Late Quaternary paleoenvironments of Eastern Bolivia deduced from geomorphological and paleopedological archives

Inauguraldissertation
der Philosophisch-naturwissenschaftlichen Fakultät
der Universität Bern

vorgelegt von

Jan-Hendrik May
aus Deutschland

Leiter der Arbeit:
Prof. Dr. Heinz Veit

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Bern, 12.4.2007

Der Dekan:
Prof. Dr. P. Messerli

„Man braucht in Südamerika keine große Erfindungsgabe. Man steht eher vor dem Problem, das, was man in der Wirklichkeit vorfindet, glaubhaft zu machen."

Gabriel Garcia Márquez (*1927)

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SUMMARY

Regional paleoenvironmental research in the South American lowlands is required for an improved understanding of the tropical climate system. The Eastern Bolivian lowlands are located at the transition between the tropical humid climate of Amazonia and the semi-arid Gran Chaco. Therefore, they should be particularly suitable for the detection of past environmental and climatic changes.
This study aims at *reconstructing Late Quaternary paleoenvironments* in Eastern Bolivia. In a first step, the regional geomorphological framework was established using various types of remote sensing data. Mapping and the inquiry of landforms in Eastern Bolivia provided the base for the deduction of large-scale paleoenvironmental changes and served as a departing point for further studies. In a second step, paleosol-sediment-sequences were studied with more detail at three locations along the Andean piedmont in order to reconstruct the regional sedimentary, geomorphological and paleoenvironmental evolution.

The *large-scale analysis of the geomorphological processes and landforms* in the Eastern Bolivian lowlands provided evidence for several phases of extensive landscape activity in the past. This is particularly evident from large paleodune fields. At least three generations of dune formation were distinguished and indicate significantly increased sediment supply for aeolian deflation. Numerous paleochannels on the fluvial megafans of the Río Grande and the Río Parapetí reveal large-scale river shifts in the past. Both observations are interpreted to reflect generally drier conditions favorable to higher sediment loads and/or enhanced deflation. On the contrary, a series of paleolakes in the Bolivian Chaco bear evidence for substantially wetter climate. Similarly, fluvial dissection and incision along the Andean piedmont is interpreted to be the result of wetter conditions in the more recent geological past.

Incision into the piedmont has exposed numerous *paleosol-sediment-sequences*. These paleoenvironmental archives were subject to more detailed analysis at three localities (Santa Cruz, Cabezas, Charagua) along a north-south transect. The strong north-south climatic gradient characteristic for the Andean piedmont is expressed in a marked decrease in number and intensity of paleosols contained in the mainly alluvial sequences. Owing to these differences, the applied methods of analysis had to be adapted depending on the characteristics of each sequence. In general, the interpretation of the sequences was based on the concept of landscape activity and stability: regional-scale pedogenesis is associated with a dense vegetation cover under wet climatic conditions, whereas dry conditions cause widespread sedimentation and/or erosion. This concept, however, had to be expanded by the integration of all available sedimentological, geomorphological and – to a lesser extent - paleopedological data.

The most extensive paleosol-sediment-sequences are exposed at *Cabezas* and reach back to > 22 cal ka BP. At the base of the sequences, coarse fluvial gravel and sands indicate a braided-river environment with high sediment supply and transport capacities, probably pointing to very dry environmental conditions during the last glacial cycle. A minor increase of moisture availability around the Last Glacial Maximum (LGM) may be interpreted from deposition of decreasing grain sizes in the aggrading fluvial system. In these sediments, a paleosol has developed and represents a marked increase in total precipitation during the Lateglacial. Very fine-grained, organic rich sediments were deposited in extensive and frequently inundated wetlands during the Pleistocene-Holocene transition. A reduction of seasonality and an increase in winter precipitation under persisting wet climatic conditions could account for the apparent contrast between lateglacial pedogenesis and subsequent formation of wetlands. Initial erosion and deposition of massive sands in all sequences represents the return to highly active landscapes and overall aggrading fluvial systems during the Early to Mid-Holocene. This observation implies drier environmental conditions causing a significant reduction in vegetation cover and increased sediment input to the fluvial system. Since ~4 cal ka BP, the depositional history of the piedmont is ended by lateral erosion of the Río Grande and a well-developed soil started to form under wet climatic conditions similar to today. Nevertheless, intervals of renewed deposition of fluvial sands within a lower Río Grande terrace may be interpreted to reflect significant hydrological changes during the Late Holocene. These findings from Cabezas constitute further evidence for the assumption that the intensity of the South American Summer Monsoon and the position of the Intertropical Convergence Zone played a key role in controlling the environmental conditions in the Eastern Bolivian lowlands.

Despite some chronological limitations, the investigations of paleosol-sediment-sequences near Santa Cruz and Charagua largely corroborate and partly supplement the results from Cabezas. At Charagua, the sedimentological/stratigraphical analysis of a large number of sequences was combined with detailed geomorphological observations. The results provide evidence for major hydrological changes, which have caused massive local sedimentation and widespread intense incision along the Andean piedmont within the last two millennia. Similar changes are observed at Santa Cruz where incision was repeatedly interrupted by sedimentation and dune formation. These relatively young dynamics had previously not been documented in the Eastern Bolivian lowlands and are possibly related to decadal to centennial precipitation changes or human impact, which will be the main focus of further research.

1

INTRODUCTION

1.1 MOTIVATION AND BACKGROUND

Not only since the Intergovernmental Panel on Climate Change (IPCC; http://www.ipcc.ch/) has published the assessment report of *climate change* in February 2007, the understanding of the global climate system and the related complex environmental dynamics has become a key issue of highest political, economic and social relevance with regard to the planetary welfare. In this regard, the documentation and interpretation of present and past environmental dynamics is the necessary precondition for any substantial prediction and simulation of future scenarios (e.g. Bradley, 2000). Given the large complexity of the Earth’s system, this challenge does certainly apply to all fields and time scales involved in geoscientific research.

Particularly *Quaternary research* plays a key role for the investigation of longer term dynamics, thereby extending and complementing the efforts of research concerned with recent and present global changes. The International Union for Quaternary Research (INQUA; http://www.inqua.tcd.ie/) promotes improved communication and international collaboration in all aspects of Quaternary research. The INQUA explicitly emphasizes the multi-disciplinary character of Quaternary studies and points out two approaches essential for the reconstruction of the past: i) the study of climate variations through time is necessary in order to learn about the mechanisms and forcings leading to climate and environmental change, and ii) the reconstruction of past surface environments (boundary conditions) provides the base for the development and validation of predictive models.

As part of the International Geosphere-Biosphere Programme (IGBP) the Past Global Changes (PAGES; http://www.pages.unibe.ch/) project is concerned with the reconstruction and understanding of Earth’s past environment. Despite the importance of interhemispheric linkages within the global climate system, the number of relevant paleoenvironmental studies and data available for the *Southern Hemisphere* has remained comparatively scarce. As one of several PAGES research foci, the PANASH (Paleoenvironments of the Northern and Southern Hemispheres) project was launched in order to improve this situation. PANASH reconstructs paleoenvironments and paleoclimates along three terrestrial pole-equator-pole (PEP) transects and thereby draws particular attention to the Americas (PEP1).

The Swiss National Science Foundation (SNF) has funded numerous projects concerned with paleoclimatic and paleoenvironmental reconstruction in *South America*. Particularly the Institute of Geography at the University of Berne has established a long tradition of research in several South American countries. Most of these multidisciplinary projects concentrated on the investigation of glacial and periglacial archives across the climatically sensitive “arid diagonal” in order to infer past variability of the tropical climate system and the extratropical system of the southern westerlies (Fig. 1-1).

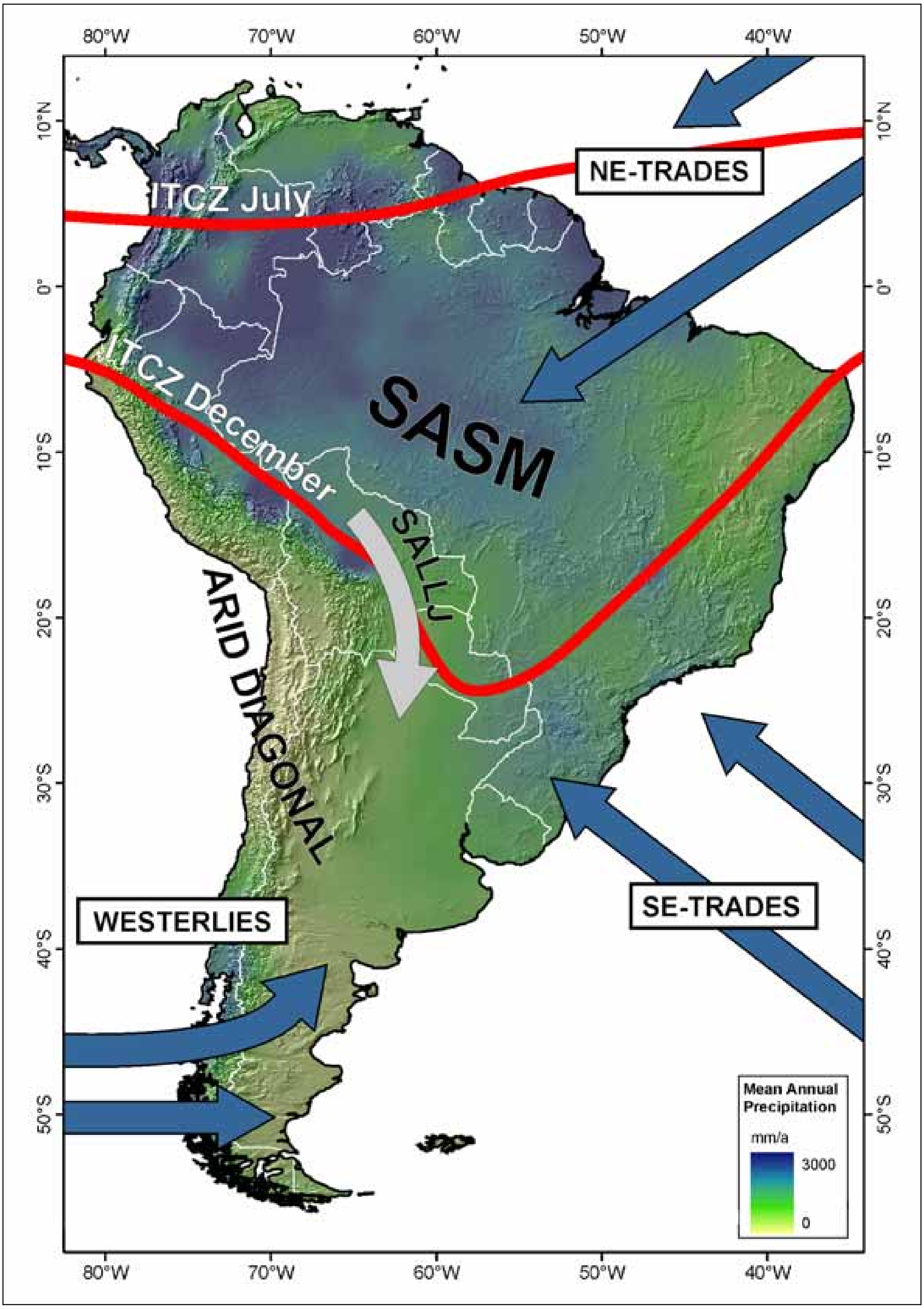

Fig. 1-1: *The main elements of South American climatology and mean annual precipitation pattern based on data from New et al. (2002).*

Increasing importance was given to fluvial and aeolian archives along the eastern side of the Andes of NW Argentina within the SNF-project "Paleoclimate of the Central Andes" (2000-056908.99/01), thereby shifting the focus towards a region essentially influenced by the tropical and subtropical climate regimes (Fig. 1-1). In a further step, two SNF-projects (200020-105228/1, 21-067937.02/1) were funded since the beginning of 2003. The central aim of these projects was the reconstruction of landscape and climate history in tropical and subtropical *Eastern Bolivia*. In every way, these projects constituted the necessary logistical and academic framework for this dissertation.

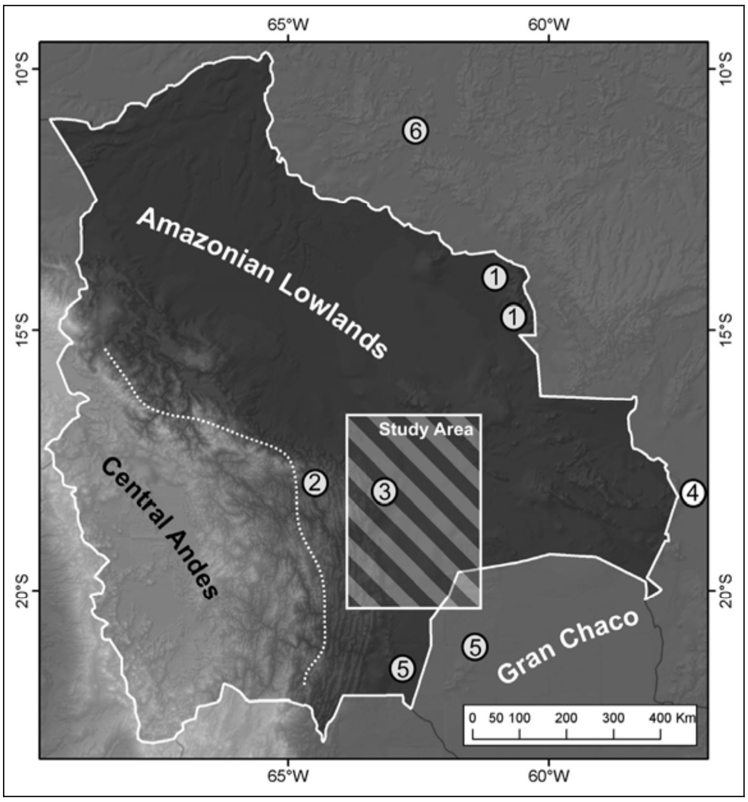

Fig. 1-2: *Locations of relevant paleoenvironmental studies in the closer geographical context of the Eastern Bolivian lowlands: 1) Mayle et al. (2000) and Burbridge et al. (2004), 2) Mourgiart and Ledru (2003), 3) Servant et al. (1981), 4) Assine and Soares (2004), 5) Geyh et al.(1996), Kruck (1996), Barboza et al. (2000), Pasig (2005).*

As mentioned above, paleoenvironmental data from the Southern Hemisphere is still comparatively scarce. In South America, the greatest density of records exists in the Andean highlands. Despite an increasing effort, large regions in the lowlands such as Amazonia and the Gran Chaco are still lacking detailed studies (Coltrinari, 1993; Markgraf, 1998; Latrubesse, 2003). Aside from a variety of logistical limitations, this probably owes to the limited availability of high temporal resolution archives (Markgraf, 1998). In Eastern Bolivia, only a very limited number of paleoenvironmental studies with a tolerable temporal resolution has been conducted and published in the literature so far (Fig. 1-2). All the more, regional investigations are needed in order to close the existing gaps and complement the spatially limited conclusions drawn from high-resolution proxies (Baker, 2000; Markgraf et al., 2000). For this purpose, the South American lowlands with their large fluvial systems offer an enormous potential (Baker, 2000).

Therefore, this dissertation is partly considered as a first systematic approach in order to obtain an overview of the available paleoenvironmental archives in Eastern Bolivia and assess their suitability for paleoenvironmental research. In a second and more important step the analysis of appropriate archives allows the deduction of new regional data regarding the Late Quaternary landscape and climate evolution of the lowlands in Central South America in general.

1.2 QUATERNARY OF THE CENTRAL SOUTH AMERICAN LOWLANDS

Due to the comparatively small number of paleoenvironmental studies in South America several aspects regarding the Late Quaternary climate and landscape evolution are still controversially debated. This applies particularly for the extensive lowlands of Amazonia and central South America (Markgraf, 1998). Here, four key issues relevant for the Late Quaternary paleoenvironmental research in the Eastern Bolivian lowlands are briefly summarized:

i) The reconstruction of *landscape and vegetation history in Amazonia* continues to be a subject of intense discussion and was approached by different methods. Manifold paleobotanical (mostly palynological) investigations could not clarify to what extent the continuous lowland forest cover (rainforest, semi-deciduous forest and Chaco dry forest) disappeared or fragmented into refuges during the last glacial cycle (Ledru et al., 1996; Hooghiemstra and van der Hammen, 1998; Colinvaux and Oliveira, 2000; van der Hammen and Hooghiemstra, 2000; Haffer and Prance, 2001). Similarly, no consensus was reached concerning the persistence of the montane rain and cloud forests along the eastern and northern Andean slopes during the Late Quaternary (Mourguiart and Ledru, 2003; Bush et al., 2004; Urrego et al., 2005). Finally, studies of marine sediments on the Amazon cone were concerned with the overall development of the Amazon drainage basin but did not come to unambiguous conclusions (Haberle and Maslin, 1999; Harris and Mix, 1999; Maslin and Burns, 2000; Kastner and Goñi, 2003). However, evidence for significant hydrological changes in Amazonia during the last glacial cycles has been provided by a growing number of studies along the numerous large and medium-scale drainage basins of the tropical lowlands (summarized in Latrubesse, 2003). Thereby, geomorphological and sedimentological studies on the extensive fluvial (and aeolian) archives were mentioned to offer a good potential to complement and corroborate paleobotanical findings in Amazonia (Baker, 2000; Latrubesse, 2003).

ii) In South America, long-term records covering the entire Quaternary with sufficient resolution for paleoclimatic interpretation are known exclusively from Colombia and NW Argentina (Hooghiemstra, 1984; Schellenberger, 2004). Otherwise, the temporal frame of the published paleoenvironmental studies is quite limited. Particularly for the *Last Glacial Maximum (LGM)* records in central South America are controversial. Aside from dating uncertainties, this dilemma often seems to be the consequence of interpolation across sedimentary hiati (Ledru et al., 1998). In turn, the general scarcity of sedimentary records from the LGM likely reflects generally increased aridity in Amazonia and the adjacent lowlands during that time (Ledru et al., 1998). The very limited number of LGM fluvial records documented in South America point in the same direction (Stevaux, 2000; Latrubesse, 2003). Aside from reduced precipitation, the global fall in sea level may have caused widespread incision and a lowering of water tables within large parts of the Amazonian drainage basins (Clapperton, 1993a). The available geomorphological evidence for the LGM in South America is summarized by Clapperton (1993a), Heine (2000) or Latrubesse (2003) and implies highly active landscapes and generally more arid paleoenvironmental conditions throughout lowlands (Fig. 1-3). Despite their general character and low spatial resolution, these considerations deliver a hypothesis, which once again emphasizes the need for additional regional geomorphological investigations and chronologies.

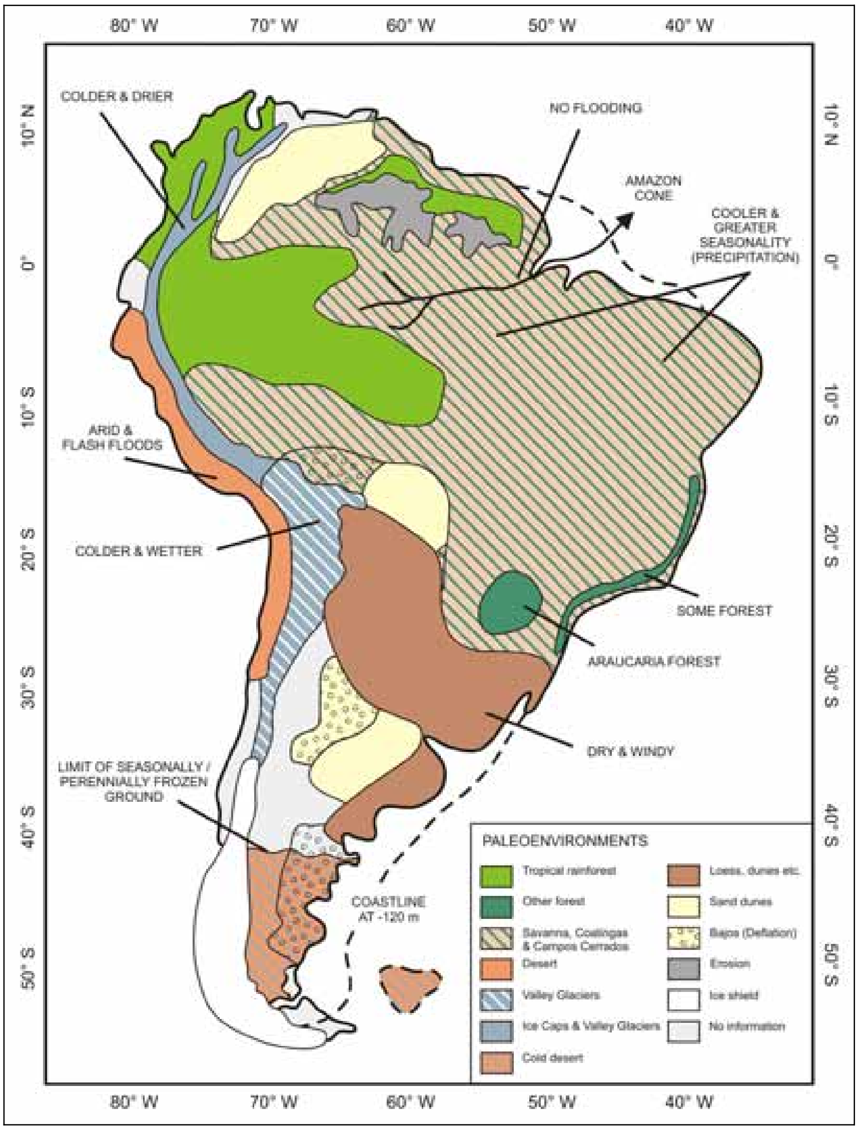

Fig. 1-3: *Paleoenvironmental conditions in South America during the Last Glacial Maximum based on various geomorphological evidence (modified from Clapperton (1993a)).*

iii) Recent advances have been made in the understanding of the *South American Summer Monsoon (SASM)* on short time scales, but relatively little is still known regarding the variability of the monsoon system and its controlling mechanisms on longer Late Quaternary time scales (Marengo et al., 2004a; Marengo et al., 2004b). Modeling studies corroborate drier climatic conditions during the LGM in Amazonia due to reduced moisture input from a cool Atlantic and significantly delayed onset of the South American monsoon (Wainer et al., 2005; Cook and Vizy, 2006). In this context, a variety of aeolian and fluvio-aeolian landforms has been described from many locations throughout the South American lowlands (Tricart, 1974; Khobzi, 1981; Clapperton, 1993b; Santos et al., 1993; Claudino-Sales and Peulvast, 2002; Barbosa and Dominguez, 2004; Teeuw and Rhodes, 2004). More detailed research on these aeolian archives could add information on past wind regimes as an essential component for the reconstruction of the SASM.

iv) On much *shorter time scales*, several climatic phenomena such as the Medieval Climatic Optimum or the Little Ice Age (LIA) are known from Northern Hemisphere records (Mann et al., 1999). Aside from general concerns regarding the nature of these climatic anomalies, their relevance for South America is still a matter of ongoing debate (Ruddiman, 2001). In any case, increasing evidence points to important environmental changes within the last two millennia in the tropical Andean highlands (Thompson et al., 1985; Thompson et al., 1986; Chepstow-Lusty et al., 1998; Valero-Garcés et al., 2000; Valero-Garces et al., 2003; Liu et al., 2005; Rabatel et al., 2005; Polissar et al., 2006). A limited number of records from the last two millennia with sufficient temporal resolution are available for the tropical lowlands so far, and seem to confirm considerable paleoenvironmental variability during this time (Servant et al., 1981; Latrubesse and Franzinelli, 2005).

