberlain et al., 1999; Garzione et al., 2006; Mulch et al., 2006; Mulch and Chamberlain, 2007; Garzione et al., 2008; Mulch et al., 2008). Simple comparisons between reconstructed meteoric water compositions based on isotopic proxy materials and data for modern meteoric waters, however,

* Corresponding author. Tel.: +49 511 762 2170; fax: +49 511 762 2172.
E-mail address: mulch@geowi.uni-hannover.de (A. Mulch).

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frequently suffer from poorly constrained assumptions concerning e.g. long-term changes in Earth's climate and atmospheric circulation patterns, corrections for decreased ice volume at the poles or differences in the magnitude of monsoonal precipitation patterns surrounding large plateau regions. Quantitative stable isotope paleoaltimetry, therefore, requires low-elevation stable isotope records that provide a 'bench-mark" against which changes in the oxygen and hydrogen isotopic composition of meteoric water at high elevations can be tested (Garzione et al., 2000; Mulch et al., 2006; Rowley and Currie, 2006; Mulch et al., 2007). Low-elevation records of regional climate and elevation change are key parameters for the interpretation of stable isotope data acquired within highly elevated (and commonly dry) continental plateau regions (e.g. Quade et al., 2007), because these records may constrain the primary moisture flux into the orogen, the extent of moisture recycling during transport, the effects of secular changes in mean annual temperature and their effect on precipitation patterns prior to orographic uplift, and ultimately the isotopic composition of precipitation at or near sea level. This is of particular concern at the flanks of orogenic plateaus such as Tibet or the Puna–Altiplano where regional (and global) atmospheric circulation patterns are influenced by the creation of orographic barriers (e.g. Roe, 2005; Takahashi and Battisti, 2007).

At present, the Andean orogen has profound implications on South American climate zonation (Strecker et al., 2007a), precipitation regimes (e.g. Garreaud et al., 2003; Vera et al., 2006, Bookhagen and Strecker, 2008; Insel et al., 2009), and the position of the ITCZ during the austral summer over the Amazon basin (e.g. Lenters and Cook, 1997) as well as within the western Pacific (enhanced coastal upwelling and strengthening of the Pacific anticyclone; e.g. Takahashi and Battisti, 2007). Takahashi and Battisti (2007) present results of coupled atmosphere–ocean models that indicate that the complex pattern of water upwelling, lowered sea surface temperatures and a northward shift of the Pacific ITCZ are modulated by the modern Andean topography. In these models the pronounced meridional extent of the Andes induces a southern hemisphere climate perturbation that affects the northern hemisphere heat and moisture transport by a magnitude too large to be offset by the competing effects of highly elevated land surface of the North American Cordillera and the Tibetan Plateau. It is therefore important to reconstruct not only the vertical growth of the Andean chain and the Altiplano, but also the temporal and spatial patterns of topography development along the orogen and its impact on atmospheric circulation patterns (Ehlers and Poulsen, 2009; Insel et al., 2009). It is at this point where stable isotope records of foreland basins become important archives of the coupled effects of surface uplift and associated changes in moisture flux and precipitation patterns. In view of competing (stable isotope based) models that describe the Late Miocene surface uplift history of Bolivian Altiplano (e.g. Garzione et al., 2006; Sempere et al., 2006; Garzione et al., 2008; Ehlers and Poulsen, 2009) we consider it necessary to document upstream conditions of precipitation to arrive at a better understanding of trans-Andean moisture flux during critical time intervals of Andean orogeny and surface uplift.

Here we present oxygen, carbon, and strontium isotope data from late Miocene pedogenic carbonate in fluvio-lacustrine deposits collected in the Bolivian Subandes fold-and-thrust belt along the paleo-Rio Pilcomayo (Fig. 1). The combined isotopic and sedimentological data indicate that at ~8.5 Ma regional climate and precipitation patterns at 21°S latitude changed to a more seasonal or cyclic moisture flux into the orogen, most likely as the result of buildup of topography and high surface elevations in the Eastern Cordillera and Bolivian Altiplano and related southward deflection of the South American low-level jet (LLJ). Even though the combined isotopic, geochronological, and sedimentological data (as in any other developing mountain range) cannot uniquely quantify the competing effects of surface uplift and regional and global climate change, we suggest a scenario that involves changes in moisture flux into the Andean orogen. These changes were amplified by the development of increased relief along the Eastern Cordillera

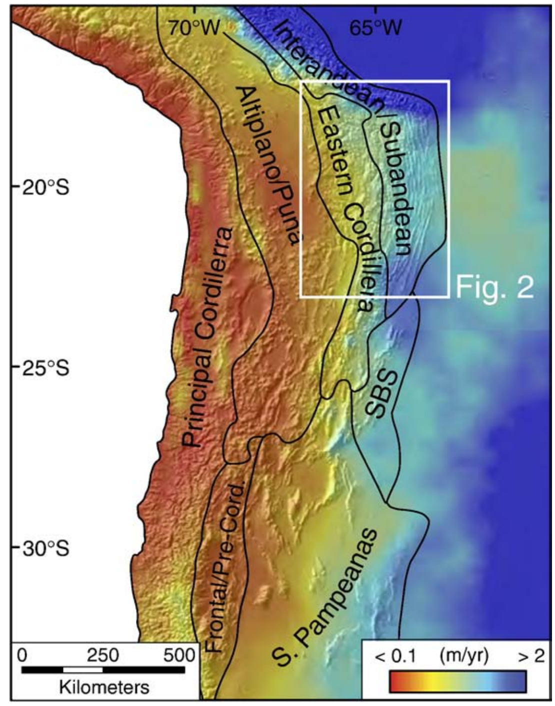

Fig. 1. Shaded relief map with principal morphotectonic provinces, and present-day rainfall patterns of the southern central Andes. Mean annual rainfall distribution derived from Tropical Rainfall Measurement Mission satellite data (TRMM) following methods in Bookhagen and Burbank (2006). SBS, Santa Barbara System; S. Pampeanas, Sierras Pampeanas; Frontal/Pre-Cord., Frontal and Precordillera. Square outlines study area shown in Fig. 2.

(Fig. 2) and created a new spatial and temporal configuration of precipitation within and along the Eastern Cordillera and the Subandes. Such rearrangements along the eastward flanks of the Andean orogen necessitate changes in trans-Andean moisture flux and hence contribute to the oxygen and hydrogen isotope composition of precipitation within the plateau interior.

