Late Miocene climate variability and surface elevation in the central Andes

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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 (10⁵–10⁶a) 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 (87Sr/86Sr), sedimentologic, and stable isotope (δ¹⁸O) data from Subandean foreland deposits of the Chaco Basin (Bolivia) show a rapid (<200 ka) transition towards higher δ¹⁸O and 87Sr/86Sr 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 δ¹⁸C 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 Cordiller a at 20–22°S and possibly associated surface uplift of the Altiplano. Contemporaneous rapid positive shifts in δ¹⁸O and 87Sr/86Sr 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 87Sr/86Sr 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.

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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 (δ¹⁸O) 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 (δ¹⁸O 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,

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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 monsoon precipitation patterns surrounding large plateau regions. Quantitative stable isotope paleoaltimetry, therefore, requires low-elevation stable isotope records that provide a "benchmark" 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., 2007), precipitation regimes (e.g. Garreaud et al., 2003; Vera et al., 2006, Bookhagen and Streeker, 2008; Insel et al., 2009), and the position of the ITCZ during the austral summer over the Amazon basin (e.g. Linters 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 continental plateau regions (e.g. Quade et al., 2007), other models (e.g. Garzione et al., 2000; Sempere et al., 2006; Garzione et al., 2008; Ehlers and Poulsen, 2009) consider it necessary to document upstream conditions 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).

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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 (δ18O) 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..
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 subsequent 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
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 calcarious 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

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

**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 δ18O data; solid symbols represent binned averages. δ18O values show a continuous decrease followed by a rapid increase at ~8.5 Ma. There is a contemporaneous shift to more radiogenic 87Sr/86Sr 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 δ18O 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 δ18O 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 δ18O values of paleosol carbonate decrease by ∼5‰ (Fig. 4). During the same time interval (0–380 m of section) ⁸⁷Sr/⁸⁶Sr values of pedogenic carbonate
remain relatively constant at 0.71433 ± 0.00028. Second, there is a short time interval between ~9 and 8 Ma where δ¹⁸O and ⁸⁷Sr/⁸⁶Sr 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 Formation. Following this negative excursion, δ¹⁸O values abruptly increase, maintaining that greater variability compared to the lower part of the Yecua Formation. At the same time ⁸⁷Sr/⁸⁶Sr 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 δ¹⁸O pattern in the Puesto Salvacion 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 δ¹⁸O, yet again with relatively high δ¹⁸O 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 δ¹⁸O 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 δ¹⁸O 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 δ¹⁸O 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 (Streck 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 δ¹⁸O values (16.0 to 20.6‰), yet again with relatively high δ¹⁸O values and large sample-to-sample variability.

Fig. 6. Paleosol oxygen isotope, Sr, and Ca/Mg data of Puesto Salvacion section. The positive δ¹⁸O 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), 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 δ18O values could indeed account for some of the measured shift to more positive δ18O values at 8.5 Ma. However, the combined δ18O, 87Sr/86Sr, 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 δ18O 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 δ13C 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 isotopic values is inconsistent with the direct input of monsoon precipitation, as monsoonal air masses deliver precipitation with δ18O values up to 20‰ lower in the wet season than during the dry season (Grootes et al., 1989; Vimeux et al., 2005). These low δ18O 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 δ18O 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 δ18O 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 δ18O values during the calcite growth season (e.g. Quade et al., 2007). The increased variability in our δ18O data is further consistent with large seasonal differences in δ18O in precipitation and fluctuating soil water storage with wet season (low) δ18O into the dry calcite growth season. Since soil water storage (and carryover of the wet season δ18O “fingerprint”) may be highly variable on short time scales (10° to 101 a) we expect the increased variability in δ18O of pedogenic carbonate observed in our data at the 104 to 105 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 87Sr/86Sr ratio. We interpret the change to higher 87Sr/86Sr ratios in the pedogenic carbonates to be the result of a change in composition of the deposited sediment. Thereby the shift towards more radiogenic 87Sr/86Sr ratios can be caused by an increased input of Rb-rich minerals (such as K-bearing amphiboles and micas) with high 87Sr/86Sr ratios due to a change in weathering regime and delivery of less weathered material. The shift towards more radiogenic 87Sr/86Sr ratios, however, could also be the result of a change in the eroded bedrock lithology in the source region (i.e. predominant erosion of more old bedrock that developed high 87Sr/86Sr 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 87Sr/86Sr 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 87Sr/86Sr rivers typically drain radiogenic Silurian–Devonian sandstones and mudstones of the Eastern Cordillera as well as subordinate Neogene volcanics (e.g. Los Frailes complex 87Sr/86Sr = 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. Gubbelts 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 (Gubbelts 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 km2 (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 87Sr/86Sr 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-87Sr/86Sr 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 87Sr/86Sr 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 clastic 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 Stuecker, 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 δ18O 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 δ18O value and hence a smaller amount effect (e.g. Rozanski et al., 1993). However, since the change in δ18O 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 δ18O 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 Stuecker, 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 δ18O) 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 northeastern 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 δ18O 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 δ18O values that depend upon location within an orogen? There is isotopic (increase in δ13C 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 δ13C 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 δ13C 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 δ18O 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 δ18O 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 δ18O 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 isotopic 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 δ13C 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 δ18O and 87Sr/86Sr 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 δ18O 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 δ18O 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 plate 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 plate region unlike isolated records from within the plateau interior.

References