1.3 STUDY AREA – THE EASTERN BOLIVIAN LOWLANDS

Andean uplift and deformation associated with the subduction of the Nazca plate has progressively migrated eastward throughout the Cenozoic, leading to thickening and horizontal shortening of the continental crust (Isacks, 1988; Gubbels et al., 1993). The resulting fold-and-thrust belt of the Eastern Andes has been divided into the structural zones of the Eastern Cordillera, the Interandean Zone and the Subandean Zone (Kley, 1999; Kley et al., 1999). Initial uplift and shortening commenced in the Oligocene, but major deformation and thrusting onto the Brazilian shield propagated into the Subandean Zone not before the Miocene (Sempere et al., 1990; Herail et al., 1996; Gregory-Wodzicki, 2000). The erosional products of this active deformation were transported into the foreland at least since the Miocene (DeCelles and Horton, 2003). Thus, from a geological point of view the *Eastern Bolivian lowlands* are considered a retroarc foreland basin system (Horton and DeCelles, 1997; Uba et al., 2006). The *Chaco Plain* (~18°-24° S) is one of several different active foreland depocenters adjacent to the Central Andes (Coudert et al., 1995; Uba et al., 2006), roughly corresponding to the study area of this dissertation.

The western margin of the Chaco plain is delimited by the Andean deformation front and coincides with the eastern boundary of the Subandean Zone. However, the structural deformation front is not always expressed topographically (Welsink et al., 1995; Hinsch, 2001). Therefore the Subandean foothills can be regarded as the topographic transition from the Subandean Zone into the foreland basin, representing the easternmost topographic emergence of thrust-faults (Hinsch, 2001). Beyond this zone, the thrust-faults of the active deformation zone are buried beneath accumulating sediment within the present foreland basin (Horton and DeCelles, 1997; Hinsch, 2001). While this proximal part of the foreland basin has been referred to as wedge-top depozone, the sediments of the foredeep depozone has not yet been affected by Andean deformation.
The Cenozoic sediments of the foredeep thin out towards the east and onlap onto the pre-Andean basement. Thereby, the northeastern limit of the Chaco plain is delimited by the outcrop of the Precambrian Brazilian shield (or Guaporé craton), which has likely been subject to peneplanation and erosion during most of the Tertiary. The transition between the Chaco plain and the Brazilian shield is interrupted by the Chiquitos ranges. These ranges are the result of extensionally reactivated normal faults (Welsink et al., 1995) and consist mainly of sedimentary rocks of the Paleozoic Chaco basin (Suárez-Soruco, 2000). Paleozoic rocks, which onlap the topographic and structural high of the Andean forebulge (Izozog arch), are unconformably overlain by a thin cover of Mesozoic rocks (Suárez-Soruco, 2000). In contrast to the proximal foreland basin, the forebulge is characterized by only thin Cenozoic sediment cover.

Neotectonic activity as directly observed from thrust faults in Quaternary sediments has been reported only from very few locations in the Subandean Zone (Strub et al., 2005). However, active tectonics within the entire foreland have been inferred based on the orientation of drainage patterns (Hinsch et al., 2003), and the analysis of fluvial morphology of the Pilcomayo River (Mugnier et al., 2005). In addition, several studies have deduced velocity rates of up to 15 mm/a of crustal shortening within the Subandean Zone from GPS measurements (Norabuena et al., 1998; Kendrick et al., 2001; Allmendinger et al., 2005). Recent tectonic activity therefore has to be expected to some extent within the adjacent Chaco plain and should be considered with any geomorphological analysis over longer time scales.

The *present climatic conditions* of the study area reflect the transitory position of the Eastern Bolivian lowlands between tropical wet climatic regimes to the north (Amazonia) and subtropical semi-arid climatic regimes to the south and east (Gran Chaco). During austral summer the complex system of the South America Summer Monsoon (SASM) dominates the atmospheric circulation over most of continental South America (Zhou and Lau, 1998; Nogues-Paegle et al., 2002). NE-trade winds are responsible for moisture advection from the tropical Atlantic source area into the Amazon basin (Nobre and Shukla, 1996). The southward transport of the Amazonian moisture into the

Eastern Bolivian lowlands and towards the South Atlantic Convergence Zone (SACZ) is accomplished by the *South American Low Level Jet (SALLJ)* (Berri and Inzunza, 1993; Nicolini et al., 2002; Saulo et al., 2004). Despite its intra-annual variability, the SALLJ is a strong N-S wind system east of the Andes active throughout the year (Marengo et al., 2004b; Nicolini et al., 2004; Saulo et al., 2004). It is thereby an atmospheric phenomenon of enormous climatic and geomorphological relevance (Fig. 1-4).

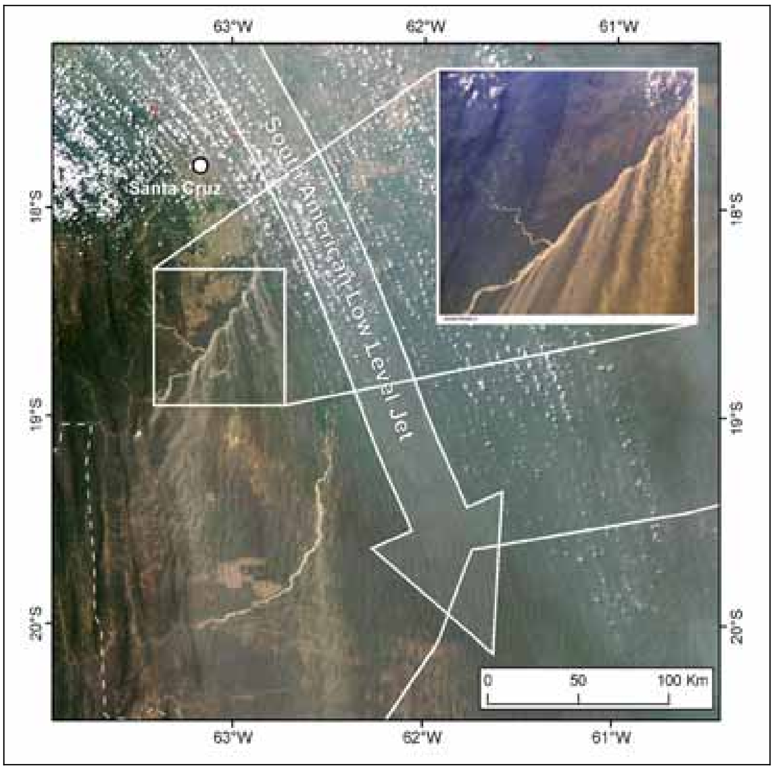

Fig. 1-4: *A South American low level jet event (SALLJ) and the resulting large-scale deflation of aeolian material from the major Eastern Bolivian rivers as seen in a MODIS satellite image and a ISS space photograph. MODIS image date 15/08/2004, image source http://rapidfire.sci.gsfc.nasa.gov/; ISS space photography 21/05/2003, image source http://eol.jsc.nasa.gov/*

However, relatively little is known regarding the long-term variability of the SALLJ and the SASM (Robertson and Mechoso, 2002; Marengo et al., 2004a). Clearly, the onset of moisture advection and the intensity of convection over Amazonia are key factors, which need to be considered within the larger context of Atlantic sea surface temperature (Nobre and Shukla, 1996; Robertson and Mechoso, 2002). In turn, the variability of the SACZ seems to influence the southward extent of the SASM (Barros et al., 2002). Furthermore, the Pacific pressure gradient and mechanisms related to the El Niño Southern Oscillation (ENSO) exert an important control on the upper-air circulation over South America, in turn influencing the southern hemisphere westerlies and the intensity and spatial effects of the SALLJ (Garreaud et al., 2003).

Due to the lack of topographic barriers, cold air incursions from mid-latitude South America (surazos, friagems) penetrate deep into the Amazon basin throughout most of the year (Garreaud, 2000; Garreaud, 2001). While they cause enhanced convective activity and precipitation during austral summer, in austral winter they lead predominantly to significant lowering of temperatures, which can even lead to frost in the southern Chaco Plain (Garreaud, 2000; Pezza and Ambrizzi, 2005). Consequently, long-term variability of these cold surges may have played a crucial role for both the past precipitation as well as the past temperature regime in Eastern Bolivia (e.g. Mourguiart and Ledru, 2003; Servant and Servant-Vildary, 2003; Bush and Silman, 2004).

Precipitation amounts and distribution in Eastern Bolivia depend to a large extent on the SASM and its components and clearly reflects the transitory position of the study area. Total annual precipitation decreases from >1500 mm/a north of 16°S to <500 mm/a south of 21°S (Rafiqpoor et al., 2004; AGTECA, 2005). This trend is accompanied by an increasing duration of the dry season (seasonality) from 1-2 months north of Santa Cruz to 7-8 months in the Gran Chaco (Gerold, 1985; Rafiqpoor et al., 2004). Most precipitation falls as a direct result of convective activity during the rainy season in the months of December to February, even though precipitation events of little intensity make up 40-50% of the total precipitation at Santa Cruz (Gerold, 1988). Total annual precipitation and particularly seasonality play an important role for the hydrological conditions in general, and the soil water budget in particular. Thereby, climate contributes the essential control on the large-scale distribution of vegetation pattern, pedogenesis and geomorphic processes (Navarro and Maldonado, 2002; Gerold, 2004), characterizing the Eastern Bolivian lowlands as the transition between the tropical wet climate of Amazonia and semi-arid conditions in the Gran Chaco (Fig. 1-5).

Five ecoregions of different vegetation types characterize the Eastern Bolivian lowlands (Ibisch et al., 2004), with four of them being part of the study area. The area around Santa Cruz (~18°S) is characterized by the transition between Amazon evergreen forests to the northwest and the semi-deciduous Chiquitano Dry Forest to the northeast. The eastern margin of the Chaco plain is represented by the open and wooded savannas of the Cerrado formations. The largest part of the Chaco plain however is part of the Gran Chaco, a vast region of low deciduous dry forest extending far into Brazil, Paraguay and Northern Argentina. Corresponding to the north-south climatic and ecological gradient, the weathering intensities and types show a marked gradient within the study area as well. Generally clay translocation and luvisols are typical around Santa Cruz, whereas cambisols, arenosols and regosols are found towards the semi-arid Chaco (Cochrane, 1973; Guamán, 1981; Gerold, 1985; Guamán, 1999; Gerold, 2004). Considerable variability characterizes the small-scale distribution of soils due to hydrological conditions, topography and polygenesis (Gerold, 2004).

Going along with a significantly growing population, natural vegetation in the Eastern Bolivian lowlands has been extensively removed or modified for agricultural purposes since the mid-20th century (Steininger et al., 2001; Pacheco, 2006). This profound human interference has measurable effects on soils, hydrology and even climate (Gerold, 1988; Krüger and Gerold, 2003; Bounoua et al., 2004; Cochrane et al., 2004).

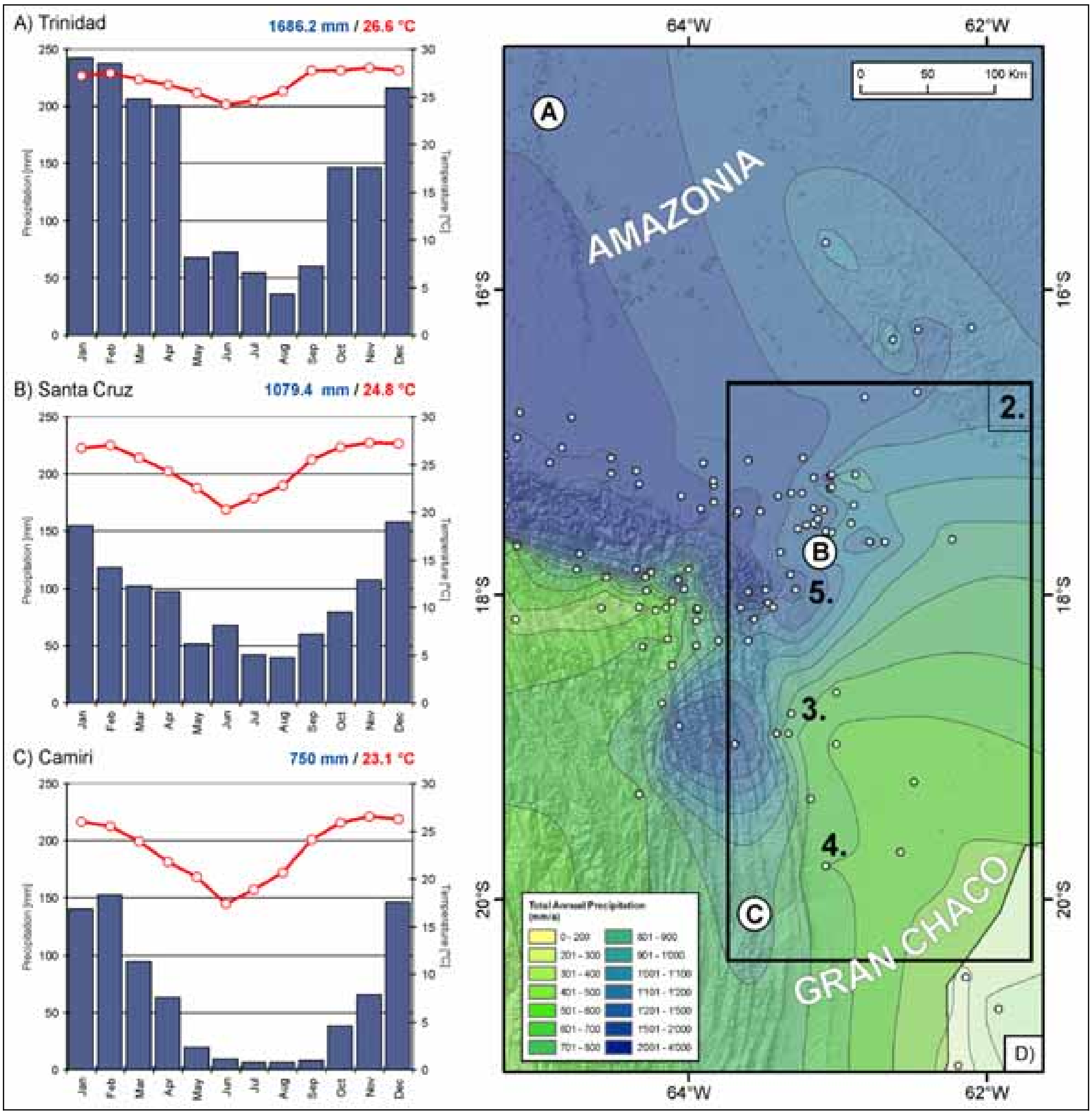

Fig. 1-5: *Temporal distribution of mean monthly precipitation and temperature for a) Trinidad, b) Santa Cruz and c) Camiri. d) Spatial pattern of mean annual precipitation in the Eastern Bolivian lowlands illustrating the strong N-S gradient between humid Amazonia and the semi-arid Chaco (numbers refer to the individual chapters).*

1.4 STUDY OBJECTIVES AND SCIENTIFIC APPROACH

In the context of climate change and Quaternary research, the brief overview given in the previous chapters reveals that there is an apparent need for further regional paleoenvironmental data in the tropical lowlands of South America. The Eastern Bolivian lowlands are a particularly suitable area for paleoenvironmental research because of the *scarcity of previous investigations* and their *susceptibility for climatic and environmental changes* due to the transitional location between the humid climatic regime of the Amazon and the semi-arid Chaco. Based on these observations, the main objectives of this study are basically twofold:

i) In a first step of gaining an ***overview of the paleoenvironmental framework***, a geomorphological inquiry of the existing landforms needs to be established in order to deduce sequential landform history, which provides the base for further studies.

In many ways, this approach follows fundamental concepts of historic-genetic geomorphology such as the recognition of landscape as a complex and polygenetic system, and the assumption of climate as an important control on morphogenesis (Büdel, 1980; Baker, 1983; Baker, 1986). Large-scale geomorphological studies have always made use of satellite imagery and aerial photography (Verstappen, 1977; Rosenfeld, 1984; Embleton and Liedtke, 1990). Since recently, however, extensive geomorphological analysis profits from the increasing availability and quality of various kinds of remote sensing data (Butler, 2006; Gebelein and Eppler, 2006). The combination of these data with extensive field work and reconnaissance constitutes the methodological approach for the establishment of a historic-genetic framework of landscape evolution. In addition, it provides data for subsequent and more detailed, regional geomorphological investigations.

ii) In a second step the ***analysis of adequate archives*** aims at reconstructing landscape evolution in Eastern Bolivia, thereby providing data for regional and continental scale paleoenvironmental interpretation, respectively. For this purpose, paleosol-sediment-sequences have proved as valuable archives of past geomorphological – and therefore paleoenvironmental – variability.

Numerous sequences were studied in three different settings along the Andean piedmont. More detailed, regional analysis, however, requires the integration of adequate geomorphological concepts for the interpretation of the paleosol-sediment-sequences. In this regard, well-developed paleosols of regional character (marker horizons) are assumed to reflect sustained landscape stability indicative of a dense vegetation cover under wetter environmental conditions (Rohdenburg, 1970). On the contrary, landscape activity refers to the dominance of sedimentation and erosion processes, implying increased sediment supplies resulting from degradation of vegetation cover under more arid conditions (Fig. 1-6).

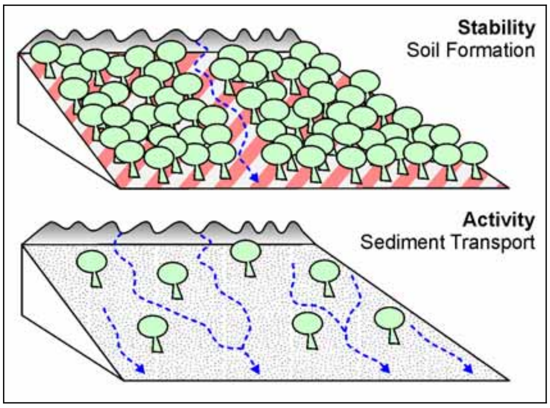

Fig. 1-6: *Conceptual model of landscape stability (with pedogenesis) and landscape activity (with extensive erosion, transport and sedimentation) based on Rohdenburg (1970).*

Whereas this concept offers a possibility to distinguish between two general modes of landscape systems – each of them with contrasting environmental relevance – the concept does not account for the constant dynamic changes *within* a particular geomorphic system (Chorley, 1962). In this context, the concept of landscape sensitivity considers the geomorphological effect of a given environmental change (e.g. increasing seasonality or decreasing seasonality). This effect does not only depend on the direction of the change (e.g. from dry to wet conditions), but is essentially controlled by the environmental conditions before the change (Langbein and Schumm, 1958; Wolman and Miller, 1960; Rohdenburg, 1989; Thomas, 2001). This is particularly true for the interpretation of fluvial systems because of the dependent and non-linear character of the system internal variables such as vegetation cover, lithology, topography and slopes and land use (Wolman and Gerson, 1978; Phillips, 2003). Sedimentation, erosion or stability (pedogenesis) – which are ultimately controlled by the available stream energy (stream power) to transport sediment – can therefore result from different combinations of sediment supply and discharge and have to be interpreted carefully (Bull, 1979; Bull, 2000).