2. Stable isotope paleoaltimetry and models of Andean surface uplift

Stable isotope paleoaltimetry of the Bolivian Altiplano (Garzione et al., 2006; Ghosh et al., 2006; Quade et al., 2007; Garzione et al., 2008; see also Hartley et al., 2007) has provided a new set of boundary conditions to tectonic models that describe the interaction of lithospheric and mantle processes and their surface response. Here we provide a high-resolution long-term stable isotopic ($\delta^{18}O$) record of pedogenic carbonate from the low-elevation (~600 masl) Chaco foreland basin of the Bolivian Subandean Zone that covers the critical time interval (12 to 6 Ma) of late Miocene climate change and postulated surface uplift (e.g., Garzione et al., 2006, 2008) of the northern Bolivian Altiplano. There is general consensus that the central part of the Andean chain (and Altiplano) underwent major changes in relief and surface elevation during the late Miocene (e.g. Allmendinger et al., 1997; Coutand et al., 2006; Deeken et al., 2006; Barke and Lamb, 2006; Thouret et al., 2007; Garzione et al., 2006, 2008). However, the driving mechanisms for the rise in surface elevation remain intensely debated. These debates center on surface uplift and the timing and rates at which current elevations were attained. Whereas one view holds that rapid late Miocene uplift of the plateau occurred in response to removal of lithospheric mantle material (e.g., Garzione et al., 2006; Ghosh et al., 2006; Molnar and Garzione, 2007; Garzione et al., 2008), others call for a protracted uplift history that may be controlled by the combined effects of crustal shortening, lower and middle crustal flow, and temporally variable boundary forces at the subducting plate margin (e.g. Lamb and

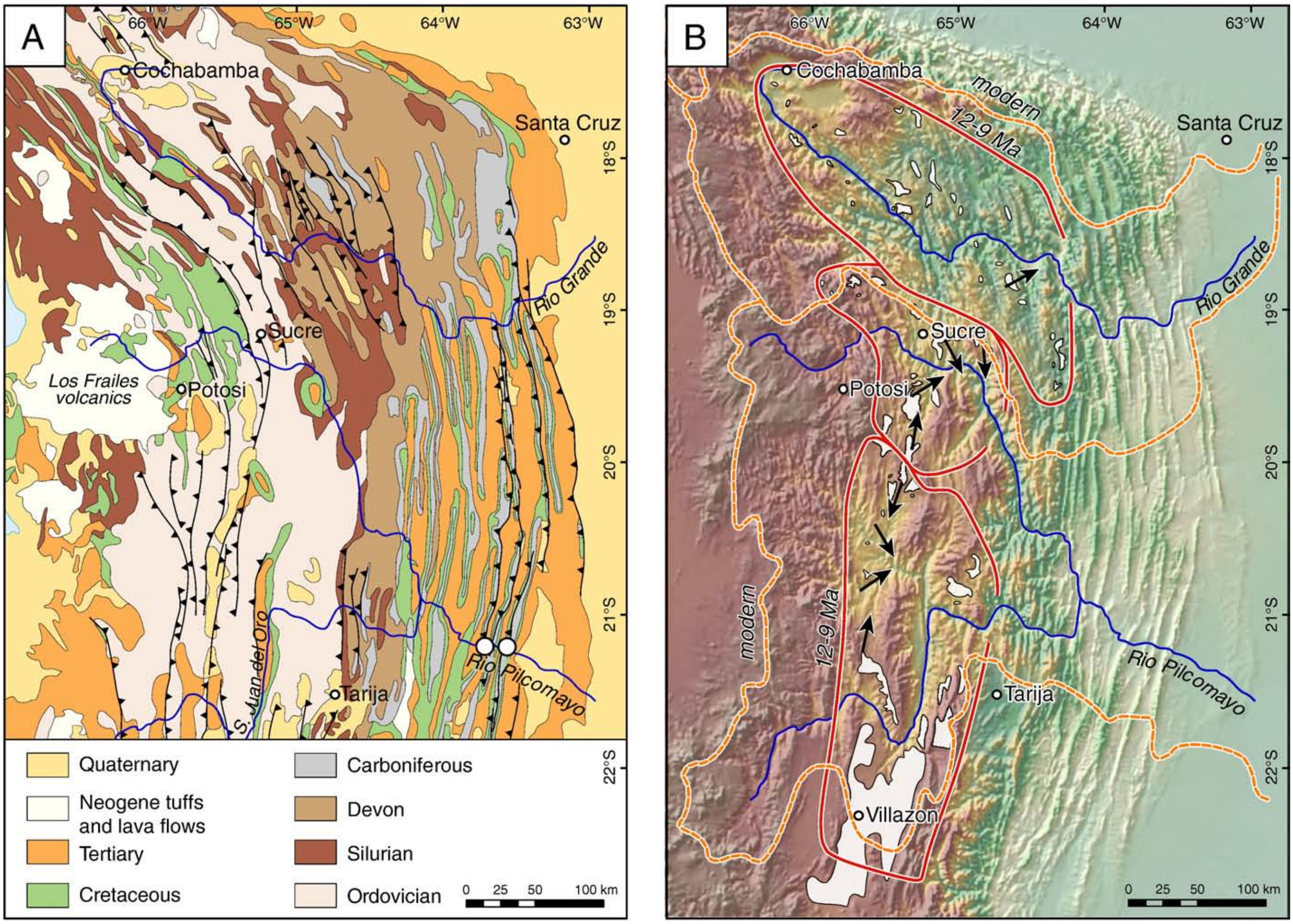

Fig. 2. A.) Simplified geological map of the south central Andes of Bolivia showing measured sections and sampling locations at Puesto Salvacion and Angosto de Pilcomayo (circles). B.) Shaded relief map of the study area showing modern (orange) and late Miocene (red) (paleo-)drainage systems in the Eastern Cordillera and Subandes. Modern catchments of Rio Pilcomayo and San Juan del Oro (Barnes and Pelletier, 2006) largely coincide with Late Miocene (12–9 Ma) paleocurrents (arrows) and paleodrainage systems (Barke and Lamb, 2006) but extend much farther west most likely as a result of progressive headward erosion. Westward widening of the catchment shortly after ~9 Ma is consistent with changes in sedimentation rates and sediment provenance (see below). Filled surfaces represent 12–9 Ma high-elevation San Juan del Oro pediment surfaces.

Davis, 2003; Barke and Lamb, 2006; Hartley et al., 2007). Particular attention with respect to the erosion, exhumation, sedimentation, and uplift history of the Altiplano needs to be paid to the timing of surface uplift, river incision and sediment evacuation of the plateau-bounding ranges to the East and West of the (now) internally drained plateau region. Thermochronological data indicate that the Subandes experienced at least two pulses of eastward propagation of deformation that may reflect the readjustment of critical taper of the Andean wedge (Barnes et al., 2008; McQuarrie et al., 2008). Most relevant for this study is the partitioning of upper crustal strain from the plateau interior (prior to 10–8 Ma) into the Subandes (Isacks, 1988; Gubbels et al., 1993) and the contemporaneous onset of exhumation in the Subandes at ~8 Ma (Ege et al., 2007). The late Miocene (12–8 Ma) is therefore undoubtedly a time interval of major tectonic activity within the Eastern Cordillera.