1.5 STUDY OUTLINE

The outline of this volume reflects the cumulative character of the dissertation. The introduction (chapter 1) serves to clarify the relevance and scientific background of the study on a global, continental and regional scale. These considerations lead to the preceding formulation of the two main research objectives. Within the following chapters, these objectives set the stage for documentation of the detailed paleoenvironmental analysis. Given the different spatial and temporal scales of investigation, the regional scale investigations of chapters 3 to 5 are built to some degree on the large-scale analysis of chapter 2. Nevertheless, each of these chapters is considered an individual study towards an understanding the paleoenvironmental evolution of Eastern Bolivia.
Chapter 2 is a contribution to a special issue of the journal *Geographica Helvetica* titled "Paleo-geoecology of the Central Andes" (May, 2006). As such it complements the paleoecological results gained over several years in the Central Andes by adding the lowland perspective of Late Quaternary landscape evolution. In particular, this study aimed at providing an inventory of geomorphological landforms and landform evolution in Eastern Bolivia based on field work and analysis of remote sensing data.
Chapter 3 is a manuscript in review for publication in a special issue of the journal *Geomorphology* titled "Geomorphological and palaeohydrological changes and adjustments to climatic, human and tectonic controls" (May et al., in review). It investigates the extensive outcrops of paleosol-sediment-sequences along the Andean piedmont at Cabezas with a focus on stratigraphy and paleopedology. Aside from establishing a record for the regional Late Quaternary geomorphological and environmental evolution of the Andean piedmont, this study highlights the importance

of a combined stratigraphical and geomorphological approach in records of high sedimentological variability.

Chapter 4 is a manuscript submitted for publication in the journal *Palaeogeography, Palaeoclimatology, Palaeoecology* (May et al., submitted). It investigates a series of paleosol-sedimentary-sequences along the Andean piedmont at Charagua. Based on the results from Cabezas (chapter 3), it thereby concentrates on thorough stratigraphical analysis leading to a reconstruction of regional Holocene landscape evolution with a particular focus on the Late Holocene. The spatial extrapolation and validation of these results are mainly achieved by the integration of remote sensing methods.

Chapter 5 is a manuscript prepared for publication in the journal *Catena* (May et al., to be submitted). It investigates four paleosol-sediment-sequences along the Andean piedmont at Santa Cruz regarding the regional paleoenvironmental evolution. As a result of the high sedimentological, paleopedological and chronological complexity inherent to these sequences, stratigraphical correlation proves difficult. Therefore this study sets a focus on the application of paleopedological methods in order to identify paleopedological processes and interpret their paleoenvironmental significance.

Finally, chapter 6 provides a synthesis of all obtained results. The discussion of these results in the context of regional to continental scale paleoenvironmental evolution emphasizes results of overall validity. In addition, unsolved problems are briefly mentioned. Finally, this dissertation closes with the suggestion of possibilities for future research within a multi-disciplinary context.

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2

GEOMORPHOLOGICAL INDICATORS OF LARGE-SCALE CLIMATIC CHANGES IN THE EASTERN BOLIVIAN LOWLANDS

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modified from Geographica Helvetica 61(2): 121-134

ABSTRACT

This study provides an inventory of geomorphological landforms in Eastern Bolivia at different spatial scales. Landforms and associated processes are interpreted and discussed regarding landscape evolution and paleoclimatic significance. Thereby, preliminary conclusions about past climate changes and the geomorphic evolution in Eastern Bolivia can be provided. Fluvial and aeolian processes are presently restricted to a few locations in the study area. A much more active landscape has been inferred from large-scale channel shifts and extensive paleodune systems. Mobilization, transport and deposition of sediments are thought to be the result of climatic conditions drier than today. However, there are also indications of formerly wetter conditions such as fluvial erosion and paleolake basins. In conclusion, the documentation and interpretation of the manifold landforms has shown to contain a considerable amount of paleoecological information, which might serve as the base for further paleoclimatic research in the central part of tropical South America.

2.1 INTRODUCTION

Late Quaternary tropical paleoclimatic research has become successively more important for our understanding of the global climate system. However, the major part of paleoclimatic data in tropical South America still originates from the Andean highlands. Data from the tropical lowlands are relatively scarce and in some cases contradictory. Without additional records from the tropical lowlands, any conclusion regarding the paleoclimatic history of tropical South America will thus be biased (Coltrinari, 1993). Situated at the transition zone between the tropical-humid and the subtropical semi-arid climatic regimes, the Eastern Bolivian lowlands are therefore particularly suited for the detection of large-scale climate changes.

Up to now, only few studies have been concerned with the geomorphology, landscape evolution and paleoclimatic history of the Eastern Bolivian lowlands (EBL). A general geomorphological overview is provided by Werding (1977) and Iriondo (1993). Servant et al. (1981) conducted first studies of paleosol-sediment-sequences, and only recently Mayle et al. (2000) and Burbridge et al. (2004) published results of vegetation and climate reconstructions deduced from pollen analysis in northeastern Bolivia. Another pollen record comes from a bog within the Andean cloud forest (Mourguiart and Ledru, 2003).

This study provides a revised inventory of geomorphological landforms in Eastern Bolivia at various spatial scales, benefiting from the increased availability and simplified use of remote sensing data (University of Maryland, 2005). In combination with field studies remote sensing turned out to be a powerful tool for area-wide geomorphological mapping. Landforms and landform associations are interpreted and discussed regarding landscape evolution and paleoclimatic history. This is the base for further and more detailed paleoclimatic research currently conducted in Eastern Bolivia.

2.2 STUDY AREA

Mountain building and Andean deformation associated with the subduction of the Nazca plate has progressively migrated eastward throughout the Cenozoic (Gubbels et al., 1993; Isacks, 1988), leading to thickening and horizontal shortening of the continental crust and the formation of the Eastern Cordillera and the Subandean Zone (Fig. 2-1). At least since Miocene times, the erosional products of active deformation in the Subandean Zone have been transported into the foreland of Eastern Bolivia (Gubbels et al., 1993). Therefore, the Eastern Bolivian lowlands are a retroarc foreland basin system with the Chaco Plain (~18°-24°S) being one of several active depocenters adjacent to the Central Andes (Horton and DeCelles, 1997).

The Subandean foothills can be regarded as the topographic transition from the Subandean Zone into the foreland basin (Fig. 2-1). To the east, active deformation structures are buried beneath Cainozoic sediments (Hinsch et al., 2002; Horton and

DeCelles, 1997), which thin out towards the east and onlap the pre-Andean basement. The northeastern margin of the Chaco plain is delimited by the outcrop of the Precambrian Brazilian shield. The transition between the Chaco plain and the Brazilian shield is interrupted by the Chiquitana ranges consisting mainly of sedimentary rocks of the Palaeozoic Chaco basin. Palaeozoic rocks are unconformably overlain by a thin cover of Mesozoic rocks (Welsink et al., 1995) and extend onto a topographic and structural high to the south (Izozog arch) representing the flexural forebulge of the Andean deformation (Horton and DeCelles, 1997).

The present climatic conditions of the EBL reflect their location between the tropical wet climate regime of the Amazon basin and the subtropical semi-arid climate to the south. During austral summer the South America Summer Monsoon (SASM) dominates the atmospheric circulation over most of continental South America (Nogues-Paegle et al., 2002; Zhou and Lau, 1998). NE-trade winds are responsible for moisture advection from the tropical Atlantic into the Amazon basin. From there, the southward transport of the Amazonian moisture into the EBL and towards the South Atlantic Convergence Zone (SACZ) is accomplished by the South American Low Level Jet (SALLJ) (Berri and Inzunza, 1993). The SALLJ is a strong N-S wind system east of the Andes active throughout the year (Saulo et al. 2004). However, due to the lack of topographic barriers, cold air incursions from mid-latitude South America periodically penetrate deep into the Amazon basin (Garreaud, 2000) leading to significant lowering of temperatures and enhanced precipitation during austral winter (Garreaud, 2000; Pezza and Ambrizzi, 2005).

Precipitation amounts and distribution in Eastern Bolivia depend to a large extent on the SASM and its components. Total annual precipitation decreases from ~ 1500 mm/a at 17° S to <500 mm/a at 21° (AGTECA, 2005). This trend is accompanied by increasing duration of the dry season (seasonality) towards the south. Most precipitation (~ 40%) falls as a direct result of convective activity during the rainy season in the months of December to February. The distribution of potential vegetation and ecosystems largely reflects the present climatic conditions. Ibisch et al. (2004) differentiate four ecoregions: The Amazon evergreen forests and the semi-deciduous Chiquitano Dry Forest in the north grade into the open and wooded savannas of the Cerrado formations in the east and into the low deciduous dry forest of the Gran Chaco in the south.

2.3 METHODS

In order to achieve a complete coverage of the study area, various kinds of remote sensing data have been integrated within this study. Increased availability and improved management of satellite imagery on a low-cost basis have made the use of these data efficient (Butler, 2006; University of Maryland, 2005; USGS, 2005). Depending on their characteristics, different types of data have been used for different purposes (Table 2-1).

Mission / Data	Spatial Resolution	Spectral Resolution	Temporal Resolution	Use
LANDSAT MSS	80 m	multispectral	1972-1992	
LANDSAT TM	30-120 m	multispectral	1982-present	multi-temporal analysis (observation of change, deduction of processes), medium-scale mapping
LANDSAT ETM	15-60 m	multispectral	1999-present	
ASTER	15-90	multispectral	2000-present	multi-temporal analysis, medium to small-scale mapping with high temporal coverage (recent events)
CORONA	3-5 m	panchromatic	1960-1972	small to medium-scale mapping (deduction of change / processes)
MODIS	250-1000 m	multispectral	2000-present (daily)	large-scale mapping, up-to-date observations
AERIAL PHOTOS	1-2 m	panchromatic	since 1950's (in Bolivia)	small-scale regional mapping
SRTM	30-90 m	-	February-2000	geomorphic analysis (quantitative & qualitative interpretation)

Table 2-1: *Remote sensing data used for geomorphological mapping and their characteristics.*

For the detection and mapping of geomorphological features from remote sensing data, various methods have been proposed in the literature, each applying to a specific purpose of mapping (Barsch and Liedtke, 1980). The deduction of landscape evolution (*genetic geomorphology*) results from comparison of past landforms and present processes, which requires spatially and temporally diverse information. Visual interpretation incorporates colour, density and texture of the imagery, but also deduces information from elevation, vegetation and land-use patterns (Rosenfeld, 1984; Verstappen, 1977). Apart from the remote sensing data, this study integrates information collected during several months of field work conducted over three years from 2003-2005.

2.4 RESULTS

The EBL can be outlined following structural and topographic criteria. In contrast to the adjacent Andes to the west and the Brazilian shield to the east, the generally low relief is due to active sedimentation processes throughout the recent geological past. The visualization and analysis of digital elevation data allows the subdivision of the lowlands into three distinct geomorphological units (Fig. 2-1):

- ***A1 and A2:*** *Alluvial slopes of the piedmont (northern and southern part) bordering the Subandean Zone*
- ***B1, B2 and B3:*** *Fluvial megafans of the three large river systems in the study area from south to north (Río Parapetí, Río Grande and Río Piray)*
- ***C:*** *Topographically elevated upland areas corresponding to the structural high of the Andean forebulge*

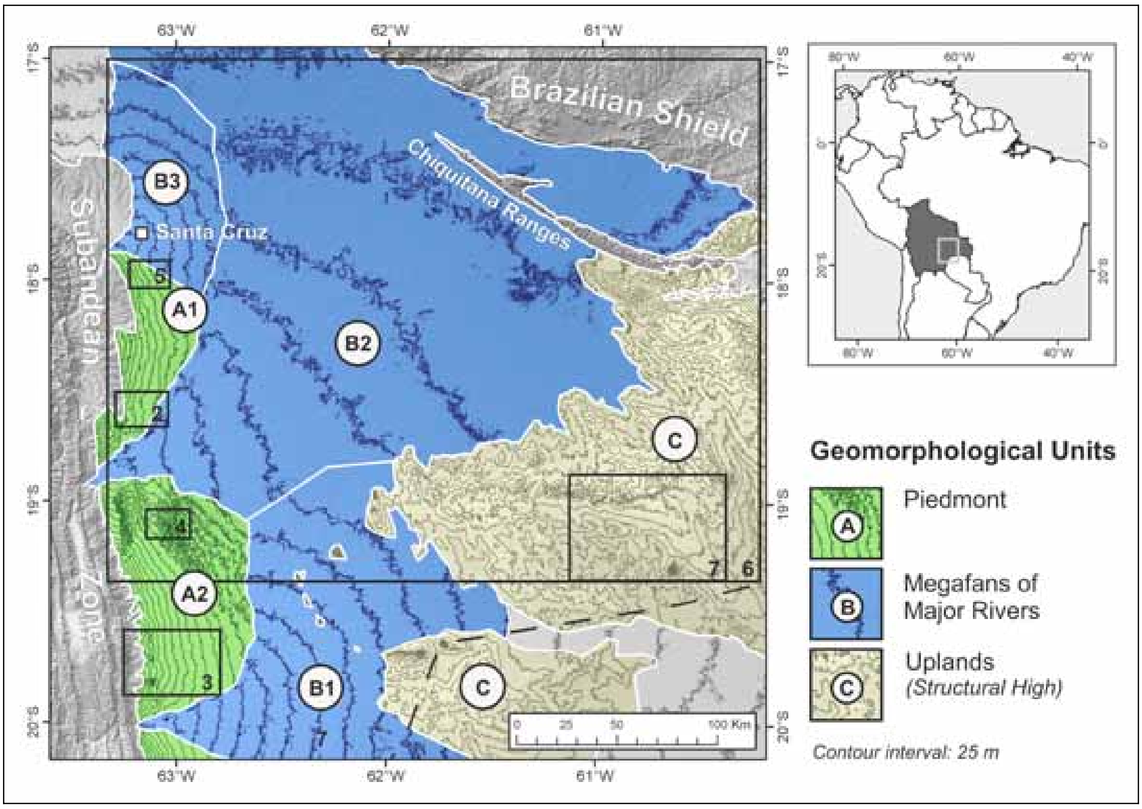

Fig. 2-1: *Macro-scale geomorphological units in the study area as deduced from digital elevation data (black boxes refer to location of figures).*

These units are genetically distinct macro-scale geomorphological landforms. Their age and evolution have to be considered within the context of the formation of the Andes extending back into the Tertiary (Baker, 1986; Horton and DeCelles, 1997). On shorter timescales focussing on Late Quaternary landscape and climate history, present processes typical for each of these three landscape elements can be compared to relict landform generations. Thus it is possible to detect changes in geomorphic processes over time, which in turn serves as indicator for changes in the controlling parameters of landscape evolution, namely tectonics, climate and humans (Schumm, 1999; Summerfield, 2000).

2.4.1 PIEDMONT

The Andean piedmont forms the transition zone between the Subandean ranges and the fluvial systems of the large rivers of Eastern Bolivia. Morphologically, it is a gently eastward inclined slope). Low slope angles of ~0,35–0,55 % and the apparent lack of alluvial fan morphology indicates that confined stream flow is the main process of piedmont construction (Smith, 2000). With the piedmont being a typical alluvial slope, paleoclimatic implications may be derived from its sedimentological architecture and the reconstruction of paleohydrology.

In the study area, the piedmont can be subdivided into a northern and a southern part (A1 and A2) separated by the Río Grande megafan. Both parts are situated in climatically different environments, with the northern part being characterized by higher total annual precipitation and less pronounced seasonality. Therefore differences in type and intensity of the dominant geomorphic processes can be expected.

Drainage network

The Subandean foothills are the catchment areas of the piedmont (Fig. 2-2). Bordered by a topographically sharp thrust-fault, they are characterized by a highly integrated drainage network and an advanced stage of dissection. Today the entire area is covered by dense forest and drainage channels within the foothills are largely inactive. Floodplains and channel beds do not show evidence for active sediment transport on the piedmont. In some cases valleys several hundred meters wide are presently not occupied by any recognizable stream. Therefore the dissection of the foothills must have occurred under past climatic conditions different from today.The drainage network on the piedmont follows the inclination of the piedmont slope. No drainage channels presently reach the Río Grande or Río Parapetí. Active floodplains and significant sediment transport on the piedmont have only been observed in the northern part of the piedmont (A1) in the vicinity of Santa Cruz and along the southern part of piedmont (A2). In both areas the drainage channels have incised into the proximal part of the piedmont surface. In between these areas, the drainage channels are essentially inactive and do not show any evidence for neither sediment transport nor incision (Fig. 2-2).

Along the southern piedmont the drainage channels deposit their bed-load when emerging from the incised reach of the channel (Fig. 2-3). This process causes a delta-shaped lobe of coarse fluvial sediments referred to as floodout (Tooth, 2000). These floodouts seems to have been located significantly further downslope in the past as evident from large areas of reduced density of forest cover. The shift of the floodouts to the proximal parts of the piedmont probably indicates reduced intensities of the discharge events.

Paleodunes

The most characteristic geomorphological features along the northern part of the piedmont are several paleodune fields (Fig. 2-2). They all consist of NW-SE to N-S trending parabolic dune forms, corresponding to the dominant wind direction (AGTECA, 2005). The parabolic dune forms indicate a uniform wind regime and the presence of a vegetation cover dense enough to fix the lateral limbs of the dunes during dune migration (Mc Kee, 1979).

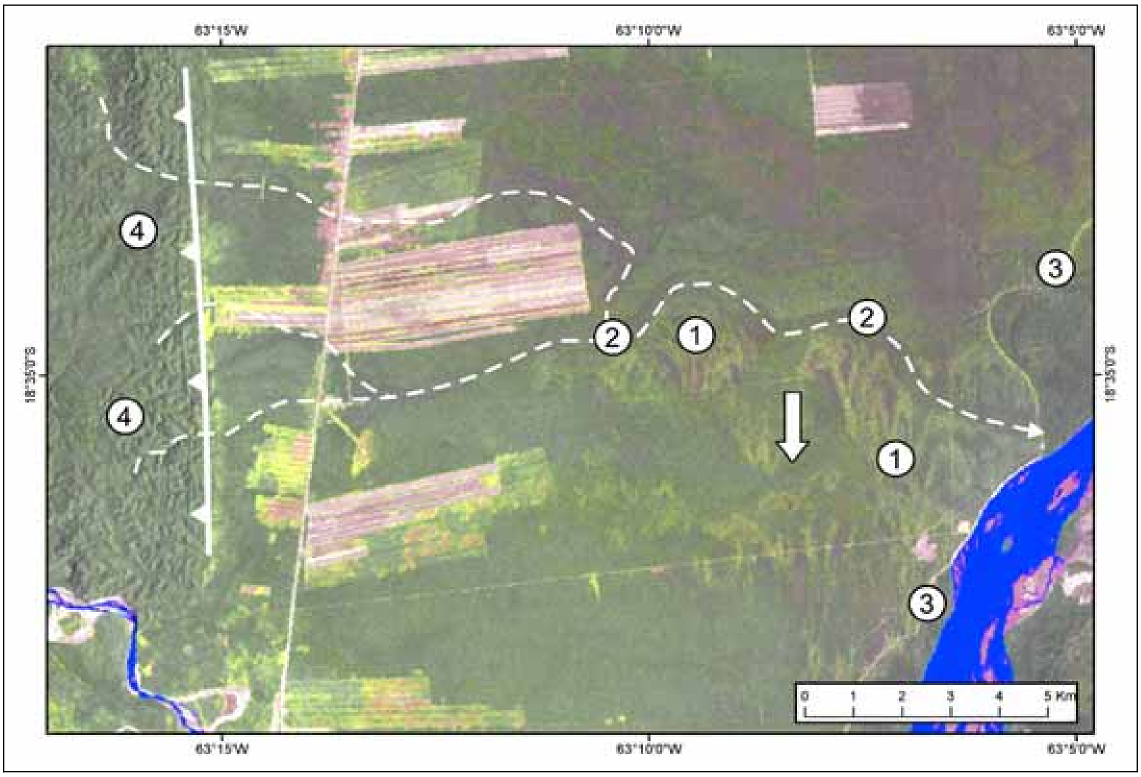

Fig. 2-2: *Paleodunes (1) and largely inactive drainage channels (white dashed lines, 2) are most characteristic features on the piedmont between the erosional scarp (3) of the Río Grande and the uplifted and dissected Subandean foothills (4) (arrow = paleowind direction); Landsat TM 230/73, 5-4-3.*

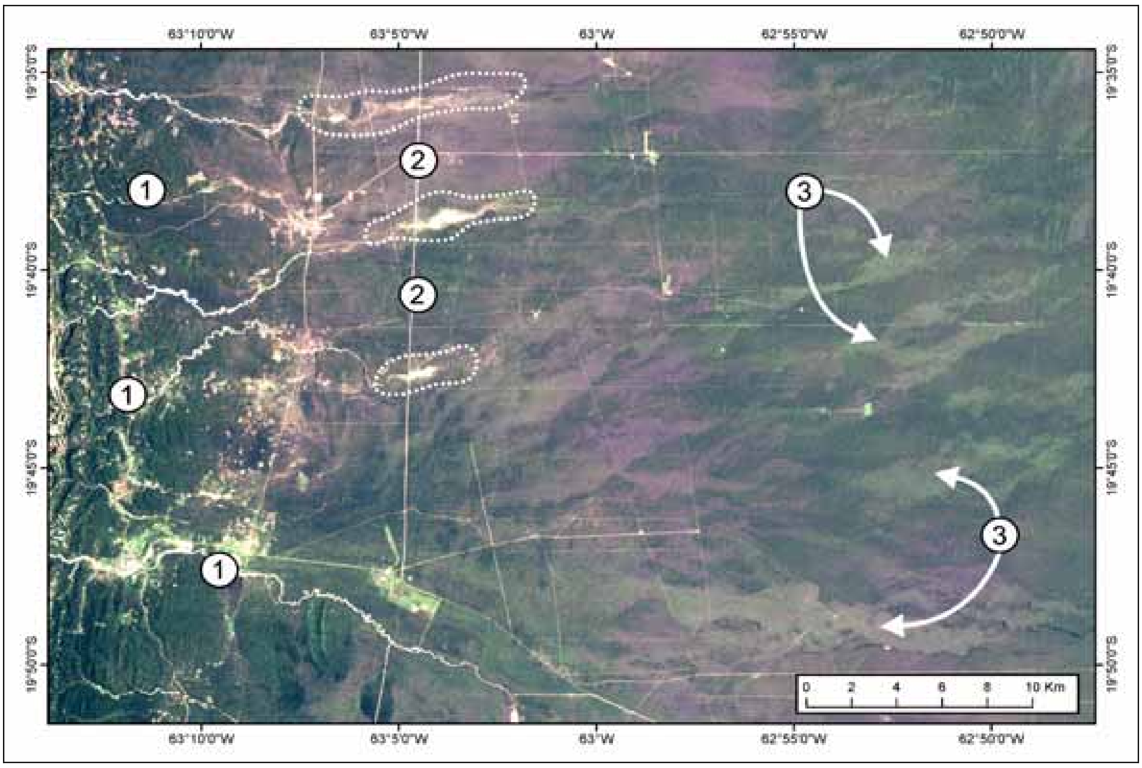

Fig. 2-3: *Incised drainage channels (1), floodouts (2) and area of paleo-floodouts (3) along the southern piedmont; Landsat TM 230/74, 3-2-1.*

In some cases the limbs are several kilometres long, implying a high movement rate and/or a relatively long time period of dune activity. Paleodune systems have only been observed along the southern margins of drainage channels. Apparently, past dune formation was closely tied to sufficient sediment supply. Both, the fluvial transport of sediment out of the Subandean catchments onto the piedmont, and the subsequent aeolian reworking most likely indicate generally drier climatic conditions with reduced forest cover, intensified discharge events and a prolonged dry season.