On an even larger scale, strong positive feedbacks between East–West moisture flux across the Andes and sediment supply to the trench-subduction zone system have been postulated that are controlled by the height and topographic structure of the Andean orographic barrier. Such feedbacks are considered first-order drivers of Andean shortening and surface uplift by effectively modifying the stress balance within the accretionary wedge and subduction system (Lamb and Davis, 2003). If such feedbacks exist, reconstructions of the precipitation, climate, and uplift dynamics along the Eastern Cordillera and Bolivian Subandes therefore, not only add to refine stable isotope estimates of surface elevation within the plateau, but provide key information on trans-Andean (E–W) moisture flux and ultimately Andean geodynamics.

3. Sedimentologic and climatic history of the Chaco foreland basin

Situated in the Subandean Zone of south-eastern Bolivia, the Chaco foreland basin (Uba et al., 2005) is bound to the west by the frontal thrusts of the Andes (Sempere et al., 1990) and to the east by the Brazilian Shield. The Chaco basin developed in response to far field stresses of subduction of the Nazca plate beneath South America and simultaneous underthrusting of the Brazilian Shield. Together, these processes led to widespread Oligocene shortening in the Eastern Cordillera and subsequent folding and eastward migration of the active thrust front into the Interandean and Subandean Zones (Baby et al., 1992; Gubbels et al., 1993, Kley, 1996; Horton, 1998; Uba et al., 2006; Ege et al., 2007; Barnes et al, 2008; Uba et al., 2009a). The eastward advance of crustal shortening controls the cratonward younging and migration of depozones in the Andean foreland (DeCelles and Horton, 2003; Echavarria et al., 2003; Uba et al., 2006) with onset of sediment accumulation in the Chaco basin during the late Oligocene (Marshall et al., 1993; Uba et al., 2005, 2006). It has previously been postulated that the deformation front arrived in the Chaco foreland basin at 10 Ma ago (Gubbels et al., 1993; Moretti et al., 1996; Echavarria et al., 2003). Recently, however, Uba et al. (2007, 2009a) presented a revised chronology that dates the onset of deformation in the Subandean

Fig. 3. Pedogenic carbonate (nodules and rhizoconcretions) in late Miocene Yecua formation sandstones and mudstones (Puesto Salvacion section).

Zone to as early as 12.4 m.y. before present. Deformation within the Subandes is characterized by, thin-skinned thrusting, including ramp anticlines, passive roof duplexes (Baby et al., 1992; Dunn et al., 1995; Kley et al., 1996), and blind thrusts (Horton and DeCelles, 1997; Uba et al., 2006).

3.1. Stratigraphy, basin history, and timing of deposition

The base of the Cenozoic sedimentary units in the Subandes is defined by the 250-m-thick 26–12.6 Ma Petaca Formation. This formation consists of paleosols that formed from reworked fluvial conglomerates, sandstones, and subordinate mudstones (Uba et al., 2005). The Petaca Formation is overlain by the ~500-m-thick late Miocene Yecua Formation. Deposition of the lacustrine-fluvial mudstones and calcareous sandstones and formation of numerous paleosols of this unit (Fig. 3) (Uba et al., 2005, 2006) started approximately at 12.5 Ma (Uba et al., 2007) based on U–Pb ages of zircons in a silicic basal tuff. The Yecua Formation is overlain by up to 3000 m of fluvial sandstone- and mudstone of the Tariquia Formation. A volcanic ash at the base of the Tariquia Formation with an age of 7.93 Ma (U–Pb, zircon), thus constrains the oldest depositional age of the Tariquia Formation to ~8.5 Ma (Uba et al., 2007). The Tariquia Formation transitions into the up to 1600-m-thick Guandacay Formation. This unit is 5.94 to 2.1 m.y. old and consists of sandstone, conglomerate, and subordinate mudstone deposited in a medial fluvial megafan environment (Uba et al., 2005, 2006). It is superseded by the more than 1500-m-thick 2.1 Ma-to-recent Emborozú Formation. The latter is composed dominantly of conglomerate and sandstones deposited in a proximal fluvial megafan environment (Uba et al., 2005).

Up to 7.5 km of late Cenozoic sediment was deposited in the deepest (western) part of the Chaco basin, which constitutes the Subandean fold-and-thrust belt (Uba et al., 2005), while sediment thickness decreases progressively eastward (Uba et al., 2006). Thrust-front propagation, creation of accommodation space, and sediment supply were highly variable through time but sediment accumulation rates and the eastward growth of depositional pinch-outs peaked during the late Miocene (Coudert et al., 1995; Echavarria et al., 2003; Uba et al., 2009a).

Recently, Uba et al. (2007, 2009a) documented a four-fold increase in accumulation rates from 130 to 628 meters per million years (m/m.y.) between 12–8 Ma and 8–6 Ma, respectively, which they attributed to climatic forcing. The increased sedimentation rate between 8 and 6 Ma does not match increased shortening rates, but it correlates with the timing of inferred climate change in the Chaco basin (Strecker et al., 2007a; Uba et al., 2009a) and changes in the sediment source (Hulka et al., 2010). Additionally, the Chaco basin experienced expansion of river systems from small, sinuous fluvial systems to fluvial megafans at ~8 Ma (Uba et al., 2005). This interpretation of climate-induced high accumulation rates is further supported by structural and thermochronologic

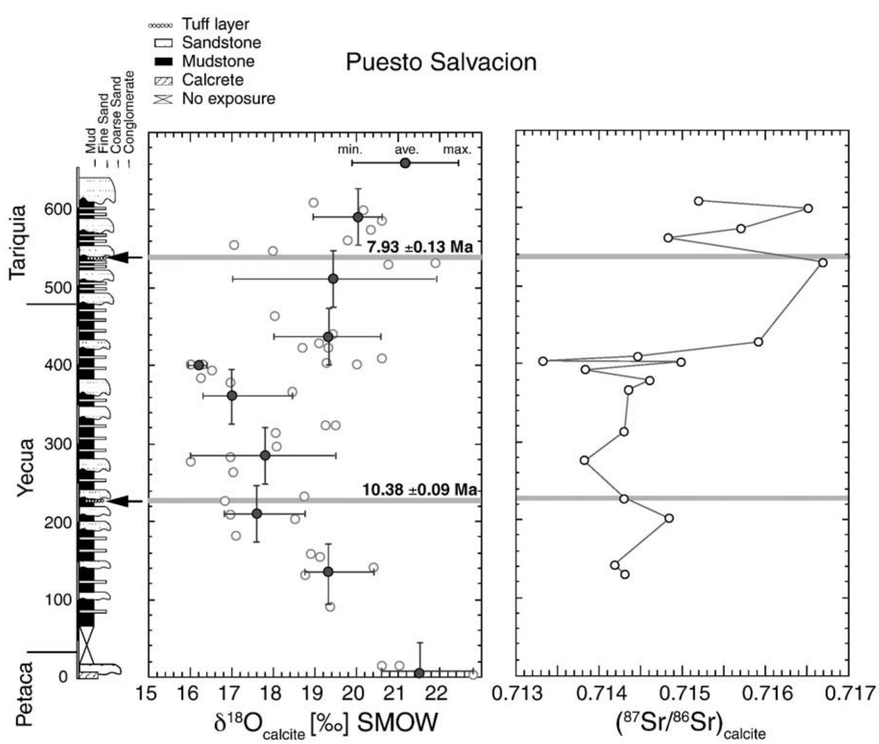

Fig. 4. Oxygen and strontium isotope data of pedogenic carbonate in the Puesto Salvacion section plotted by stratigraphic position. Age and position of dated tuff samples shown by black arrows and grey horizontal markers (after Uba et al., 2007). Open symbols represent measured $\delta^{18}O$ data; solid symbols represent binned averages. $\delta^{18}O$ values show a continuous decrease followed by a rapid increase at ~8.5 Ma. There is a contemporaneous shift to more radiogenic $^{87}Sr/^{86}Sr$ compositions indicating that the oxygen and carbon isotope shifts are accompanied by a change in sediment provenance.

studies, which show that the adjacent Eastern Cordillera and Interandean belt were tectonically inactive at that time (Ege, 2004; Ege et al., 2007; Barke and Lamb, 2006). Prior to the late Miocene increase in accumulation rate, the basin underwent rapid accommodation space creation (Uba et al., 2006, 2007). The space was then filled during the deposition of Tariquia Formation (8–6 Ma) probably as a result of increased denudation and deposition of Andean-derived clastics in the medial foredeep of the basin (Uba et al., 2005, 2006).

U–Pb SHRIMP ages from samples of six reworked tuffs intercalated in the Yecua, Tariquia and Guandacay formations robustly constrain the age of the different sedimentary units (Uba et al., 2007) and permit a correlation with stable isotopic records of similar age on the Altiplano (Garzione et al., 2006; Quade et al., 2007). The U–Pb data indicate ages of 12.4 ± 0.5 Ma, 7.93 ± 0.26 Ma, and 5.94 ± 0.20 Ma for the onset of deposition of the Yecua, Tariquia, and Guandacay formations in the Puesta Salvacion and Angosto de Pilcomayo sections, respectively (Uba et al., 2007). Based on these U–Pb ages and correlation of lithofacies we compare $\delta^{18}O$ records from two up to 1300 m long sections of fluvial deposits located within and adjacent to the course of the Rio Pilcomayo in the Subandean belt. Pedogenic carbonate nodules, rhizoliths and carbonate cemented sand- and siltstones for stable isotope measurements were collected systematically in the dated sections.

4. Results

4.1. Oxygen and strontium isotopic data of paleosol carbonate from the Rio Pilcomayo Valley

The oxygen isotope record from pedogenic carbonate of Rio Pilcomayo at the Puesto Salvacion (Fig. 4) and Angosto de Pilcomayo (Fig. 5) sampling sites shows two first-order trends in the $\delta^{18}O$ data. The time interval between 12 and 8 Ma is best represented by the Puesto Salvacion section. First, between ~12.5 Ma (onset of deposition of Yecua Formation) and ~9.0 Ma the $\delta^{18}O$ values of paleosol carbonate decrease by ~5‰ (Fig. 4). During the same time interval (0–380 m of section) $^{87}Sr/^{86}Sr$ values of pedogenic carbonate