A large dune field (Lomas de Guanacos) exists on the southern part of the piedmont (Fig. 2-4, 2-6). It is largely inactive today. Its size (~2.250 km^2) as well as its position along the southern border of the Río Grande megafan point to the Río Grande as the source of the aeolian sands that build up the Lomas de Guanacos. In contrast to the smaller paleodune formations to the north, the Lomas de Guanacos exhibit a complex internal structure. Three dune generations can be distinguished. The peripheral parts of the dune field consist of long, N-S trending dune ridges. These ridges are interpreted as limbs of large parabolic dunes. They show smooth morphology, which points to fluvial erosion after their fixation and indicating a relatively old age. Towards the central part, the Lomas de Guanacos are characterized by a more undulating surface morphology and smaller parabolic forms. Within this younger generation, inactive dunes have been distinguished from active dunes based on the density of forest cover. A marked change in paleowind strength and/or direction must have occurred between the formation of the older and the younger dune generations, as the NNE-SSW direction of the younger generation does not correspond to the N-S direction older dunes (Fig. 2-4).

Active dunes

Two active dune complexes form the nucleus of a dune field (Lomas de Arena) ~15 km south of Santa Cruz (Fig. 2-5). The dune fronts actively advance into the forest, forming a large parabolic dune with limbs of various kilometers length. Most of the active inner dunes, however, are barchanoid forms, illustrating the missing influence of vegetation on dune mobility (Mc Kee, 1979). The evolution of the Lomas de Arena has passed through at least two distinct phases. This is evident from the inactive paleodunes surrounding the active dune fields. Sand deflation and initiation of dune migration is presently observed along the floodplains of various small drainage channels (Jordan, 1981), suggesting that the Subandean foothills are an essential source for the aeolian sands apart from the Rio Piray. The ongoing activity of the Lomas de Arena dune fields is therefore probably closely tied to the development of the drainage channels. This example illustrates that dune formation does not require desert like conditions, but sufficient sediment supply, strong winds and a pronounced dry season in order to transfer the material out of the floodplains. Based on the extent and occurrence of paleo- and active dunes, areas prone to present deflation and dune formation are apparently more restricted (Fig. 2-5). Increased discharge intensity and sediment supply may also have played a role for the initial evolution of the Lomas de Arena.

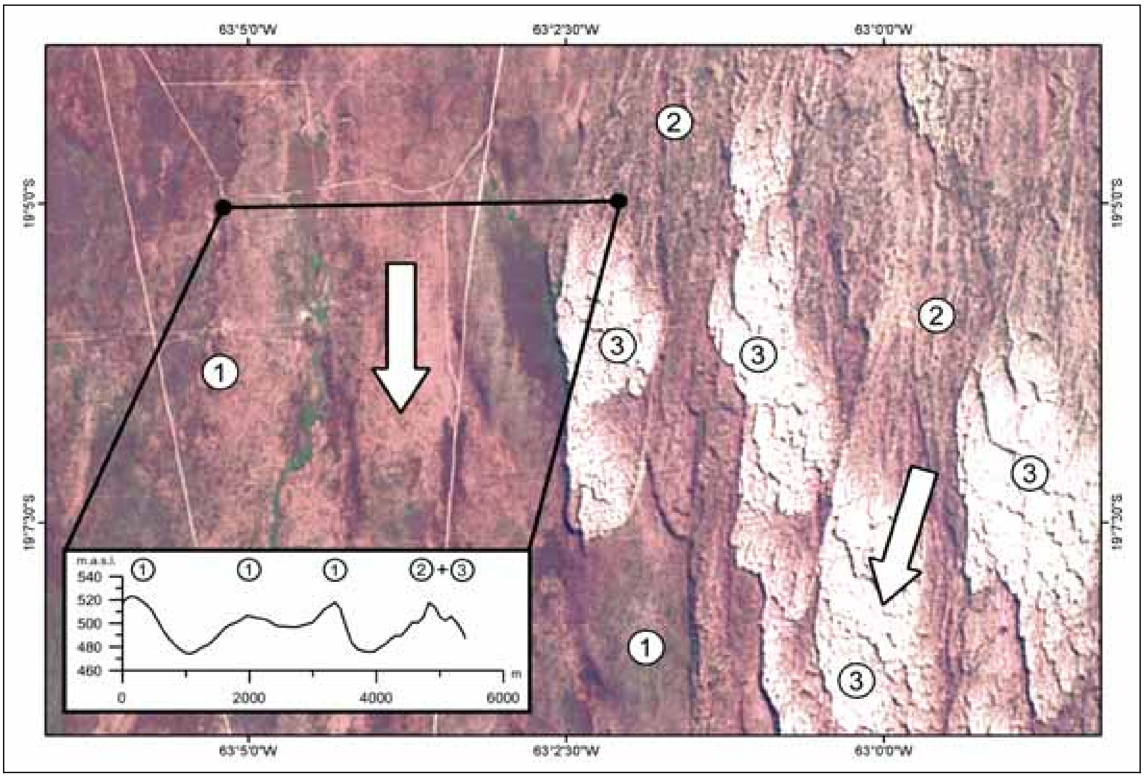

Fig. 2-4: Paleodune field of the Lomas de Guanacos with oldest dune generation (1), younger formations (2) and active dunes (3) (arrow = paleowind direction); Landsat ETM 230/73, 5-4-3.

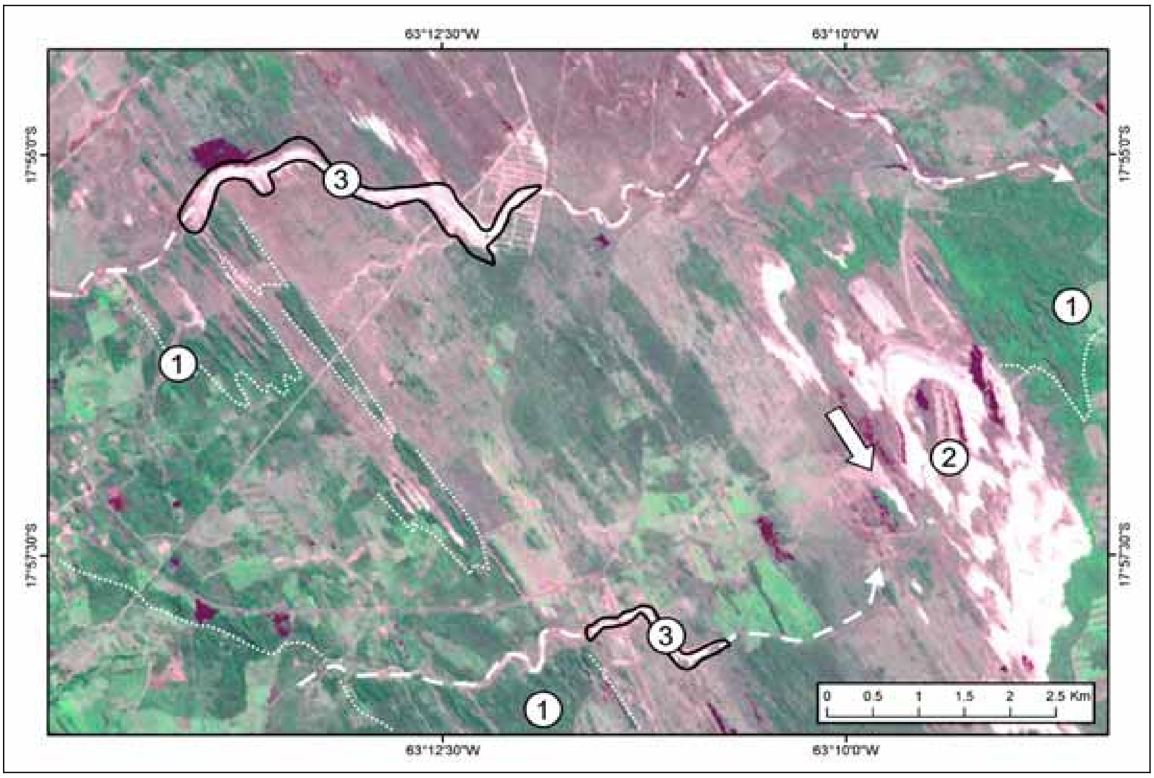

Fig. 2-5: Paleodunes (dotted, 1) and active dunes within the Lomas de Arena dune field; deflation on restricted floodplain areas (3) (arrow = paleowind direction); ASTER VNIR, 2-3-1.

2.4.2 MEGAFANS

Three fluvial megafans have been formed by the three major rivers in Eastern Bolivia. The Río Piray megafan northeast of Santa Cruz de la Sierra (~4.300 km^2) is the smallest one; the Río Grande (~37.500 km^2) megafan and the Río Parapetí megafan (15.000 km^2) are considerably larger. Large-scale channel migrations on the megafans have described previously (Horton and DeCelles, 2001; Werding, 1977). Megafans are characteristic for large subtropical rivers (Leier et al., 2005) and show a downstream zonation depending on the hydrological and geomorphological characteristics of each megafan (Shukla et al., 2001). Shifts in the zonation are therefore likely to reflect paleoclimatic and paleohydrological changes in the megafan.

Today, the Río Parapetí (B1) flows along the north-western margin of its megafan. Several paleochannels of the Río Parapetí can be reconstructed from vegetation differences on the megafan. The pattern of the paleochannels implies a northward shift of the river course through time. Based on the topographic data, the southernmost paleochannel can be traced into Paraguay, where it formerly contributed to the Río de la Plata basin (Barboza et al., 2000). Along the southern megafan margin, the oldest visible paleochannel grades into a large paleodune field (14.500 km^2), exclusively composed of parabolic dunes. It extends almost to the Argentinean border and into Paraguay. Probably, the Río Parapetí maintained its southern position for a prolonged period of time before the onset of the northward shift. Parabolic paleodunes occur along the southern margins of all paleochannels. They are larger than the active dunes along the present channel, indicating increased sediment supply and enhanced deflation during the time of channel migration.

At ~19°S the Río Parapetí deposits most of its coarse sediment load within a highly migrational inland delta, the wetlands of the Bañados de Izozog. A large paleodune field of mainly parabolic and longitudinal morphology exists along the southeastern margin of the Bañados de Izozog in the Kaa' Iya National Park (Fig. 2-6). Based on the large size of this paleodune field (800 km^2) we suspect that a former channel of the Río Grande has been the source for the aeolian sands.

Near the proximal part of the megafan, the Río Parapetí has formed two distinct terrace levels corresponding to enhanced incision, probably indicating decreasing sediment loads at the transition to wetter conditions and increased humidity.

The present course of the Río Grande (B2) is confined to the northwestern margin of the megafan (Fig. 6). In analogy to the Parapetí megafan, several paleochannels due to a northward shift of the river channel from a formerly W-E direction towards the present SW-NE-NW direction. At the eastern border of the Río Grande megafan the Río Parapetí cuts through the Chiquitana ranges at the Quimome gap (Fig. 2-6). This gap is probably an antecedent gorge resulting from stable discharge conditions over a long period of time. The antecedence is assumed to be inherited from the formerly W-E flowing Río Grande under conditions wetter than today, because the present Río Parapetí rarely produces discharge events powerful enough to reach the gap.

Although parabolic paleodunes (3-10 km^2) occur at several places along the southern margins of the Río Grande paleochannels, they do not match the paleodunes along the Río Parapetí paleochannels in size. Most likely this can be explained with the N-S climatic gradient. Due to a shorter dry season the Río Grande was less prone to sand deflation than the Río Parapetí.

Along the proximal part of its megafan, the Río Grande has laterally eroded the piedmont, forming pronounced erosional scarps along the western and southern margin (Fig. 2-2, 2-6). Meander-like curvature of the scarps possibly implies a phase of enhanced meandering under wetter conditions (Fig. 2-2). In addition to lateral erosion, incision has occurred postdating the major river migration, possibly at the transition to wetter conditions.

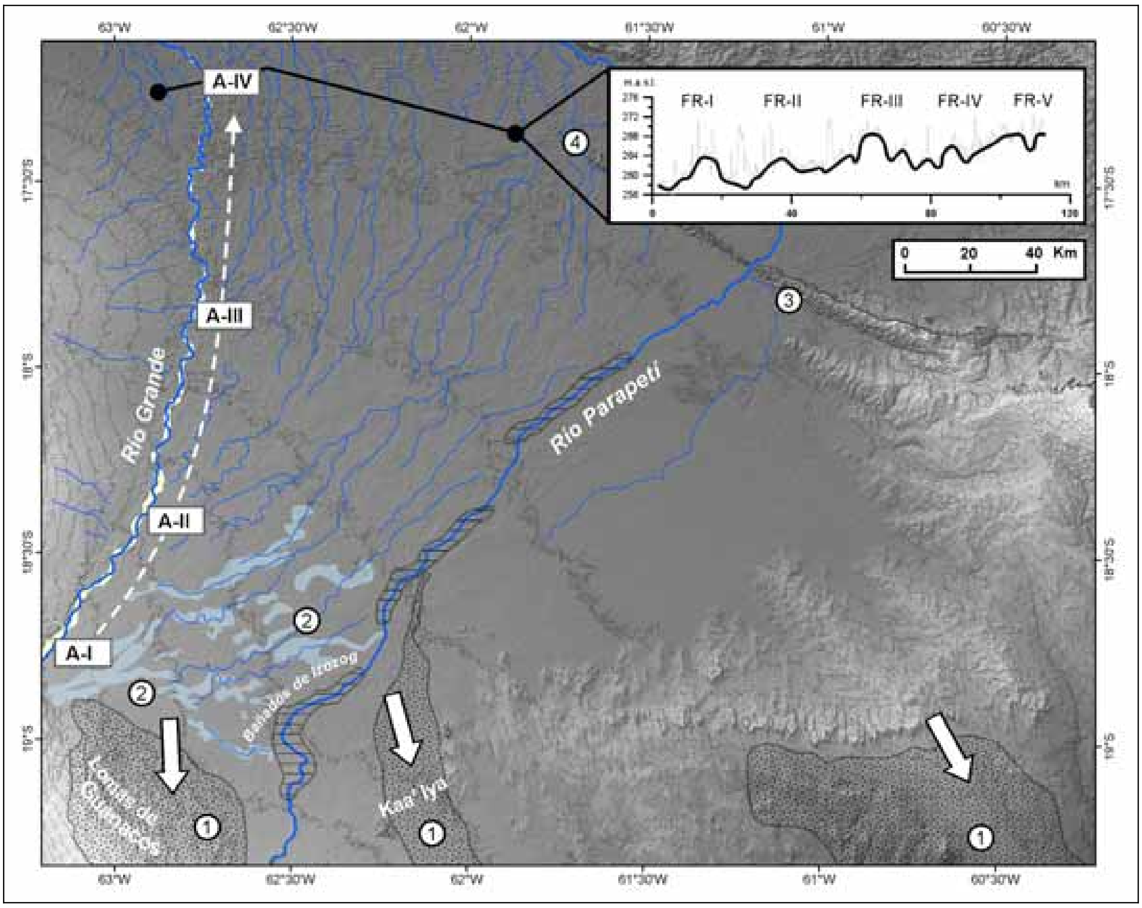

Fig. 2-6: *Overview of the Río Grande megafan and the associated paleodune fields (1), the paleochannels (shaded blue, 2), antecedent Quimome gap (3), mapped cañadas (blue lines), fluvial ridges (FR-I to FR-V) based on topographic transect (4) and northward propagation of the avulsion point (white dashed arrow, A-I to A-IV); arrow = paleowind direction.*

In contrast to the Parapetí fan, small episodic secondary drainage channels (*cañadas*) have formed on the Río Grande megafan within several of the paleochannels as well as in the areas between the paleochannels. The orientation of the cañadas and their coupling to the paleochannels indicate the existence of topographically elevated fluvial ridges (Brierley, 1997). These ridges mark the former courses of the Río Grande. Thus, the reconstruction of the paleochannels in the northern part of the megafan can be inferred from the network of cañadas (Fig. 2-6), whereas in the southern part it is based predominantly on the interpretation of vegetation patterns. In general, cañadas become more frequent towards the northern part of the Río Grande megafan owing to climatic conditions characterized by increased humidity. In addition, the patterns of cañadas on the Río Grande megafan indicate that avulsion point - the location where the river abandons its channel to occupy a new one - has significantly moved downstream through time (Fig. 2-6). While this might reflect the natural process of propagating fluvial deposition into actively aggrading sedimentary basins (Hanagarth, 1993), the large-scale shift of the avulsion point might also document a change towards more constant discharge and sediment supply, and gradual construction of fluvial ridges under wetter climatic conditions (Bristow et al., 1999).

The Río Piray (B3) presently flows along the western margin of its megafan. The orientation of cañadas and land-use patterns indicate the presence of paleochannels. Two distinct terrace levels have formed due to incision in the proximal part of the Río Piray megafan. The terrace scarps show meander-like curvature at various places, pointing to enhanced meandering during or following the phase of incision. Meandering might be the result of finer sediment loads and smoothed discharge regimes, possibly under overall wetter conditions (Schumm, 2005).

Several authors have reported on the large-scale river shifts of the Río Grande and the Río Parapetí. However, there is no consensus concerning the causes of this phenomenon. Dumont (1996) argues that tectonic subsidence might be the main reason for the shifts. However, the Río Parapetí has shifted from slightly steeper longitudinal gradients (0,185 %) towards less inclined gradients (0,165 %), which contradicts fluvial adjustment to tectonic uplift. Horton and DeCelles (2001) suggested stream capture as responsible for channel abandonment and migration without specifying the causes and mechanisms of this process. Werding (1977) proposed that the successive northward channel displacement could be explained by enhanced aeolian accumulation along the southern channel margin under dry climatic conditions. The relatively small number and extent of paleodunes along the Río Grande paleochannels in comparison to the Parapetí paleochannels cast doubt on this mechanism being responsible for large-scale shifts in both megafans. In addition the northward displacement of the avulsion point is not explained by enhanced dune accumulation alone. Hanagarth (1993) points out that increased sedimentation rates could accelerate the process of channel migration on the Río Grande megafan. Within the context of the geomorphological framework and the manifold indicators of climatic change, increased sedimentation rates resulting from climatic and paleohydrological changes could have substantially altered the fluvial regime of the megafan rivers and are likely responsible for the large-scale channel shifts.

2.4.3. UPLANDS (STRUCTURAL HIGH)

In contrast to the Subandean Zone or the Brazilian Shield, the structural high corresponding to the Andean forebulge has no well-developed drainage network. The most striking features are the W-E orientated cuestas (escarpments) of Mesozoic and Palaeozoic rocks and the isolated mesa of the Cerro San Miguel, representing geomorphological evidence for the long erosional history of these upland areas (Fig. 2-7). The dissection of the cuesta essentially follows a NW-SE direction. To the south, an elongated, ramp-like and topographically elevated area extends in NW-SE direction to Paraguay (Fig. 2-7).

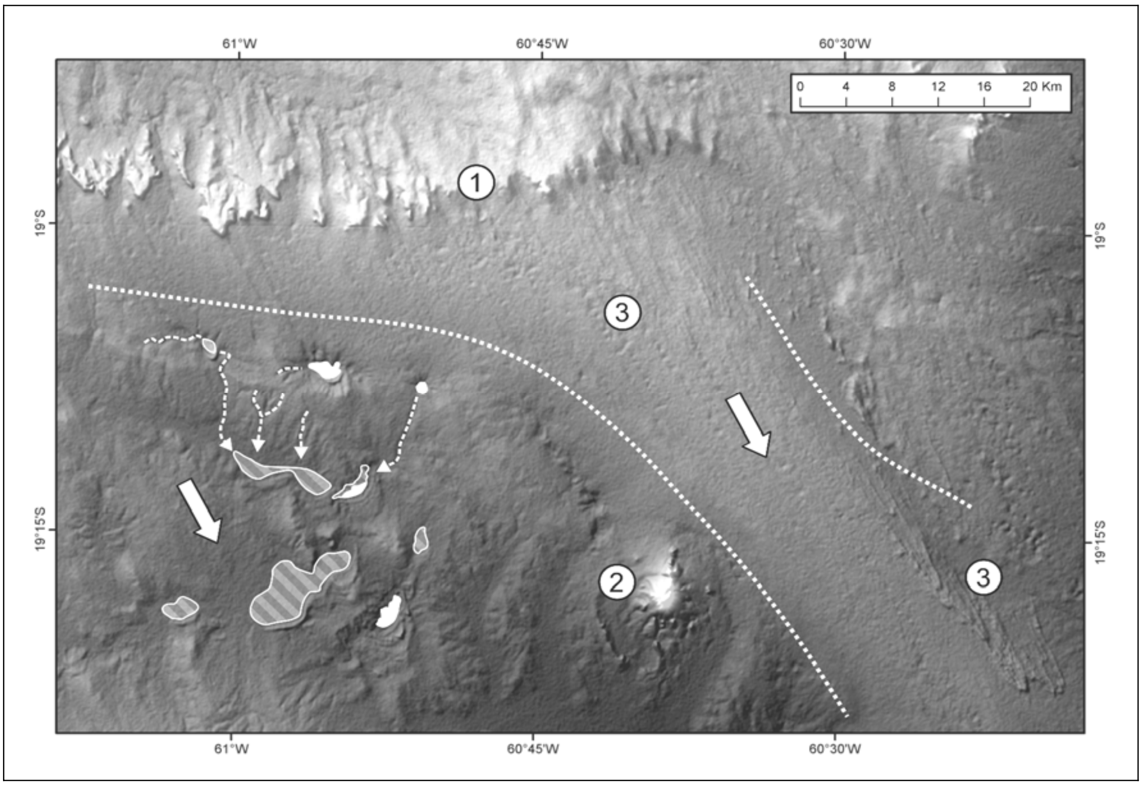

Fig. 2-7: *Cuesta (1), mesa (2) and assumed sand-ramp with paleodunes (dotted, 3); note paleolake basins (hatched) and present saline lakes (white) with lunette paleodunes and incised drainage network between basins (dashed lines) (arrow = paleowind direction).*

Several fields of parabolic paleodunes are superimposed on top of this ramp. These paleodunes can be interpreted as the product of past deflation from the Río Grande megafan, aeolian transport over the uplands and deposition below the southern rim of the cuestas. In this context the ramp-like feature is assumed to represent a multiphase sand-ramp from repeated phases of aeolian deposition, giving evidence for the importance of aeolian processes in long-term landscape evolution of the entire EBL. A series of small lake basins occurs in the area between the cuesta and the Paraguayan border. Most of the basins are presently covered by forest; few of them contain seasonally inundated saline lakes and salt flats (Fig. 2-7). The basins do not seem to be integrated into an active drainage network. However, several incised valleys/gorges characterize the former drainage network within the lake catchment areas (Fig. 2-7). It is assumed that higher lake levels, overflowing and incision prevailed under substantially wetter climatic conditions. Along the south-eastern rim of the basins ridges of up to 10 meters height have been detected and interpreted as parabolic paleodunes (lunette dunes). All of these paleodunes are presently inactive and covered by forest. Their formation likely documents increased aeolian activity during dry conditions pre-dating the modern conditions, which favour forest growth.

2.5 DISCUSSION

The inventory of landforms presented in this study provides manifold evidence for changing geomorphic processes in Eastern Bolivia during the Late Quaternary. Figure 2-8 summarizes the sequential succession of landforms and associated processes for each investigated geomorphological unit. However, only a tentative correlation can be accomplished, because very few absolute age datings are available so far. Nevertheless, a careful interpretation is attempted in order to correlate events and distinguish phases of landscape evolution.

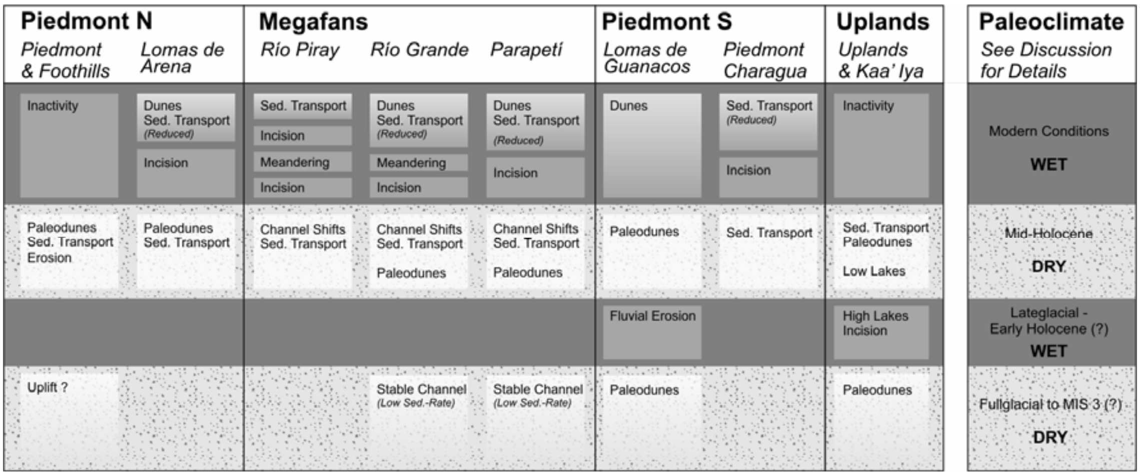

Fig. 2-8: *Sequential landscape evolution as observed for the geomorphological units of the study area and the tentative correlation to paleoclimatic phases (grey shades and black dots).*

The concept of landscape stability and activity (Rohdenburg, 1970) uses the intensity and spatial distribution of geomorphic processes (activity and stability) as an indicator for paleoecological conditions. Due to the complexity of feedbacks within the geomorphic system and the difficulties to define thresholds, the effects of climate changes do not only depend on the direction of the change (e.g. from dry to wet) but also on the climatic and geoecological conditions before the change (total precipitation, seasonality etc.) (Thomas, 2004; Wolman and Gerson, 1978). Therefore, the discussion of landscape evolution and climate history is restricted to the identification of regional sequences of events and landforms, providing a large-scale paleogeoecological frame rather than quantitative paleoclimatic data for the Eastern Bolivian lowlands.

Geomorphological activity in Eastern Bolivia is presently restricted to a limited number of locations. The overall stable landscape (forest cover, inactivity of drainage channels) is an actualistic example for relatively wet climatic conditions. The onset of modern climatic conditions occurred around 3 ka BP in northeastern Bolivia (Burbridge et al., 2004; Mayle et al., 2000) and in Rondônia (de Freitas et al., 2001; Pessenda et al., 1998), and around 4 ka BP in the Subandean cloud forests (Mourguiart and Ledru, 2003), suggesting relative landscape stability in the study area within the last 4 ka.

In contrast, the observation of numerous paleodune fields and the wide-spread shifts of the floodouts and paleorivers document a generally active landscape under more arid climatic conditions. The reduction of vegetation cover probably enhanced erosion in the catchment areas (e.g. the Subandean foothills, Cordillera Oriental etc.) and reduced infiltration capacity. The resulting high-magnitude and low-frequency run-off events (Wolman and Miller, 1960) transported large quantities of coarse sediment onto the piedmont and the megafans, causing rapid sedimentation and channel shifting. Simultaneously, aeolian activity favoured by the reduced vegetation cover and the existence of extensive deflation areas lead to the formation of paleodune fields.

The Mid-Holocene (~8-3 ka) in central South America has been reported to be arid, with widespread sand accumulation of the fluvial systems (Barboza et al., 2000; Kruck, 1996), the expansion of savanna type vegetation (de Freitas et al., 2001; Pessenda et al., 1998) and frequent forest fires (Mourguiart and Ledru, 2003; Servant et al., 1981). Therefore, the above findings have been tentatively correlated with this Mid-Holocene arid period. This correlation is supported by several preliminary radiocarbon dates on charcoal from fluvio-aeolian sands near Santa Cruz (4880 ± 20 ^{14}C yr BP, 5090 ± 40 ^{14}C yr BP), Cabezas (6580 ± 40 ^{14}C yr BP) and Charagua (4220 ± 35 ^{14}C yr BP, 4950 ± 35 ^{14}C yr BP), as well as from aeolian sands at Pelícano (4860 ± 30 ^{14}C yr BP, compare Fig. 2-2).

At some places the geomorphological evidence points to increased humidity in the study area, preceding the highly active interval of sediment transport and dune formation. This is the case for the markedly smoothed morphology of the older dune generations, which must have undergone a time of erosion and reshaping, and the paleolake basins, which document even wetter conditions than today, possibly because of a significant increase of precipitation during the dry season. Despite of the limited number of observations, these findings corroborate previous studies reporting increased moisture availability in the Paraguayan Chaco (Barboza et al., 2000; Kruck, 1996) and the Subandean cloud forest (Mourguiart and Ledru, 2003) during Lateglacial times and the transition into Holocene.

Large paleodune fields along the southern margins of the megafans (Río Grande, Río Parapetí) document long time intervals of aeolian activity and constant sediment supply from the megafan rivers. The position of the Río Grande and the Río Parapetí should have been relatively stable lacking frequent and large-scale channel shifts. This indicates intense discharge events and high transport capacities. In fact, Werding (1977) notes the existence of coarse fluvial gravel throughout the Río Grande megafan.

An overall much more torrential fluvial regime has been reported from several tropical rivers in lowland South America during marine isotope stage 3 (MIS 3) (Latrubesse, 2003). Whether the older paleodune generations indeed correspond to MIS 3 or to the Last Glacial Maximum (LGM) and early Late Glacial cannot be decided on the basis of the available data. However, several preliminary radiocarbon dates on charcoal from fluvial sands at Santa Cruz (15140 ± 70 ^{14}C yr BP) and Cabezas (18700 ± 90 ^{14}C yr BP) indicate aridity in Eastern Bolivia during the LGM and early Late Glacial.

2.6 CONCLUSIONS

Based on detailed field work and remote sensing data it has been shown that the thorough description and interpretation of landforms and geomorphic processes has the potential to considerably contribute to the reconstruction of landscape evolution and climate history. In combination with existing records of climate change an overall picture of the Late Quaternary could be drawn for the central part of South America. The results presented in this study are the basis for further paleogeoecological studies. These focus on specific locations and include the establishment of absolute chronologies for the succession of processes and events.

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3

LATE QUATERNARY PALEOSOL-SEDIMENT-SEQUENCES AND LANDSCAPE EVOLUTION ALONG THE ANDEAN PIEDMONT, BOLIVIAN CHACO

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In review: Geomorphology

ABSTRACT

As part of the Bolivian Chaco, the Andean piedmont is situated in the transitional zone between the tropical-humid climate regime to the north (Amazonia) and the subtropical-semiarid regime to the south (Gran Chaco). In this zone, which is sensitive to climatic changes, Late Quaternary landscape and climate history was reconstructed based on detailed sedimentological, pedological and geochemical analyses of paleosol-sediment-sequences along the Andean piedmont. The determination of characteristic lithofacies allowed correlation between the investigated profiles and their interpretation in terms of paleoenvironmental conditions, i.e. geomorphic stability (soil formation) or geomorphic activity (fluvial or fluvio-aeolian sedimentation, erosion, etc.). Coarse fluvial deposits (gravels, sands) form the base of the investigated profiles and have likely been deposited in a braided-river environment with low vegetation cover and intensive discharge events before and during the Last Glacial Maximum. Well-developed paleosols formed in the upper part of these sediments during the Lateglacial documenting geomorphic stability (high vegetation cover) and wet conditions. Overlying palustrine sediments, dated to the Early Holocene, indicate a dramatic change in seasonality, i.e. increased winter precipitation and decreased summer precipitation. Subsequent erosion, followed by accumulation of fluvial and fluvio-aeolian sands, points to much drier conditions during the Mid-Holocene. Since ~2.9 cal ka BP soil formation indicates a return to geomorphic stability and wetter conditions (characteristic of the present day climate) interrupted by short arid intervals.

Keywords: Quaternary, paleohydrology, paleosol-sediment-sequences; climate change; piedmont; Chaco; Bolivia

3.1 INTRODUCTION

Over the last few decades tropical paleoclimatology has become more and more important for the understanding of the global climate system and its variability in the past. One research focus in tropical South America has traditionally been the Andean Altiplano and the Eastern Cordillera (Servant et al., 1981a; Seltzer, 1992; Clapperton, 1993; Argollo and Mourguiart, 2000; Mourguiart and Ledru, 2003; Servant and Servant-Vildary, 2003). However, significant contributions to the reconstruction of Late Quaternary landscape evolution also come from geomorphological research in the Amazonian lowlands (Räsänen et al., 1990; Latrubesse and Rancy, 1998; Latrubesse and Franzinelli, 2002; Latrubesse and Kalicki, 2002) and the aeolian and fluvial plains of northern Argentina and southern Brazil (Iriondo and Garcia, 1993; Iriondo, 1999; Stevaux, 2000). In addition, palynological studies help to improve our understanding of the paleoenvironmental history of the Amazon basin and the adjacent lowlands (van der Hammen and Absy, 1994; Ledru et al., 1996; Behling, 1998; Ledru et al., 1998; Colinvaux and Oliveira, 2000; van der Hammen and Hooghiemstra, 2000; Behling, 2002). All these investigations have provided evidence for a complex Late Quaternary landscape evolution in tropical South America characterized by major geomorphic, hydrological and ecological changes.

The Eastern Bolivian lowlands lie at the transition between the tropical wet climate regime of the Amazon basin and the subtropical semi-arid climate regime of the Chaco. Paleoclimatic and especially hydrological changes should therefore be sensitively recorded in suitable archives and the landscape in general. Nevertheless, up to now only few studies have focused on the geomorphic and paleoenvironmental evolution of the Eastern Bolivian lowlands. The large-scale geomorphology of the Bolivian Chaco has, for example, been discussed in Iriondo (1993), May (2006) and Werding (1977). First chronological results from Late Pleistocene and Holocene sediments and groundwater were reported from the Paraguayan Chaco by Geyh et al. (1996), Kruck (1996) and Pasig (2005), whereas Servant et al. (1981b) investigated the Andean piedmont in Eastern Bolivia using paleosol-sediment-sequences. Mostly, these studies lack the chronological control that is necessary for more detailed paleoclimatic interpretation and regional comparison, but show evidence for important paleoenvironmental changes in the Bolivian Chaco.

Here we present results from stratigraphical, grain size and geochemical analyses of paleosol-sediment-sequences that are exposed along the Andean piedmont. It has previously been emphasized that fluvial systems in tropical South America have a large potential for paleoclimate research (Baker, 2000; Latrubesse, 2003). Accordingly, our results are discussed in the context of the general landscape evolution of the Bolivian Chaco and the Eastern Bolivian lowlands. Thus, this study can contribute to the overall paleoclimate reconstruction of tropical and subtropical South America.

3.2 REGIONAL SETTING

The investigated paleosol-sediment-sequences are situated along the proximal part of the piedmont bordering the Andes approximately 100-130 km south of Santa Cruz de la Sierra (Fig. 3-1). Although situated at the southern margin of the Amazon basin, the climatic conditions in the Eastern Bolivian lowlands and the Bolivian Chaco area are dominated by the monsoonal tropical circulation system. During austral summer the South American Summer Monsoon (SASM) (Zhou and Lau, 1998; Nogues-Paegle et al., 2002) leads to intensive convective rainfall and causes a summer precipitation maximum. Cold air incursions from the south can periodically cause severe temperature drops and additional rainfall throughout the year (Garreaud, 2000). Total annual precipitation shows a pronounced N-S gradient and ranges from 1100 mm/a (Ing. Mora, 18.45°S, 63.22°W) to 650 mm/a (Río Seco, 18.65°S, 63.23°W); the dry season lasts 5-6 months during austral winter (AGTECA, 2005). Seasonality plays an important role for the hydrological regime and the regional vegetation. Today, the potential vegetation cover in the study area is mainly semi-deciduous Chaco forest (Ibisch et al., 2004) and due to its climatic and biotic characteristics the study area is considered part of the Bolivian Chaco.

The soils that have developed under the prevailing climate conditions are predominantly Luvisols, but Cambisols and Arenosols occur as well (Agrar- und Hydrotechnik GmbH, 1976; Guamán, 1999; Gerold, 2004). The high spatial variability of the soil types has been attributed to the heterogeneity of the parent material and to small-scale topographical differences (Guamán, 1999).

From a geological point of view the Eastern Bolivian lowlands are a retroarc foreland basin system (Horton and DeCelles, 1997). Due to denudation and erosion of the uplifting Eastern Andes, mainly fluvial sediments have been deposited here at least since Miocene times (Gubbels et al., 1993; Eji Uba et al., 2006). The Subandean foothills represent the easternmost topographic expression of Andean uplift and deformation (Hinsch et al., 2002). They consist of Tertiary and Pleistocene conglomerates and sands of mostly fluvial origin (Marshall and Sempere, 1991).

The Andean piedmont forms the topographic transition between the foothills and the large fluvial systems of the lowland (Fig. 3-1). It is a gently eastward inclined alluvial slope (~0.35 – 0.55 %) of 50-60 km maximum width. In contrast to alluvial fans, the piedmont was mainly built up by confined stream flow, i.e. by fluvial sedimentation of ephemeral and perennial drainage channels (Smith, 2000). Unlike the large fluvial systems of the Río Grande or the Río Parapetí, which receive sediment and runoff from many more extensive drainage basins reaching far into the Eastern Cordillera of the Andes, the Subandean foothills are the sediment source for the piedmont. Today the ephemeral drainage channels of the piedmont are partly inactive. At several locations they are associated with paleodunes (May, 2006), which document the dynamic interaction between fluvial and aeolian processes – a phenomenon that is well-known from the geomorphic system of the Chaco (Werding, 1977; Iriondo, 1993; Kruck, 1996).

In the sedimentary sequence of the piedmont, changes in the dominant geomorphic processes are recorded – and, accordingly, also changes in the prevailing hydrological and climate conditions during the Late Quaternary. Due to lateral migration of the Río Grande the piedmont is truncated and eroded, forming a terrace of approximately 40 km length and 5-25 meters height (Fig. 3-1, 3-2). At several locations vertical outcrops expose paleosol-sediment-sequences, which were studied in detail near Cabezas and Pelícano Ranch (Fig. 3-1). The profiles CAB-B, C1, C2 and D are situated directly at the banks of the Río Grande, CAB-A is located at a former meander scar (Fig. 3-2). The investigated profile at Pelícano Ranch (PCN) exposes the sedimentological and pedological sequence of the piedmont some 35 km northeast of Cabezas (Fig. 3-1, 3-2).