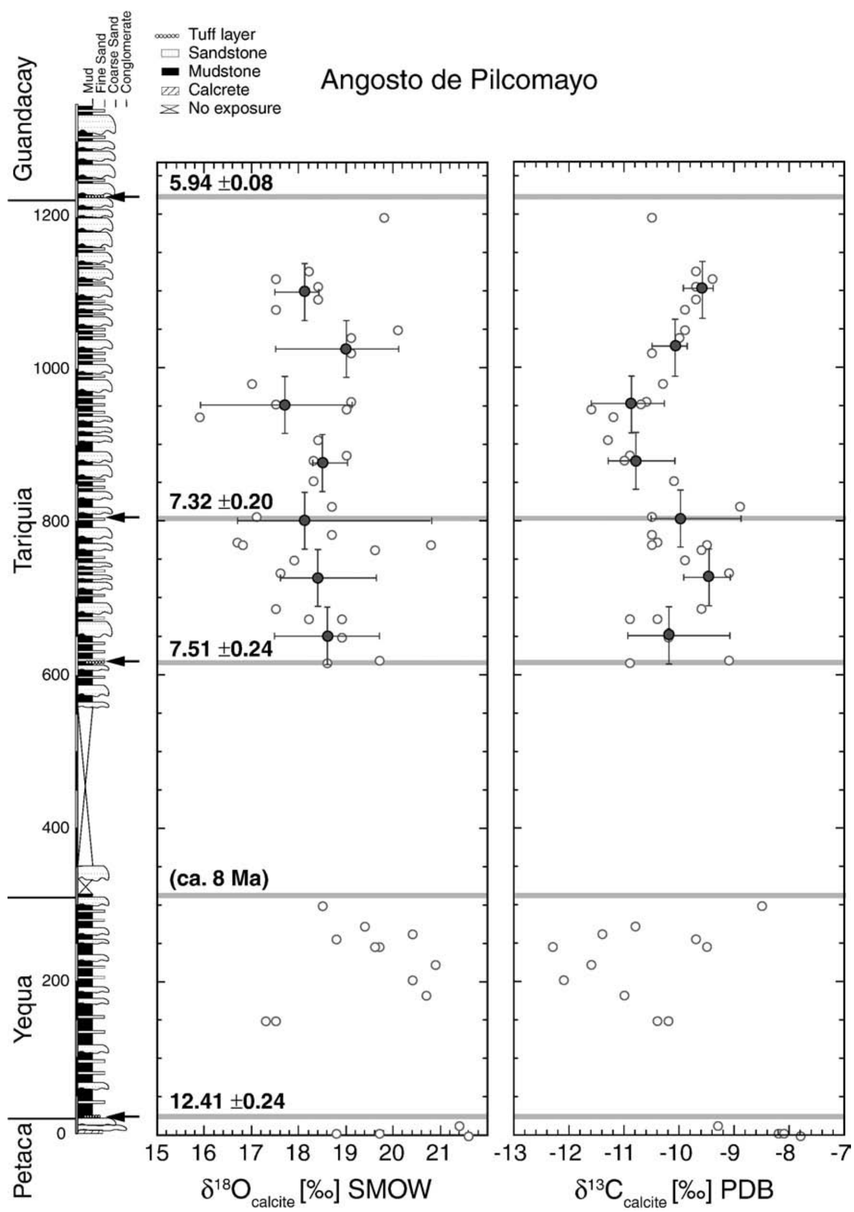

Fig. 5. Oxygen isotope data of pedogenic carbonate in the Angosto de Pilcomayo section plotted by stratigraphic position. Age and position of dated tuff samples (after Uba et al., 2007) shown by black arrows and grey horizontal markers. The Angosto de Pilcomayo section extends the Puesto Salvacion section (Fig. 4) to younger ages of ~6 Ma. The pre-8.5 Ma history is less well expressed, however, the $\delta^{18}O$ data are comparable to the Puesto Salvacion section (Fig. 4). $\delta^{18}O$ of pedogenic carbonate shows no discernable trends after 7.51 Ma but is characterized by a large variability indicating increased variability in the amount and seasonality of precipitation.

remain relatively constant at 0.71433 ± 0.00028. Second, there is a short time interval between ~9 and 8 Ma where $\delta^{18}O$ and $^{87}Sr/^{86}Sr$ values of paleosol carbonate attain minimum values (390–410 m of section), yet with a higher variability compared to the lower part of the Yecua section. Following this negative excursion, $\delta^{18}O$ values abruptly increase, maintaining that greater variability compared to the lower part of the Yecua Formation. At the same time $^{87}Sr/^{86}Sr$ isotope ratios of paleosol carbonate become more radiogenic (0.71580 ± 0.00066), suggesting a change in the sediment source.

Even though our sampling density (and geochronological constraints) for the Angosto de Pilcomayo section within the 12–8 Ma time interval is not sufficiently precise to further validate these trends, available data are consistent with the $\delta^{18}O$ pattern in the Puesto Salvacíon section (Fig. 5). The Angosto de Pilcomayo paleosol carbonate data, however extend our stable isotope record from 7.51 Ma to ages as young as ~6 Ma (Fig. 5) lacking any obvious temporal trends in $\delta^{18}O$, yet again with relatively high $\delta^{18}O$ values and large sample-to-sample variability.

5. Discussion

5.1. Oxygen isotope records of late Miocene Subandean paleosoils

We interpret the oxygen and strontium isotopic profiles presented in this paper to reflect major shifts in rainfall patterns within and along the Eastern Cordillera and Interandean Zone of southern Bolivia during the late Miocene (12–8 Ma). The two first-order trends in our isotopic data record the combined effects of precipitation change as well as a topographic readjustment of the evolving Eastern Cordillera and Altiplano. Although there are other factors, most notably mean annual temperature (MAT) and diagenesis that can affect oxygen isotope values, it is unlikely that these significantly influence the trends shown in Figs. 4 and 5. For example, the systematic oxygen isotope variations are far too large to be the effect of changes in MAT as $\delta^{18}O$ values in carbonate change by only ~0.35‰/°C based on calcite–water oxygen isotope exchange experiments (Kim and O'Neil, 1997) and the correlation between oxygen isotopes in precipitation and temperature from Rozanski et al. (1993). In addition, we observe no evidence of diagenesis in these samples, such as calcite veining or sparry calcite.

As such, we interpret the decrease in $\delta^{18}O$ values in the Puesto Salvacion section (Fig. 4) from 19.4‰ (92 m) to 16.0‰ (402 m) between ~12 Ma and ~8.5 Ma to be the result of increased low $\delta^{18}O$ precipitation due to higher degrees of rainout along growing topography in the Eastern Cordillera. A simultaneous decrease in carbon isotope values further suggests that during this time local C3 plant communities adapted to decreasing water stress, and/or more biologically productive soils (Strecker et al., 2007a,b). The 9–8 Ma (380 to 425 m) transition in the Puesto Salvacion section is characterized by the most negative and most variable $\delta^{18}O$ (16.0 to 20.6‰) values. Similar variability can be observed in the carbonate Ca/Mg ratios and Sr concentrations [Sr] (Fig. 6). In analogy with carbonate compositions in lacustrine settings we assume that the elemental composition (e.g. Ca/Mg) of pedogenic carbonate reflects both, cation availability in the soil water as well as (relative) changes in cation concentration of soil water. Since pedogenic carbonate is most likely to form during the dry season, when soil water evaporation forces carbonate precipitation, we use the Ca/Mg ratio in pedogenic carbonate as a proxy for cation concentration and composition of the soil water. Together these isotopic and compositional changes point to paleosol formation during strongly fluctuating and strongly seasonal soil moisture conditions.

We feel confident that we can rule out the vanishing of an interior Yecua seaway as the cause for the changes in the isotopic composition of pedogenic $\delta^{18}O$ at 9–8 Ma since marginal marine conditions in downstream parts of the Chaco Basin prevailed until at least 7.2 Ma (Uba et al., 2009b) and $^{87}Sr/^{86}Sr$ ratios indicate a clearly non-marine origin of the analyzed pedogenic carbonate. There are at least two possibilities for the change in oxygen isotopic values beginning at ~8.5 Ma. First, it is conceivable that at this time the moisture source that brought precipitation to the Subandean foreland changed. Indeed, a rearrangement of moisture trajectories due to growth of the Altiplano has been suggested by coupled atmospheric and water vapor transport models (Ehlers and Poulsen, 2009, Insel et al., 2009) and results indicate that during plateau growth prevailing wind directions and moisture