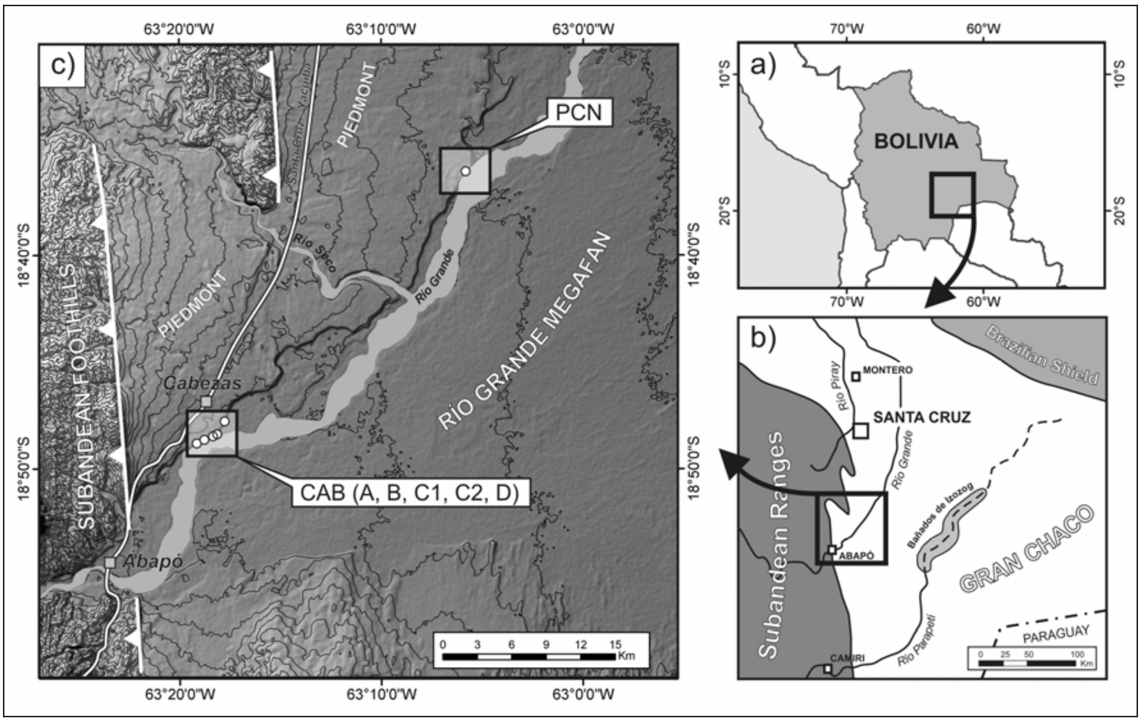

Fig. 3-1: *Location and regional setting of the study area. a) Political boundaries of Bolivia, b) Eastern Bolivian lowlands and the Subandean Ranges, c) Location of the investigated paleosol-sediment-sequences along the piedmont terraces at the banks of the Río Grande (CAB=Cabezas, PCN=Pelícano).*

3.3 METHODS

Documentation and analysis of the paleosol-sediment-sequences at Cabezas and Pelícano Ranch was conducted in three stages:

i) Reconnaissance along the terrace was necessary to detect erosional unconformities and to preliminarily determine the occurring lithofacies. Accessibility, outcrop conditions and completeness of the sedimentary units were the selection criteria to choose the six profile locations.

ii) Detailed description of the selected profiles was conducted using climbing equipment for abseiling along the vertical outcrops. Macroscopic pedological characteristics, such as colour, pedogenic texture, cutans, redox characteristics and carbonate pseudomycelia and nodules were documented according to AG Boden (1994). In addition, sedimentary features were studied, e.g. sorting, maximum clast size, and bedding. Imbrication, i.e. strike and dip of elongated clasts, was measured in the coarse fluvial gravels according to Tucker (1988) in order to reconstruct paleo-transport directions. Based on all these observations several sedimentary units and paleosols were distinguished. Three of the six paleosol-sediment-sequences (PCN, CAB-A and B) were sampled for laboratory analysis. A bulk sample of ~500 g was taken from each horizon or unit.

iii) Laboratory analyses were carried out on dry and sieved (< 2 mm) samples. A Munsell Soil Colour Chart was used to determine soil colour on dry samples. For grain size measurements, carbonates were removed with 10% HCl and organic matter was oxidized with 30% H_2O_2. In addition, micro-aggregates < 63 µm were dispersed with Na_2CO_3. The sand fractions (63-2000 µm) were separated by wet sieving and the silt (2-63 µm) and clay (< 2 µm) fractions were quantified using a Micromeritics SediGraph 5100. The carbonate content was measured with a Scheibler apparatus and the pH-values with a glass electrode in 0.01M $CaCl_2$ with a soil:solution ratio of 1:2.5. The mineral composition was measured by X-ray powder diffraction (XRD). X-ray fluorescence (XRF) was performed to determine the elemental composition. Amorphous and crystalline pedogenic iron (Fe_o and Fe_d) was extracted with oxalate and dithionite following standard procedures (Mehra and Jackson, 1960; Schwertmann, 1964) and measured using a coupled plasma optical emission spectroscopy (ICP-OES) (CAB-A) and a Hach Spectrophotometer (PCN), respectively.
Pedogenic iron is formed during soil formation (Schwertmann and Taylor, 1989) and can be used to assess the intensity of soil development and weathering (Torrent et al., 1980; Alexander, 1985; Zech et al., 2001). The proportion of crystallized and amorphous iron (Fe_d) compared to total iron (Fe_t) is commonly used to estimate the weathering intensity; the proportion of amorphous pedogenic iron (Fe_o) compared to Fe_d characterises weathering activity and soil maturity. Several other weathering indices were tested in order to quantify chemical weathering in our paleosol-sediment-sequences, e.g. the ratios Na/Al, K/Al, Sr/Ca and Sr/Ba (e.g. Gallet et al., 1996; Yang et al., 2004). In addition, weathering indices according to Kronberg and Nesbitt (1981) were applied and illustrated. Low index values indicate intensified chemical weathering.
The chronology of the profiles is based on AMS radiocarbon dating (Poznan Radiocarbon Laboratory) and conventional radiocarbon measurements (Institute of Physics at the University of Bern). In order to provide good comparability of the chronological data, our radiocarbon ages as well as other published radiocarbon ages were calibrated using the program CALIB 5.0.1 and the "intcal04" data set (Stuiver and Polach, 1977; Reimer et al., 2004).

3.4 RESULTS AND DISCUSSION

The paleosol-sediment-sequences at Cabezas and Pelícano extend several kilometres in NE-SW direction (Fig. 3-1, 3-2, Supp. Fig. 3-10). Thus, information concerning the lateral continuity of the sedimentary units can be deduced. This is particularly important regarding the interpretation of past geomorphic processes and their lateral variability, which has to be considered when correlating the investigated profiles and inferring more regional paleoenvironmental information.
At most places, for example, the terrace height varies from 15 to 20 meters; near Cabezas, however, it suddenly drops to ~8 m (Fig. 3-2). This lower terrace is a combined erosional - depositional feature (Supp. Fig. 3-8F, 3-10). It is composed of Río Grande sediments deposited onto the eroded piedmont (Supp. Fig. 3.12). On the contrary, the higher terrace is an erosional feature and exposes a more complete sedimentary history of the piedmont.
Erosional unconformities can be observed at both investigated localities. At Cabezas, the erosion is indicated by paleochannels of varying depths, whereas at Pelícano a hiatus is observed above the distinctive paleosol (Fig. 3-2, Supp. Fig. 3-8A-E).
In general, the paleosol-sediment-sequences show a fining trend towards the top and can roughly be divided into a coarser lower part with a paleosol developed at its top and an upper finer part above a more or less pronounced unconformity (Fig. 3-2). At Cabezas (CAB-B and D), the lower part of the sedimentary sequence consists of coarse fluvial gravel grading into sandy deposits. At Pelícano the lower part of the sequence consists of sand to pebble deposits. A reddish colour clearly indicates soil formation after deposition of these coarser sediments (CAB-A, B, D and PCN). This paleosol is overlain by thin layers of dark, fine-grained deposits of varying thickness. At both localities the uppermost part of the profiles consists of massive sands. At Pelícano these sands belong to paleodune formations as evident from sedimentological characteristics and surface morphology (Fig. 3-2). The sequence is topped by well-developed soils at Cabezas and a less well-developed soil at Pelícano. Locally, unweathered sands overlie these modern soils. The lower terrace outcrops at Cabezas (CAB-C1 and C2, Supp. Fig. 3-10, 3-12) also expose coarse piedmont gravel deposits at their base. In contrast to the profiles along the higher terrace segments, the upper part of the piedmont sediments is truncated and the transition to the overlying sandy and silty Río Grande sediments is very sharp. Young soils are developed at the top of the profiles.

3.4.1 SEDIMENTOLOGY AND GRAIN SIZES: DIFFERENTIATION AND INTERPRETATION OF LITHOFACIES

Grain size distributions from the profiles CAB-A, CAB-B and PCN have been analysed in order to confirm and refine the sedimentological field observations and to define various lithofacies, which are associated with specific geomorphic processes. Detailed description and interpretation of the sediments concerning their depositional environments, e.g. fluvial versus aeolian, can generally be based on the grain size

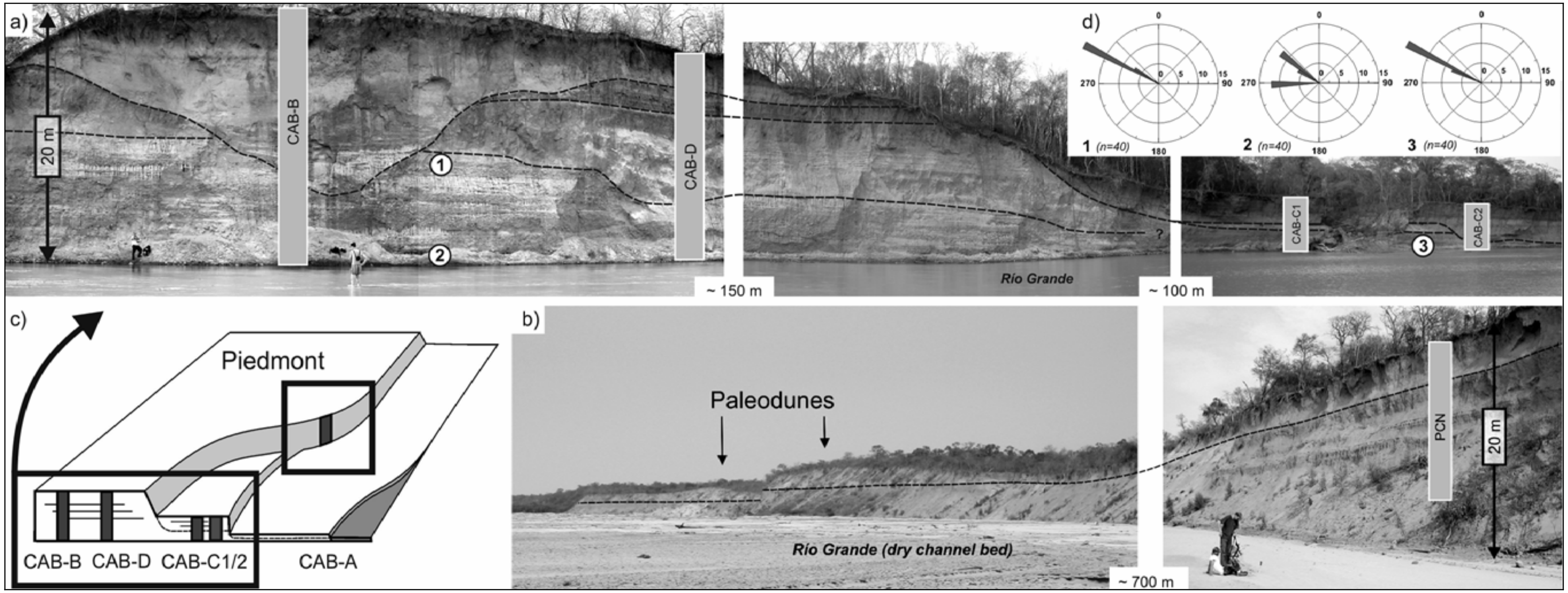

Fig. 3-2: *Composite panoramic view of the paleosol-sediment-sequences at Cabezas (a) and Pelícano Ranch (b). Grey boxes mark the profile locations along the outcrop (no photographic illustration of CAB-A). The sketch illustrates the geomorphological context of the higher and the lower terrace at Cabezas (c). The diagrams show the transport directions of the fluvial gravels in the lower parts of the profile at Cabezas (d). The dashed lines indicate the unconformity and/or hiatus between the lower, coarse part of the piedmont sequence and the finer, upper part.*

frequency distributions (Passega, 1964; Ahlbrandt, 1979) and cumulative frequencies serve as an estimate for sorting (Moiola and Spencer, 1979). The combined results of the sedimentological field observations and grain size analyses are illustrated in Figure 3-3.

The clast-supported gravel in the lower parts of the profiles have maximum clast sizes of 15-40 cm and do not show any recognizable grading (Supp. Fig. 3-9A). Gravel beds are horizontally stratified, but also have cut trough beds. The individual gravel beds are between 50 and 100 cm thick, and are interbedded with coarse and massive sands (Supp. Fig 3-8A). Such deposits typically indicate fluvial deposition in a wandering or meandering gravel-bed braided river (Miall, 1985). In the absence of apparent foreset beds, imbrication measurements of elongated gravel clasts can be used to reconstruct the direction of the paleocurrent and sediment provenance. At Cabezas (CAB-B, C1 and D; Fig. 3-2D) the imbrication measurements at all three locations indicate sediment transport directions from the northwest and west. Deposition of coarse gravel in a meander bend of a highly sinuous meandering river from the south or southwest seems unlikely. Accordingly, the sediment source areas are located in the Subandean foothills ~10 km west of Cabezas.

Sediments of mainly sandy grain sizes show considerable differences in their sorting. For moderately-sorted fine and medium sands with relatively high contents of silt and clay a fluvial origin can be deduced (e.g. Fig. 3-4, CAB-A9). These fluvial sands can be interpreted as channel bedforms or accretionary macroforms of shallow sand-bed braided rivers (Miall, 1996). On the contrary, well-sorted fine or medium sands with low silt and/or clay content (e.g. Fig. 3-4, PCN4) are characteristic for aeolian processes (Ahlbrandt, 1979).

In general, fluvial reworking of aeolian material and vice versa is typical for subtropical river systems in the Bolivian Chaco (Werding, 1977; Iriondo, 1993) and elsewhere (Langford, 1989). Therefore sandy sediments with aeolian characteristics are referred to as (fluvio-) aeolian sediments (Supp. Fig. 3-9B).

Sediments of mainly silty or loamy grain sizes and moderate sorting have been classified as fluvial muds documenting deposition from suspension under reduced flow velocities (Miall, 1996, e.g. Fig. 3-4, Supp. Fig. 3-9D, CAB-A7). These overbank sediments were probably deposited during high-magnitude flood events or in lateral parts of the channel during a low-water stage of a seasonal (ephemeral) fluvial system.

The finest sediments found in the paleosol-sediment-sequences are moderately sorted silty clays (Fig. 3-4, Supp. Fig. 3-9C, CAB-A10). They are highly fissured and turbated, which is probably the result of post-depositional swelling and shrinking of the clay minerals. Apart from their dark colour, a high density of snail shells and root traces is characteristic for these deposits and points to a moderate intensity of bioturbation and a sustained influence of fauna and flora during sedimentation. The combination of persistent sediment accumulation of mainly clays and constant organic input reflects a low-energy environment, possibly wetland or shallow-palustrine conditions due to frequently occurring inundations.

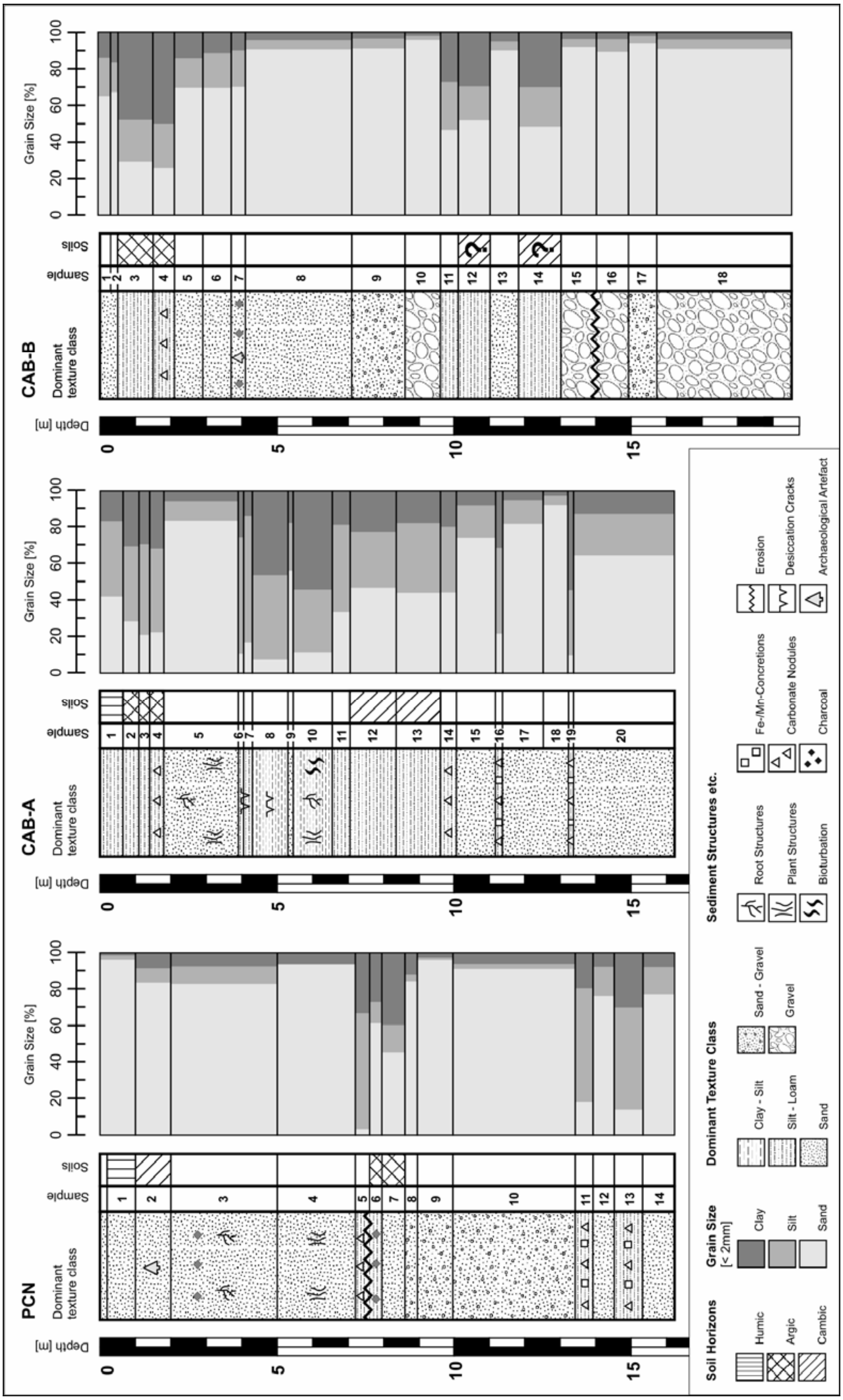

Fig. 3-3: *Sedimentological description, soil development and grain size depth profiles of the paleosol-sediment-sequences CAB-A, CAB-B and PCN*

Loamy sediments of poor sorting are typical for soils and paleosols. Well-developed soils show an increase in clay content due to weathering. Some of the respective horizons (Fig. 3-4, CAB-B3) have macroscopic clay cutans and can be classified as argic horizons of Luvisols (FAO-UNESCO, 1990). Loamy sediments with lower clay content or without macroscopic clay cutans are nevertheless characterized by their reddish colour (e.g. CAB-A12) and have been classified as cambic soil horizons of Cambisols (FAO-UNESCO, 1990). In cases where a gradual lower horizon boundary is absent, the loamy sediments could also be interpreted as reworked and re-deposited material of former soil horizons (Fig. 3-4, CAB-B14).

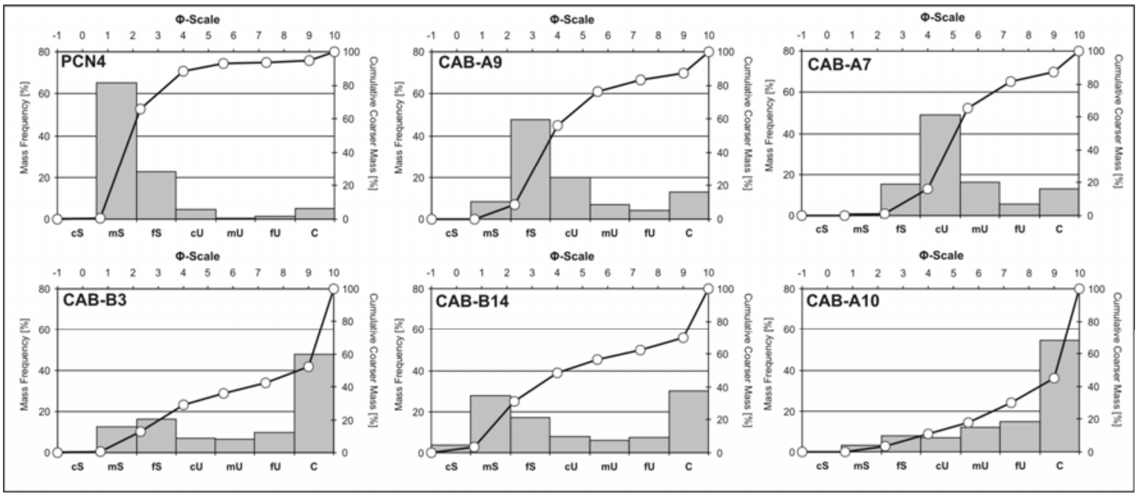

Fig. 3-4: *Typical grain size distributions for different lithofacies: (fluvio-)aeolian sand (PCN4), fluvial sands (CAB-A9), fluvial overbank deposits (CAB-A7), soils (CAB-B3 and CAB-B14) and swampy deposits (CAB-A10) (cS, mS, fS – coarse, medium, fine sand; cU, mU, fU – coarse, medium, fine silt; C – clay). The cumulative frequency curves can be used to infer sorting.*

3.4.2 PEDOGENESIS AND GEOCHEMISTRY: CARBONATE, PH, ELEMENTAL AND MINERALOGICAL COMPOSITION

Carbonate content, pH-values and iron fractions (Fe_d, Fe_o) are available for the CAB-A and PCN profile (Fig. 3-5, Supp. table 3-3). In addition, major elements and the mineral composition were determined for most samples of these profiles (see Supp. table 3-3, 3-4). In Figure 5, the depth profiles of selected geochemical data are plotted in order to characterize pedogenic processes, especially carbonate enrichment and weathering.

The $CaCO_3$ content varies between 0 and > 6% and carbonate nodules of up to 20 mm in diameter occur in some horizons. Low carbonate contents in the (former) top horizon of soils and paleosols (CAB-A1, 2, 3, 12, 13 and PCN1, 2, 6), and high carbonate contents in the (former) subsoil horizons (CAB-A4, 14 and PCN3, 7) are evidence for decalcification (weathering) and carbonate precipitation, respectively, during pedogenesis in semi-arid to sub-humid regions (Retallack, 2005).