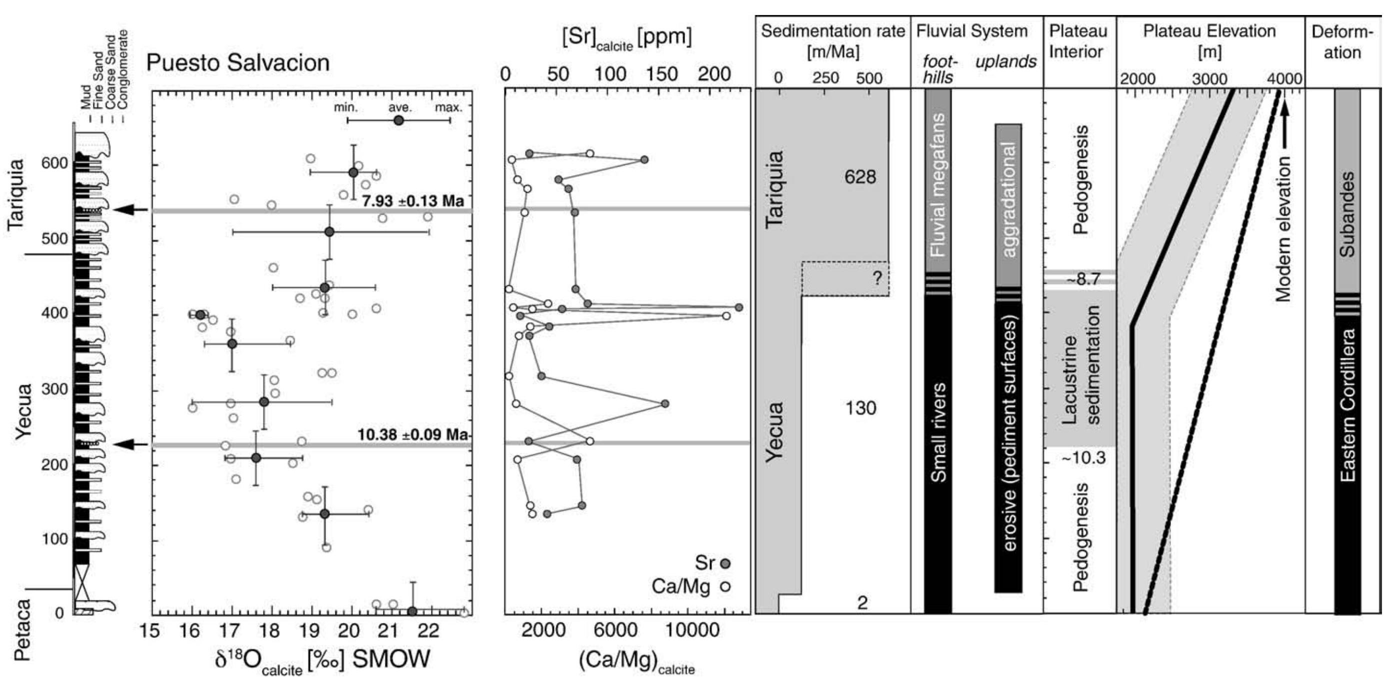

Fig. 6. Paleosol oxygen isotope, Sr, and Ca/Mg data of Puesto Salvacion section. The positive $\delta^{18}O$ shift at ~8.5 Ma coincides with highly variable Ca/Mg ratios and Sr concentrations indicating transient soil water concentrations and rapid wet–dry cycling. Compilation of changes in sedimentation rates (Uba et al., 2005, 2007), depositional and erosive character of the paleo-Rio Pilcomayo (Gubbels et al., 1993; Leier et al., 2005; Barke and Lamb, 2006), sedimentation and pedogenic history of the Bolivian Altiplano (Garzione et al., 2006), plateau elevation of the Bolivian Altiplano (Garzione et al., 2006, 2008; Ehlers and Poulsen, 2009), and deformation history in the Eastern Cordillera and Subandes (Ege et al., 2007; McQuarrie et al., 2008). Contemporaneous changes strongly suggest topographic and climatic readjustment along the eastern slopes of the south central Andes at ~8.5 Ma.

source may have switched from the South Pacific to the equatorial Atlantic. A cut-off of evolved Pacific derived moisture with presumably low $\delta^{18}O$ values could indeed account for some of the measured shift to more positive $\delta^{18}O$ values at 8.5 Ma. However, the combined $\delta^{18}O$, $^{87}Sr/^{86}Sr$, and sedimentological evidence for increased river discharge and sedimentation rates (see below) render such a process unlikely as the sole mechanism for observed changes in the isotopic composition of precipitation in the Bolivian Subandes.

In a similar fashion, it could be argued that the rapid shift to higher $\delta^{18}O$ values at 8.5 Ma is the result of threshold conditions being attained that permit moisture transport by the South American LLJ to latitudes as far South as the Chaco Basin (21–22°S). Based on analysis of $\delta^{13}C$ values in pedogenic carbonate nodules and sedimentation histories it has been suggested that the South American monsoon intensified along the eastern margin of the Altiplano–Puna region at this time (Strecker et al., 2007a; Uba et al., 2007). However, the increase in oxygen isotope values is inconsistent with the direct input of monsoon precipitation, as monsoonal air masses deliver precipitation with $\delta^{18}O$ values up to 20‰ lower in the wet season than during the dry season (Grootes et al., 1989; Vimeux et al., 2005). These low $\delta^{18}O$ values are caused by highly convective storms with large rain drops that undergo little evaporation or exchange with ambient water vapor below the cloud base resulting in relatively low $\delta^{18}O$ values (Rozanski et al., 1993) and the fact that there is little recycling of water vapor over the Amazon during the wet season when precipitation exceeds evapotranspiration (Grootes et al., 1989). That said, however, the shift towards higher $\delta^{18}O$ values could well reflect an increase in the seasonality of precipitation and increased seasonal aridity resulting in seasonally evaporative soils characteristic for monsoonal climates (e.g. Quade et al., 1989; Stern et al., 1997). Since calcite in soils generally forms during the transition from wet to dry seasons the increased aridity would result in higher $\delta^{18}O$ values during the calcite growth season (e.g. Quade et al., 2007). The increased variability in our $\delta^{18}O$ data is further consistent with large seasonal differences in $\delta^{18}O$ in precipitation and fluctuating soil water storage with wet season (low) $\delta^{18}O$ into the dry calcite growth season. Since soil water storage (and carryover of the wet season $\delta^{18}O$ "fingerprint") may be highly variable on short time scales (10^0 to 10^1 a) we expect the increased variability in $\delta^{18}O$ of pedogenic carbonate observed in our data at the 10^4 to 10^5 a time scale to be a reflection of both, increased seasonality and variable soil water storage.

5.2. Change in sediment source and drainage area

Interestingly, the sharp transition in oxygen isotopic composition coincides with the onset of the development of the late Miocene Chaco mega fan and input of sediment with a more radiogenic $^{87}Sr/^{86}Sr$ ratio. We interpret the change to higher $^{87}Sr/^{86}Sr$ ratios in the pedogenic carbonates to be the result of a change in composition of the deposited sediment. Thereby the shift towards more radiogenic $^{87}Sr/^{86}Sr$ ratios can be caused by an increased input of Rb-rich minerals (such as K-bearing amphiboles and micas) with high $^{87}Sr/^{86}Sr$ ratios due to a change in weathering regime and delivery of less weathered material. The shift towards more radiogenic $^{87}Sr/^{86}Sr$ ratios, however, could also be the result of a change in the eroded bedrock lithology in the source region (i.e. predominant erosion of much older bedrock that developed high $^{87}Sr/^{86}Sr$ ratios with time). Irrespective of the actual mechanism, Uba et al. (2009a) observed a substantial increase in sedimentation rates and hence most likely fluvial transport and erosion rates (Uba et al., 2007) that coincide with these isotopic shifts (Fig. 6).

Today, highly radiogenic $^{87}Sr/^{86}Sr$ ratios (0.716365 to 0.717820) in modern stream waters occur within the Altiplano at about the same latitude as the headwaters of Rio Pilcomayo (Grove et al., 2003). These high $^{87}Sr/^{86}Sr$ rivers typically drain radiogenic Silurian–Devonian sandstones and mudstones of the Eastern Cordillera as well as subordinate Neogene volcanics (e.g. Los Frailes complex $^{87}Sr/^{86}Sr = 0.7096–0.7115$; Deruelle et al., 2000). At present the drainage divide and ultimate western limit of catchments draining towards the Bolivian Subandes (Fig. 2) is located roughly at 66.5°W between 19° and 22°S (e.g. Gubbels et al., 1993; Barnes and Pelletier, 2006). Reconstructions of drainage patterns and paleocurrents within the pediment and upland surfaces of the San Juan del Oro and Rio Pilcomayo drainages (Gubbels et al., 1993; Barke and Lamb, 2006; Barnes and Heins, 2009) indicate that during the late Miocene (12–9 Ma) these catchments did not reach as far west as they do today. At current their combined drainage area is around 88 000 km^2 (Barnes and Pelletier, 2006) but is likely to have been smaller during the late Miocene, not extending farther west than ~65.7 W (Barke and Lamb, 2006). The observed change in $^{87}Sr/^{86}Sr$ of pedogenic carbonate from 0.7143 to 0.7158 around ~9.0 to 8.5 Ma may therefore reflect W-directed headward erosion of the Rio Pilcomayo and San Juan del Oro drainage basins, increase in river incision and concomitant deposition of high-$^{87}Sr/^{86}Sr$ sediments. As drainage area commonly scales with river discharge these processes are consistent with higher (seasonal) river discharge that ultimately led to the development of the Tariquia Formation megafans (Horton and DeCelles, 2001). These $^{87}Sr/^{86}Sr$ data are in good agreement with recent sedimentological and petrographical data from the Yecua and Tariquia Formations. At around 9–8 Ma (shortly before the onset of Tariquia deposition) orogen-sourced clastics start to dominate the Chaco Basin deposits (Uba et al., 2007; Hulka et al., 2010). Within the studied sections there is a general trend towards reduced mineralogical maturity which has been interpreted to result from decreasing transport distance, increasing topographic gradient within the catchment, and changing depositional environment of the Chaco basin immediately preceding the Yecua–Tariquia transition (Hulka et al., 2010). The change in sediment composition is further consistent with a shift from dominantly cratonic sources (Yecua) to Andean sources and coincides with a) increased accommodation space in the Chaco basin, b) high scattering of E-directed Tariquia paleocurrents, c) increased stream power, and d) beginning of fluvial megafan deposition (Uba et al., 2007; Hulka et al., 2010).

Such fluvial megafans are thought to form in response to a monsoonal climate and at present occur only in river systems with extreme seasonal fluctuations in discharge that result from highly seasonal precipitation patterns (Leier et al., 2005). Today, the Chaco megafan reduces the relief between the mountain range and the river base level at the mountain front by raising the mouth of the river outlets. A comparison of modern rainfall and relief structure north and south of the oroclinal bend of the Andes has documented that relief provides the necessary threshold conditions (1.0 to 1.5 km of relief within a 3-km-radius window of analysis) to induce orographic precipitation (Bookhagen and Strecker, 2008). It is possible that the development of the Chaco megafan and partitioning of upper crustal shortening from the internal parts of the plateau to the Subandean thrust belt at around 10–8 Ma (e.g. Ege et al., 2007) reduced the relief structure at the mountain front and threshold topography values. This may then have forced orographic precipitation to move into the Eastern Cordillera towards higher elevations. Such a shift in the focus of precipitation could partly be responsible for the positive shift in $\delta^{18}O$ values of precipitation because our sampling sites at the outlet of Rio Pilcomayo would have received smaller amounts of rainfall from less evolved cloud systems with a higher $\delta^{18}O$ value and hence a smaller amount effect (e.g. Rozanski et al., 1993). However, since the change in $\delta^{18}O$ of pedogenic carbonate coincides with the onset of megafan development (when the fan only started to grow in height) we believe that this effect is too small to account for the changes in $\delta^{18}O$ of pedogenic carbonate.

5.3. Synchronous changes in isotopes in precipitation: surface uplift or elevation thresholds to atmospheric circulation?

Today, topographic relief along the humid eastern flanks of the central Andean chain exerts the dominant control over the distribution of precipitation (Bookhagen and Strecker, 2008) including the diversion of air masses to more southerly latitudes through the South

American LLJ. Even though the large number of processes contributing to the distribution of rainfall along mountain fronts is hard to quantify individually, long-term orographic rainfall patterns are robust reflections of the integrated effect of moisture flux into the orogen and topography of a given area (Roe, 2005). In a similar fashion, the isotopic composition of precipitation (δD and δ^{18}O) correlates with elevation on the windward side of a mountain range at moderate latitudes ("altitude effect" e.g. Poage and Chamberlain, 2001). This altitude effect on the windward side of orogens forms the underlying principle for stable isotope paleoaltimetry.

While the large-scale atmospheric conditions controlling rainfall along the western flanks of the central Andes are reasonably well known (e.g. Lenters and Cook, 1997; Garreaud et al., 2003; Vuille et al., 2003; Vera et al., 2006), there exist only few geologic studies that characterize how topographic characteristics modulate orographic precipitation (e.g. Galewsky, 2009). This is even more obscure for the geologic past. One of the difficulties in interpreting continental oxygen and hydrogen isotope records is whether the values of isotopes in precipitation reflect solely climatic changes or tectonically induced redistribution of moisture. Above we have postulated that the positive oxygen isotopic excursion and increase in sedimentation rate at ~8.5 Ma is the result of the deflection of the LLJ into southern Bolivia. There is convincing evidence that the South American Summer Monsoon was established at least by 16 Ma in northeast Peru (Kaandorp et al., 2005) however, there is considerable uncertainty on the timing of southward migration of the monsoonal system and when precipitation patterns started to resemble those observed today. The question then remains what caused the monsoon to move southward — was this tectonically induced or not?