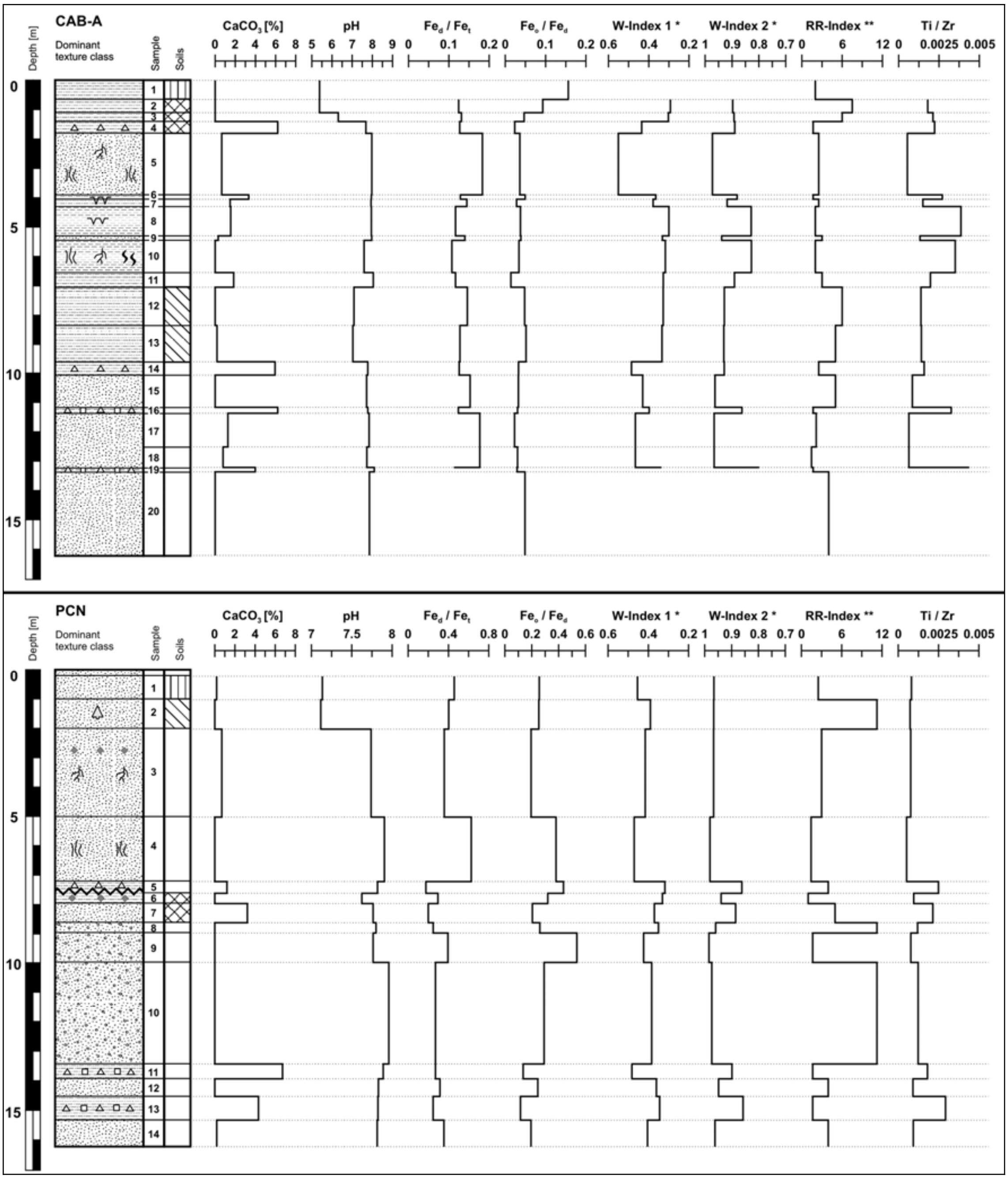

Fig. 3-5: Depth profiles of the carbonate content, pH, pedogenic iron ratios and other geochemical indices in the CAB-A and PCN profiles (W-Index 1 and 2 from Kronberg and Nesbitt (1981); ** RR-Index from Torrent et al. (1983)). The legend is the same as in Fig. 3-3.*

Pedogenic calcification is, therefore, assumed to be responsible for elevated $CaCO_3$ contents in the subsoil horizons CAB-A4, CAB-A14 and PCN7. Large carbonate nodules and high carbonate contents are found in the deposits defined as overbank and floodplain muds (CAB-A6, 8, 16, 19 and PCN5, 11, 13). The interpretation of these sediments as subsoil-remnants of capped paleosols is unlikely because their thickness is partly very limited and their lower boundary is rather sharp. Often, these fine grained muds are characterized by desiccation cracks. This might point to fast desiccation of

these overbank sediments subsequent to their deposition. Although part of the carbonate content could be due to the sedimentary carbonates or syn-depositional enrichment (desiccation and ascending water), the large size of the nodules points to post-depositional preferential carbonate precipitation in the fine grained sediments during the waning stages of groundwater fluctuations ("groundwater carbonates", Scheffer and Schachtschabel, 2002). Iron and manganese concretions that frequently co-occur with the carbonate nodules support the assumption of such groundwater-related processes.
Whereas the fine grained overbank and floodplain mud deposits show elevated carbonate contents, the lithofacies interpreted as palustrine sediments (CAB-A10) has low carbonate contents. This may indicate that syn-depositional carbonate enrichment by ascending water was significantly reduced during the deposition of the sediments, pointing to frequent inundations and reduced importance of desiccation processes as typical for wetland environments.

The pH-values in most of the samples are relatively high (~pH 8). Only in the soils at the top of the profiles do they drop to 5.5 and 7, respectively. This can be explained with presently ongoing weathering and decalcification. Although the pH-values are also slightly reduced in the paleosol horizons (CAB-A12, 13 and PCN6, 7), they are much higher than in the present soils. This is likely due to post-burial processes, like salt and carbonate transport with the groundwater.

The Fe_d/Fe_t ratio for both the CAB-A and the PCN profile is not clearly elevated in the detected soil and/or paleosol horizons. This is surprising at first glance, because the Fe_d fraction – defined as pedogenic iron – is formed during weathering and should therefore be enriched in the soil/paleosol horizons. Instead, peak values characterize sandy sediments (CAB-A5, 15, 17, 18 and PCN4), which did not show any field evidence for enhanced weathering. This could be interpreted as an artefact due to the high fractions of quartz-bearing sands. The Fe_t contents in these sediments are low and preferential weathering of the less resistant non-quartz minerals rapidly releases iron to form pedogenic iron, resulting in high Fe_d/Fe_t ratios although overall weathering is not that intensive.
For the same reason the Fe_o/Fe_d ratio seems to be of limited use to detect (past) pedogenic activity. Only in the top soil of the CAB-A profile (CAB-A1, 2) the ratio correctly indicates active weathering and soil formation. For the rest of the profiles, interpretation is not as straightforward. Neither is there a clear signal for increased (past) pedogenetic activity in the CAB-A paleosol, nor is there any correlation of the Fe_o/Fe_d ratio with the soils/paleosols in the PCN profile – here, the ratio even seems to show a minimum for the paleosol instead. In conclusion, both ratios seem to be artificially high in the sandy, quartz-dominated sediments (e.g. PCN4, 9, 10) and are not applicable in our case.

Several other weathering indices based on the elemental composition were also tested to quantify chemical weathering in our paleosol-sediment-sequences, e.g. the ratios

Na/Al, K/Al, Sr/Ca, Sr/Ba, etc. (Gallet et al., 1996; Yang et al., 2004). Here, we present and discuss only the rather sophisticated weathering indices according to Kronberg and Nesbitt (1981). Even these indices do not unambiguously differentiate between weathered horizons and 'unweathered' sediments (Fig. 3-5). Although both indices do not 'falsely' indicate intensive pedogenesis in the quartz-rich sediments (as Fe_d and Fe_o do), and the soils/paleosols are correctly characterized by relatively low values (i.e. more intensive weathering), the fine-grained overbank and palustrine deposits cannot be distinguished from the soils/paleosols. Especially W-Index 2, which is calculated including silicon, again shows a good correlation with grain size (clay content). We conclude that in-situ pedogenesis is not the only controlling factor for the elemental composition throughout the investigated profiles. None of the hitherto developed weathering indices are able to separate in-situ weathering from other influential factors. Those are either (i) the mobility and translocation of certain elements (i.e. depletion or enrichment in specific units), (ii) the above-mentioned influence of the sand-(quartz) dominance in some of the units on the weathering intensity of the remaining minerals, or (iii) the variability of grain size and thus the chemical composition of the initial soil parent material.

Varying geochemical composition in the parent material is not surprising. Firstly, Muhs and Bettis (2000), for example, showed that the chemical composition of loess may depend on transport distances and grain size. Secondly, the grain size analyses for our investigated sequences showed that completely different geomorphic processes played a role for the accumulation of the various lithofacies. In order to illustrate the original geochemical input variability, the Ti/Zr ratio was plotted in figure 3-5. Both elements are rather immobile and their ratio is not affected by pedogenesis. It should thus be more or less constant, if the input signal were unchanging (Allen and Hajek, 1989; Muhs and Bettis, 2000). The Ti/Zr ratio, however, varies dramatically between the individual units. There is a good correlation with grain size, showing that high Ti contents coincide with larger sand fractions.

Comparison of grain size results and the mineral composition provides additional evidence for the influence of the sedimentary variability on the geochemical parameters (not illustrated, see Table 3-3, 3-4). Quartz, for instance, is highly correlated with the sand fraction whereas feldspars are correlated with the silt fraction. Other, undetected minerals are also likely to be related to certain grain sizes and transport mechanisms (Allen and Hajek, 1989; Birkeland, 1999), which thus influence geochemical variability.

Summarizing, the application of geochemical proxies for pedogenesis is of limited use in our paleosol-sediment-sequences due to the highly heterogeneous parent materials. Up to now, no analytical approach has been identified that would allow verifying – not to mention quantifying – pedogenesis. Note that soil colour also only partly corroborates the distinction of the soils/paleosols. The Redness Rating Index (RR-Index), for example, which mainly correlates with the hematite content (Torrent et al., 1980; Torrent et al., 1983), increases significantly in the cambic and/or argic horizons of soils and paleosols (Fig. 3-5; CAB-A2, 3, 12, 13 and PCN2, 7), but it also shows high values in other units (CAB-A15, 20 and PCN8, 10). Similar to the previous considerations concerning iron fractions and elemental compositions, this may be the result of increased hematite contents due to iron oxide translocation, input variations, or due to preferential and rapid weathering of iron-bearing minerals.

These findings emphasize the importance of sedimentological and geomorphic analysis for the distinction of various lithofacies, which may ultimately be interpreted in terms of paleoenvironmental and paleohydrological changes in the surroundings of the Cabezas and Pelícano profiles.

3.4.3 LITHOFACIES CORRELATION AND RADIOCARBON ANALYSES

Based on the above sedimentological, grain size and geochemical analyses, the paleosol-sediment-sequences can be described and illustrated in a simplified way as a succession of various lithofacies (Supp. Fig. 3-11, 3-12). Each of the six previously defined lithofacies implies specific geomorphic processes. In Table 1 we group the dominant lithofacies, associated geomorphic processes and environmental conditions, as well as the sedimentary units I (bottom) to V (top), which constitute the complete paleosol-sediment-sequence of the piedmont.

Lithofacies	Geomorphic processes	Environmental conditions	Sedimentary Units
Soil Formation	Stable landscape and reduced geomorphic activity	Extensive forest cover (humid conditions)	**II, V**
Fluvial Gravels	Fluvial deposition in gravel-bed braided streams with high stream power	High sediment supply and torrential discharge regimes (high seasonality)	**I**
Fluvial Silts, Sands and Pebbles	Fluvial deposition in sand-bed meandering streams with high stream power	Medium sediment supply, moderate vegetation cover	**I**
(Fluvio-) Aeolian Sands	Fluvial reworking of aeolian material or aeolian deposition of floodplain material	Medium to high sediment supply and high seasonality	**IV**
Fluvial Overbanks	Fluvial overbank deposition during flood events or within the floodplain at recessional stage	More common in streams with marked dry season	**I, IV, (V)**
Palustrine (WETLAND) deposits	Slow deposition under frequent inundations	Constant moisture supply (humid conditions and low seasonality)	**III**

Table 3-1: *Summary of the dominant lithofacies and sedimentary units distinguished in the paleosol-sediment-sequences and their interpretation regarding associated geomorphic processes and environmental conditions.*

The reconstruction of landscape evolution and the interpretation of paleoenvironmental changes are based on changes in type, intensity and spatial distribution of the geomorphic processes. Generally, geomorphic stability implies stable landscapes, a dense vegetation cover and soil formation, whereas geomorphic activity means that active and extensive erosion, transport and sedimentation processes rapidly alter the surface morphology (Rohdenburg, 1970). This concept has long since been used for the interpretation of paleoenvironmental conditions, especially humidity.

Several considerations are important for the correlation of lithofacies and their interpretation: (i) Lateral discontinuities can be the result of the complex temporal and spatial behaviour of the geomorphic system (e.g. fluvio-aeolian interactions, avulsive dynamics etc., Werding, 1977; Iriondo, 1993). It is therefore important to consider the horizontal extent of lithofacies. (ii) Changes in fluvial behaviour may have a variety of causes (Schumm, 1999). Geomorphic and climatic changes probably exert the main control of landscape evolution along the Andean piedmont and the Bolivian Chaco on the Late Quaternary timescale. Neotectonic deformation is important on longer timescales only (Moretti et al., 1996), and human occupation in the Bolivian Chaco was negligible before ~1.1 cal ka BP (Dames & Moore Inc., 2001; Görsdorf, 2002). (iii) Finally, the paleoenvironmental interpretation of past fluvial systems in terms of their erosion, transport and sedimentation capacity ("stream power", Bull, 1979) needs to consider the feedback mechanisms between the manifold variables of the fluvial system (e.g. hillslope stability, catchment sediment storage, vegetation cover, magnitude and frequency of precipitation, base level changes etc., Bull, 1988).

Sample Name	Lab.-Code	Material	Depth [cm]	Age [^{14}C yr BP]	Age-Range* [cal. yr BP]
PCN (18.5995S/63.0946W)					
PCN2-S	B-8536	terrestrial shell	190	2760 ± 50 BP	2786-2921
PCN3-K	B-8539	charcoal	300	4860 ± 30 BP	5586-5642
PCN3-S	B-8538	terrestrial shell	350	2780 ± 30 BP	2845-2941
PCN4-S	Poz-9906	terrestrial shell	575	1540 ± 30 BP	1383-1513
PCN4/5-S	B-8537	terrestrial shell	700	2900 ± 30 BP	2973-3075
PCN6-K	Poz-10296	charcoal	760	10320 ± 60 BP	12035-12314
CAB-A (18.8013S/63.3005W)					
CAB-A5-S	Poz-6546	terrestrial shell	290	6580 ± 40 BP	7434-7504
CAB-A6-S	Poz-6549	terrestrial shell	395	6600 ± 40 BP	7440-7559
CAB-A8-S	Poz-6545	terrestrial shell	485	6740 ± 40 BP	7572-7651
CAB-A8-K	Poz-6631	charcoal	485	7030 ± 40 BP	7836-7932
CAB-A10	Poz-6548	terrestrial shell	615	9400 ± 50 BP	10574-10692
CAB-A10-S	Poz-6547	terrestrial shell	630	9410 ± 50 BP	10580-10697
CAB-A20-S	Poz-6551	terrestrial shell	1385	18700 ± 90 BP	22184-22357
CAB-B (18.6897S/63.3080W)					
CAB-B6	Poz-6628	charcoal	375	7950 ± 40 BP	8704-8976
CAB-B7	B-8342	terrestrial shell	385	7600 ± 40 BP	8378-8420
CAB-B11	B-8343	terrestrial shell	980	7820 ± 40 BP	8555-8630
CAB-B14	Poz-6553	terrestrial shell	1210	8250 ± 40 BP	9134-9289
CAB-B12	Poz-6629	charcoal	1035	7780 ± 50 BP	8463-8603
CAB-B14	Poz-6550	terrestrial shell	1250	7820 ± 40 BP	8555-8630
CAB-C1/C2 (18.8083S/63.3050W)					
CAB-C1-1	B-8344	terrestrial shell	410	3920 ± 40 BP	4294-4421
CAB-C2-1	B-8529	terrestrial shell	210	1580 ± 30 BP	1416-1518
CAB-C2-2	Poz-9937	terrestrial shell	320	1530 ± 30 BP	1372-1509
CAB-C2-3	B-8530	charcoal	505	1780 + 60 BP	1619-1811
CAB-D (18.8087S/63.3075W)					
CAB-D2	Poz-9933	terrestrial shell	320	9790 ± 50 BP	11191-11241
CAB-D3	Poz-9935	terrestrial shell	475	9720 ± 50 BP	11108-11215
CAB-D4 NaOH	Poz-10198	soil (humic acid)	515	9750 ± 70 BP	11107-11242
CAB-D4 RES	Poz-10218	soil (humins)	515	10110 ± 100 BP	11409-11969

Table 3-2: *List of radiocarbon ages obtained from the paleosol-sediment-sequences at Cabezas and Pelícano. (* 1σ-range; cal. = calendar, calibrated with CALIB 5.0.1. and intcal04 data set (Stuiver and Reimer, 1993; Reimer et al., 2004))*

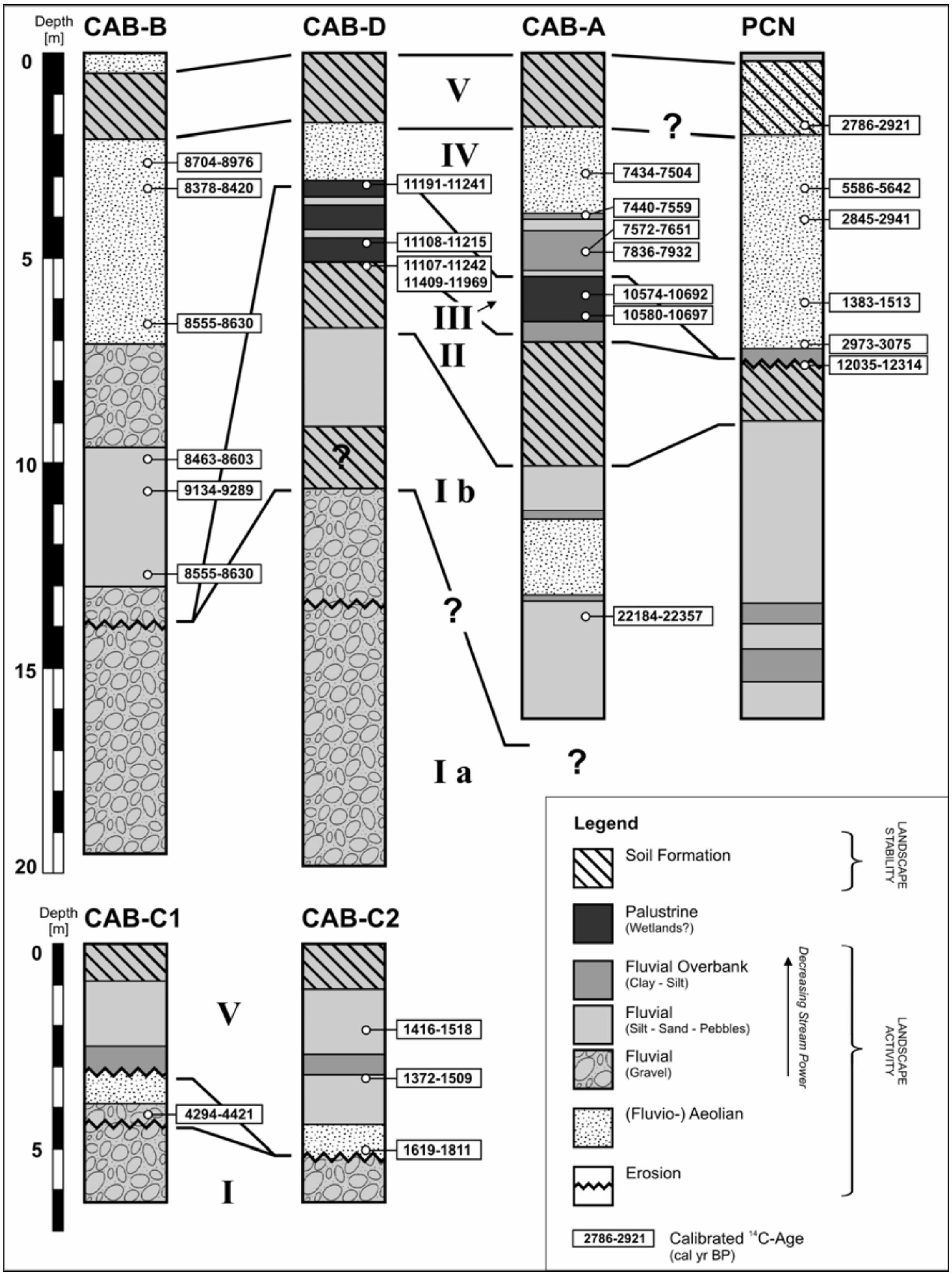

Fig. 3-6: *Correlation of the investigated profiles based on the succession of lithofacies and calibrated radiocarbon ages (see text and table 2 for details). The correlation and the sequence of the sedimentological units (I to V) are indicated by black lines.*

The succession of the lithofacies in the investigated profiles enables a correlation to be made (Fig. 3-6). In order to corroborate the correlation based on the lithofacies, and in order to establish an absolute chronology for the paleosol-sediment-sequences, a total of 27 radiocarbon ages were obtained (Table 3-2). Note that soil organic matter (humic acids and humins) only roughly dates the burial age of the corresponding paleosol. With some exceptions, the ages are stratigraphically consistent and likely date the deposition of the corresponding sedimentary unit. Age inversions occur in only two cases where they can be explained by geomorphic processes. Firstly, the radiocarbon ages of terrestrial shells and charcoal in the units CAB-B6 to 14 (i.e. the paleochannel, see Fig. 3-2) yield ages between 8378-8420 cal yr BP and 9134-9289 cal yr BP. These ages likely date the timeframe of the channel filling and may be contaminated by the incorporation of reworked material from channel banks further upstream. In the second case, five radiocarbon samples of terrestrial shells and charcoal in the units PCN2 to 4 yield radiocarbon ages between 1383-1513 cal yr BP and 5586-5642 yr cal BP. The respective sediments are mainly aeolian sands and belong to a series of parabolic paleodunes (May, 2006). Their evolution typically involves the incorporation of reworked fluvial material (Langford, 1989) and can be characterized by several cycles of stabilization and reactivation (David et al., 1999).