It has been proposed that at 10.3–6.7 Ma the Bolivian Andes underwent 2.5 ± 1.0 km of surface uplift as a result of convective removal of mantle lithosphere (Garzione et al., 2006; Ghosh et al., 2006; Garzione et al., 2008). This hypothesis is based on a 3–4‰ decrease in δ^{18}O values and 13.4 ± 2.9 °C temperature decrease recorded by clumped isotopes (Δ47) in paleosol carbonate (Ghosh et al., 2006; Quade et al., 2007). These isotope records on the Bolivian Altiplano are located about 500 km to the NW from the records presented in this study and today receive precipitation from similar moisture sources as our study area (Fig. 1). The 10.3–6.7 Ma shift towards lower oxygen isotope compositions observed in pedogenic carbonate on the Altiplano and (coeval?) ~8.5 Ma positive oxygen and carbon isotopic shifts observed in the Bolivian subandes at low (paleo-)elevation suggest a common mechanism for the redistribution of oxygen isotopes in precipitation within the Miocene Bolivian Andes.

If indeed these records respond to the same phenomenon, what process then could result in synchronous positive and negative shifts in δ^{18}O values that depend upon location within an orogen? There is isotopic (increase in δ^{13}C of pedogenic carbonate; Quade et al., 2007), sedimentological (transition from lake sediments to soil formation; Garzione et al., 2006) and paleofloral (decrease in mean annual precipitation; Graham et al., 2001) evidence of increased aridity on the northern Bolivian Altiplano post-10 Ma. Quade et al. (2007) present δ^{13}C data of pedogenic carbonate from the Corque syncline that show a positive carbon isotope shift of about +4‰, that has roughly the same magnitude and timing as a positive δ^{13}C shift in the Bolivian Subandes (Strecker et al., 2007b).

We speculate that these two isotopic records on the plateau and in the Andean foreland may reflect a change to more seasonal precipitation due to the impact of the LLJ that is recorded in the foreland paleosol record. As suggested above the positive δ^{18}O excursion observed in the Rio Pilcomayo section at ca. 8.5 Ma is the result of formation of carbonate during the end of the wet season as the soils become more evaporative. Consequently, the negative shift on the Bolivian Altiplano could in part be controlled by the same phenomenon. As the heavy rainfalls during the austral summer (DJF) have relatively low δ^{18}O values reflecting the effects of convective monsoonal storms (Vimeux et al., 2005) it is conceivable that during increased overall aridity on the plateau oxygen isotopes in precipitation are biased towards the low δ^{18}O values of precipitation during the summer months when storms are heavy and penetrate deep(er) into the Altiplano region. Since very little moisture is received during the winter (JJA) months its contribution would be negligible to the oxygen isotope budget of soil carbonate. Thus, the change to strongly seasonal precipitation may a) induce these simultaneous negative and positive oxygen isotope excursions by increased aridity on the Altiplano and a stronger seasonality in the Subandes and b) is very likely to result in less productive soils and higher water stress in local plant communities that on the Altiplano and in the Subandes would explain a shift to more negative δ^{13}C values in pedogenic carbonate. We would like to point out that we expect to see a phase of increased aridity in the southern Bolivian Altiplano and Atacama Desert further to the west coeval with the increase in seasonality of precipitation in the Bolivian Subandes at 9–8 Ma. This hypothesis, however, remains to be tested in the future.

That said, one is still left with what process drove deflection of the South American LLJ. It may be a direct reflection of large-scale surface uplift on the Altiplano. However, regional climate models suggest that topographic threshold conditions exist across the entire Andean orogen that control the source and upstream path of moisture into the orogen (Ehlers and Poulsen, 2009). In the latter case the oxygen isotopes in precipitation would only indirectly respond to uplift and development of topography of the Eastern Cordillera and Altiplano and would be indicative of coupled climate and topography thresholds rather than quantitatively reflect a direct measure of surface uplift.

Without doubt, the late Miocene is a time interval of important changes in the topographic structure, internal dynamics, and climatic regime of the Andean orogen. The rapid (100–200 ka) transitions in δ^{18}O and $^{87}Sr/^{86}Sr$ at 9–8 Ma from the Chaco basin presented here render it unlikely that (almost) instantaneous surface uplift produced the suggested change in precipitation amount and isotopic composition in the foreland. We rather suggest that a topographic threshold configuration was attained that induced a switch in atmospheric circulation mode, forced the South American LLJ towards more southerly latitudes along the Eastern flanks of the central Andes, and hence established rainfall and wind patterns that (to first-order) parallel those observed today. Whether this topographic threshold (60–70% of modern elevation; Insel et al., 2009) was a) constrained to the Eastern Cordillera/Interandean Zone or included the Altiplano and b) occurred during progressive and steady or rapid and punctual surface uplift should be subject of further studies and can only be solved with a larger (temporal and spatial) coverage of sampling sites.

6. Conclusions

The δ^{18}O values of pedogenic carbonate from Subandean foreland basins in southern Bolivia (Rio Pilcomayo) suggest a rapid (<200 ka) change towards a more seasonal precipitation and climate mode, possibly associated with the southward deflection of the South American low-level jet at around 9–8 Ma. The resulting change in seasonality was coeval with a period of increased aridity on the Bolivian Altiplano, increased sediment flux and river water discharge as well as headward erosion in the rivers draining the Eastern Cordillera. Whether episodic or gradual, the combined isotopic, thermochronologic, kinematic, and climatic data indicate that surface uplift of the Eastern Cordillera and the Bolivian Altiplano occurred during a time interval of local and regional climate readjustments at the latitudes of the central Andes. We conclude that the 9–8 Ma rapid positive δ^{18}O shift of pedogenic carbonate in the Chaco foreland basin is consistent with threshold elevations of the Eastern Cordillera/Interandean Zone being attained that were necessary to significantly modulate South American precipitation patterns. If current models (Ehlers and Poulsen, 2009, Insel et al., 2009) capture the main thresholds of changes in atmospheric circulation our data are consistent with the Eastern Cordillera attaining ca. 60–70% of its modern elevation around that time. More generally we would like to point out that stable isotope paleoaltimetry reconstructions in orogenic plateau regions frequently suffer from the absence of low-elevation constraints to separate the effects of upstream moisture transport, climate change, and surface uplift. The isotopic data presented here indicate that it may be problematic to deduce the relative roles of surface uplift and (topographically induced?) changes in atmospheric circulation patterns for the continental plateau regions uniquely from isotopic records from within the plateau interior.

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