3.4.4 RECONSTRUCTION OF LATE QUATERNARY REGIONAL LANDSCAPE EVOLUTION

The results from the geomorphological, sedimentological and geochemical analyses and the interpretation regarding the landscape evolution along the Andean piedmont is summarized for all units in Fig. 3-7. It illustrates important paleoenvironmental changes, which must have affected the paleovegetation, paleohydrology as well as the geomorphic system in general.

Unit I: ≥ Last Glacial Maximum "sensu lato" (≥ 18 cal ka BP)

At Pelícano the lower part of the sequence consists of sands and pebbles. They show no systematic vertical fining or coarsening trend. At Cabezas a distinctive change from coarse fluvial gravel (Unit I a) to overlying sands (Unit I b, see Fig. 3-6) can be observed, which is probably not exposed at Pelícano. A minimum age of ~22.2 cal ka BP for this transition is available from the CAB-A profile.

The lithofacies occurring in the Unit I sediments are typical for braided river environments. Lateral discontinuities of the individual strata and frequent interbedding with finer-grained sediment lenses point to high lateral mobility and frequent lateral channel changes. The high geomorphic activity that can be deduced from such braided river environments points to (i) increasing erosion and sediment availability in the catchment, (ii) instability of the channel banks, (iii) intensive precipitation and discharge events ("high-magnitude and low-frequency events", Wolman and Miller, 1960) and (iv) a reduced vegetation cover (Fig. 3-7).

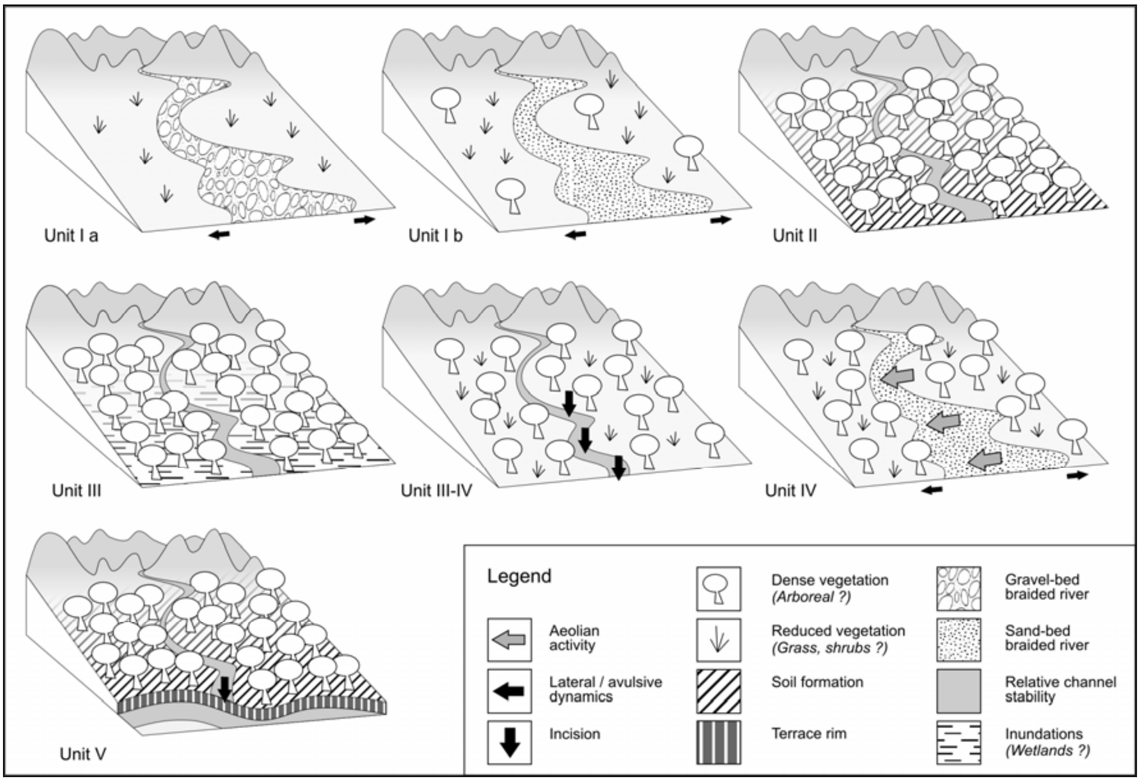

Fig. 3-7: *Summary of Late Quaternary landscape evolution in the study area based on the analyses and interpretation of the geomorphological, sedimentological and geochemical data discussed in the text.*

Our results corroborate previous fluvial studies. The Ucayali River and the Madre de Díos River in western Amazonia, for example, which both have their headwaters in the Andes, deposited coarse gravels and conglomerates between approximately 37 and > 44 cal ka BP (Räsänen et al., 1990; Dumont et al., 1992). The Upper Juruá River, which drains lowland areas in Southwestern Amazonia, shows the same paleohydrological signal, with coarse conglomerates dated between ~34 and 38 cal ka BP (Latrubesse and Rancy, 1998; Latrubesse, 2003), whereas sedimentation and aggradation along the Purus River prevailed between 23 and 29 cal ka BP (Latrubesse and Kalicki, 2002). In middle Amazonia, fluvial dynamics were characterized by intense avulsion processes around 20 ka (TL age), probably due to significantly reduced vegetation cover (Latrubesse and Ramonell, 1994; Latrubesse, 2000). A change from gravel to sand-braided rivers has also been found in the Upper Paraná River after ~24 ka (TL age) (Stevaux, 2000).

Palynological findings from NE Bolivia and from SE and S Brazil provide evidence for the replacement of forests by savannah and grasslands and, accordingly much drier conditions during the Late Pleistocene (Mayle et al., 2000; Behling, 2002; Burbridge et al., 2004). Similarly, van der Hammen and Absy (1994) deduce two intervals of savannah environments from palynological and sedimentological studies in Rondônia, SW Brazil for the time after ~45 cal ka BP with the more arid interval around ~22 cal ka BP. Changes in the vegetation cover around 20 cal ka BP were reported to be accompanied by increased aeolian activity in the southern Chaco (Iriondo and Garcia,

1993) and the Paraná river basin (Stevaux, 2000). Similarly, Kröhling and Iriondo (1999) report dry conditions with erosion and enhanced aeolian activity for the Argentinean pampa.
From a paleoclimatic point of view, all these findings suggest that Unit I was deposited during dry conditions between ~40 – 18 cal ka BP. Both speleothem data from SE Brazil (Cruz et al., 2005; Cruz et al., In Press; Wang et al., In Press) and shoreline records from the Bolivian Altiplano (Baker et al., 2001a; Fritz et al., 2004; Placzek et al., 2006) document very dry conditions between ~40-30 ka (U/Th ages) due to a weak tropical circulation. Slightly increased summer precipitation can be inferred from those records since ~25 ka ('Sajsi' wet phase (U/Th ages), Placzek et al., 2006), which probably explains the transition from coarser to finer braided-river deposits in our record (Unit I a to Unit I b) and other fluvial deposits. Apart from moisture changes it has been suggested that increased frequencies and intensities of polar air incursions could have amplified the effects of the arid conditions on the fluvial and environmental changes (Latrubesse and Ramonell, 1994; Behling, 2002; Ledru et al., 2005).

Unit II: Lateglacial (< 18 – 11.5 cal ka BP)

A well-developed paleosol formed in the upper part of Unit I at Pelícano and Cabezas (Fig. 3-6). No radiocarbon ages are available to precisely date the onset of soil formation but its intensity suggests a relatively long period of pedogenesis – probably several thousand years. The end of soil formation is dated to approximately 11.5 – 12 cal ka BP at both localities. Differences in the soil type of the corresponding paleosol (Cambisol at Cabezas, Luvisol at Pelícano) are probably due to different parent material. The paleosols are interpreted to reflect geomorphic stability – the fluvial system of the piedmont must have reached "equilibrium" conditions with neither aggradation and flooding, nor degradation and erosion – implying (i) decreased sediment supply, (ii) reduced intensities of runoff events and (iii) dense vegetation, likely forest cover (Fig. 3-7).
Geomorphic stability is also reported from the fluvial system of the Ucayali River (SW Amazonia), which seems to have developed a meandering pattern by 16 cal ka BP (Dumont et al., 1992). General dissection after ~23 cal ka BP at the Purus River (Latrubesse and Kalicki, 2002) and may be interpreted as the result of more increased precipitation. A subhumid interval has been documented in the Argentinean pampa between 15.5 and 16.5 cal ka BP (Kröhling and Iriondo, 1999). In addition, these findings are in good agreement with the development of the cloud forest in the Subandean Ranges of Eastern Bolivia since ~18 cal yr BP (Mourguiart and Ledru, 2003).
A dramatic increase of the tropical summer precipitation during the Lateglacial, likely due to an intensification and/or southward shift of the SASM and the South Atlantic Convergence Zone (SACZ) (Baker et al., 2001a; Baker et al., 2001b; Cruz et al., 2005; Cruz et al., In Press), is also seen in the lake transgression phases on the Bolivian Altiplano (Tauca and Coipasa phase ~17.4 – 12.4 cal ka BP (Argollo and Mourguiart, 2000) or 18 – 11 ka (U/Th ages, Placzek et al., 2006)), respectively and in the speleothem data from SE Brazil (Cruz et al., In Press).

Unit III: Pleistocene-Holocene transition (~11.5 – 10 cal ka BP)

The Lateglacial paleosol of Unit II at Pelícano is directly overlain by Late Holocene (fluvio-) aeolian sediments. This hiatus is explained with an erosional event although the onset and duration of this event remain unknown. However, at Cabezas, sediments of probable palustrine origin were deposited during the Early Holocene (Unit III, Fig. 3-6). As mentioned earlier, this is interpreted as evidence for flooding into a densely vegetated floodplain or even wetland (Fig. 3-7). A significant change in seasonality and a substantial increase in winter precipitation must have occurred to avoid frequent desiccation, carbonate enrichment and oxidation of organic matter.

In the Bolivian and Paraguayan Chaco, fine grained fluvial sediments were OSL/TL-dated between 12.3 and 10 ka and probably reflect slow deposition of relatively stable fluvial systems (Kruck, 1996). In addition, the deposition of these sediments seems to coincide with the widespread occurrence of paleosols (Pasig, 2005), indicating stable fluvial systems and dense vegetation in the catchments of the large rivers in the Chaco. Similar Early Holocene fine-grained and organic-rich deposits as in Unit III have been described in Uruguay (Suarez and Lopez, 2003), the southern Pampas of Argentina (Zárate et al., 2002) and the Andean piedmont of Mendoza, Argentina (Zárate, 2000). In addition, Early Holocene paleowetlands formed in the Bolivian Andes between ~11.2 and 8 cal ka BP (Servant and Servant-Vildary, 2003). Possibly, a pronounced peak of aquatic herbs in the Laguna Bella Vista, NE Bolivia between ~8.8 and 13.2 cal ka BP (Mayle et al., 2000) also corresponds to wetter and less seasonal climate during the Early Holocene.

Paleoclimatically, a significant increase in winter precipitation can either be explained with cold air incursions (Servant and Servant-Vildary, 2003) or with moisture advection via intensified SE trades. The speleothem records in SE Brazil (Cruz et al., 2005; Cruz et al., In Press; Wang et al., In Press) show an abrupt northward shift and/or weakening of the SASM/SACZ, probably related to the reorganization of the atmospheric and oceanic circulation during the Pleistocene-Holocene transition.

Unit IV: Early to Mid-Holocene (~10 – 2.9 cal ka BP)

The palustrine deposits at Cabezas and the paleosol at Pelícano, respectively, are unconformably overlain by thick accumulations of sand (Unit IV, Fig. 3-6). Sedimentation at Pelícano likely started only during Mid- to Late Holocene. It is assumed that erosion there occurred mainly in the Mid-Holocene and probably truncated the upper part of the paleosol as well as possible Early Holocene deposits. At Cabezas, the erosional unconformity has incised a deep paleochannel, which even cuts into Unit I sediments (Fig. 3-2; CAB-B). At several other localities along the outcrop, at least the upper part of Unit III and the paleosol (Unit II) are truncated. Several radiocarbon ages from the underlying and overlying units place this erosional event between ~9.2 and 10 cal ka BP. The subsequent filling of the paleochannel occurred between 8.3 and 9.2 cal ka BP. Whilst the lower part of the paleochannel contains several gravel layers, which probably represent channel lag deposits from reworking of the underlying Unit I a, the upper part consists mainly of massive fluvio-aeolian sands, and, partly, overbank deposits (CAB-A). Although the massive sands of Unit IV show lateral continuity along all profiles (CAB-B, CAB-D and CAB-A) their deposition has not exactly been simultaneous (see Fig. 3-6). Radiocarbon ages of the (fluvio-) aeolian sediments from parabolic dunes at Pelícano range between ~1.4 and 5.6 cal ka BP. The dates may indicate the persistence of dune activity until at least 1.4 cal ka BP, but could also reflect a Late Holocene reactivation of Mid-Holocene dunes.

These observations point to landscape instability with (i) erosion between ~9.2 and 10 cal ka BP (CAB-B), (ii) transition to an aggradational system with rapid channel filling (CAB-B) and overbank deposition in more distant floodplain areas (CAB-A) between ~8 to 7.5 cal ka BP and (iii) continued accumulation of fluvial and fluvio-aeolian sands, leading to frequent lateral shifts (avulsions) of the fluvial system after ~7.4 cal ka BP (Fig. 3-7). The transition from stable landscapes during formation of Unit II and III to geomorphic instability during the Mid-Holocene implies a severe change in the fluvial system. Considering the complex array of possible internal feedbacks within fluvial systems (e.g. Bull, 1988), an overall reduction of precipitation and increase of seasonality may have provided the pre-conditions for linear erosion to set in. As soon as the vegetation cover became less dense due to the aridification, the high sediment supply turned the system into an aggrading state. Braided sand-bed rivers with high lateral mobility then probably deposited the massive fluvio-aeolian sand and overbank sediments.

Mid-Holocene aridity and geomorphic instability can also be deduced from paleochannel sediments of the Pilcomayo, which have been OSL/TL-dated between ~7.7 and 3.4 ka (Geyh et al., 1996; Kruck, 1996), and parabolic paleodunes along Río Parapetí paleochannels yielded OSL/TL dates between 5.5 and 2.9 ka (Kruck, 1996). Due to the high mobility and frequent reactivation of parabolic dunes, these dates likely date the final phase of dune mobility and aeolian sand deposition. Widespread decay of forest with frequent forest fires and fluvio-aeolian sedimentation has been reported from the region around Santa Cruz between ~7.8 and 5.8 cal ka BP (Servant et al., 1981b). Even in SW Amazonia, fluvial dynamics at the Purus river were characterized by aggradation during the Early to Mid-Holocene (Latrubesse and Kalicki, 2002). In addition, these fluvial records are corroborated by palynological studies reporting the expansion of savannah and grassland vegetation in Rondônia, SW Brazil (Pessenda et al., 1998; de Freitas et al., 2001) and the Andean Cordillera (Mourguiart and Ledru, 2003).

From the paleoclimatic point of view, the geomorphic instability and aridity can be explained with the low tropical summer precipitation. Apparently, high winter precipitation was limited to the Early Holocene only. High $\delta^{18}O$ values in the speleothems of SE Brazil (Cruz et al., 2005; Cruz et al., In Press; Wang et al., In Press), formation of the salars on the Altiplano (Fritz et al., 2004; Placzek et al., 2006), and even a severe drop of Titicaca lake level (Baker et al., 2001b) record the reduced intensity of the SASM/SACZ during the Mid-Holocene.

Unit V: Late Holocene (~2.9 cal ka BP to present)

At the top of the profiles, both at Cabezas and at Pelícano, soil development indicates a return to geomorphic stability and forest expansion during the Late Holocene, likely due to a return to wetter climate conditions (Unit V, Fig. 3-6, 3-7). The exact onset of soil formation remains speculative. The differences of the soil types – Luvisols at Cabezas, versus weak Cambisols at Pelícano – may point to longer aeolian sedimentation (until 2.9? cal ka BP) or to generally drier conditions at Pelícano, implying less intensive weathering. As evident from the profiles CAB-C1 and C2, lateral erosion of the Río Grande had reached the piedmont near Cabezas at ~4.3 cal yr BP. The corresponding fall in base level marked the end of the depositional history at Cabezas.

Our results corroborate geomorphological records from the Argentinean and Paraguayan Chaco, which report soil formation since approximately 3.8 cal ka BP with a peak after ~2 cal ka BP (Barboza et al., 2000; Pasig, 2005). This is in agreement with pollen studies, which show the onset of modern climatic conditions around 4.5 cal ka BP in the Eastern Cordillera (Mourguiart and Ledru, 2003), and around 3.2 cal ka BP in NE Bolivia (Mayle et al., 2000; Burbridge et al., 2004) and Rondônia, SW Brazil (Pessenda et al., 1998; de Freitas et al., 2001).

A reduction in sediment loads and flood magnitudes can be inferred for the fluvial system during the Late Holocene, probably coinciding with channel stabilization and an increased tendency to meandering. Deposition of fluvial sands and silts by the Río Grande between ~1.7 and < 1.4 cal ka BP (CAB-C1 and CAB-C2; Fig. 3-6), as well as a possible reactivation of parabolic dunes at Pelícano (age inversions) may point to a renewed phase of landscape activity.

In the Upper Paraná basin, the deposition of massive aeolian sands was TL-dated and related to dry events in S Brazil and the Argentine plains between ~1.5 and 3.5 ka BP by Stevaux (2000). Along the Andean piedmont close to Santa Cruz, Servant et al. (1981b) document soil formation between 3.6 and 5.8 cal ka BP and aeolian activity between 1.3 and 3.6 cal ka BP. In addition, archaeological investigations show that significant human presence in the Bolivian Chaco has only commenced after ~1.1 cal ka BP (Dames & Moore Inc., 2001; Görsdorf, 2002).

The return to generally wetter conditions (characteristic of the present day climate) during the Late Holocene can be explained with a southward shift/intensification of the SASM. Respective changes in the oxygen isotopic composition in the speleothems in SE Brazil (Cruz et al., 2005; Cruz et al., In Press; Wang et al., In Press), as well as the lake level rise of Lake Titicaca (Baker et al., 2001b) have previously been interpreted accordingly. Likely, the wetter environmental conditions, which have prevailed along the Andean piedmont for the last 4 ka, were interrupted by intervals of increased aridity and landscape activity around 1.5 cal ka BP.

3.5 CONCLUSIONS

This study demonstrates that paleosol-sediment-sequences along the Andean piedmont are valuable Late Quaternary archives, which have a large potential for landscape and climate reconstruction. The succession of various sedimentary lithofacies, including paleosols and soils, reflects changes of dominant geomorphic processes and environmental conditions. Geochemical analyses revealed that the mineral and elemental composition of the deposited sediments was highly variable in time and – as deduced from the correlation with grain size – mainly dependent on the different transport mechanisms and provenances. No geochemical indices could successfully be applied to quantify in-situ weathering/pedogenesis, likely due to the inhomogenities of the parent material.

The lowest sedimentary unit (≥ LGM) documents a landscape along the Andean piedmont that was characterized by deposition of coarse sediments (gravels, sands) in braided river systems, overall dry conditions but highly seasonal and strong precipitation events, and a significant reduction of the vegetation cover. The environmental conditions seem to have become less severe some time before ~22.2 cal ka BP (sand-, instead of gravel-bed braided rivers), but only during the wet Lateglacial, landscape stability and a dense vegetation cover allowed for soil formation. The Pleistocene-Holocene transition was characterized by frequent inundations in a densely vegetated landscape, probably resulting from reduced monsoonal summer precipitation and increased winter rainfall. A widespread erosional unconformity, locally even deep channel incision, and subsequently, accumulation of massive fluvio-aeolian sands document geomorphic instability due to semi-arid/arid conditions during the Mid-Holocene. The onset of present-day soil formation reflects the return to wetter conditions since ~2.9 cal ka BP, which have likely been interrupted by at least one short interval of more arid conditions and reactivation of fluvial and aeolian sedimentation.

Our results are generally in good agreement with other paleoenvironmental findings and suggest that latitudinal shifts and changes in the intensity of the SASM/SACZ played a dominant role in controlling the hydrological and environmental conditions along the Andean piedmont. Further paleosol-sediment-sequences are currently studied in order to confirm and refine our knowledge of Late Quaternary stratigraphy and landscape evolution in Eastern Bolivia. These kinds of geomorphological and sedimentological studies are necessary to complement high-resolution records, because those alone do not provide sufficient spatial coverage, nor can they be used to infer and assess effects of climate changes on geomorphic processes and the environment in general.

ACKNOWLEDGEMENTS

The authors would like to thank the Museo de Historia Natural Noel Kempff Mercado, Santa Cruz, for scientific support in Bolivia. Field surveying and sampling would not have been possible without logistical help of Gary Correa Figueroa. We also gratefully acknowledge the help of Ivan Mercolli and Urs Eggenberger with the XRF and XRD measurements, and the Institute of Physics, University of Bern, for the conventional ^{14}C-measurements. The very thoughtful reviews of Edgardo Latrubesse (Federal University of Goiás, Brazil) and Sergey Sedov (Universidad Nacional Autónoma de México) have greatly improved the quality of this manuscript. This study contributes to the SNF-funded projects "Paleoclimate and landscape evolution in the tropical Andes of Bolivia and the adjacent lowland rainforest" (SNF 200020-105228/1) and "Paleoecology of Eastern Bolivia" (SNF 21-067937.02/1).

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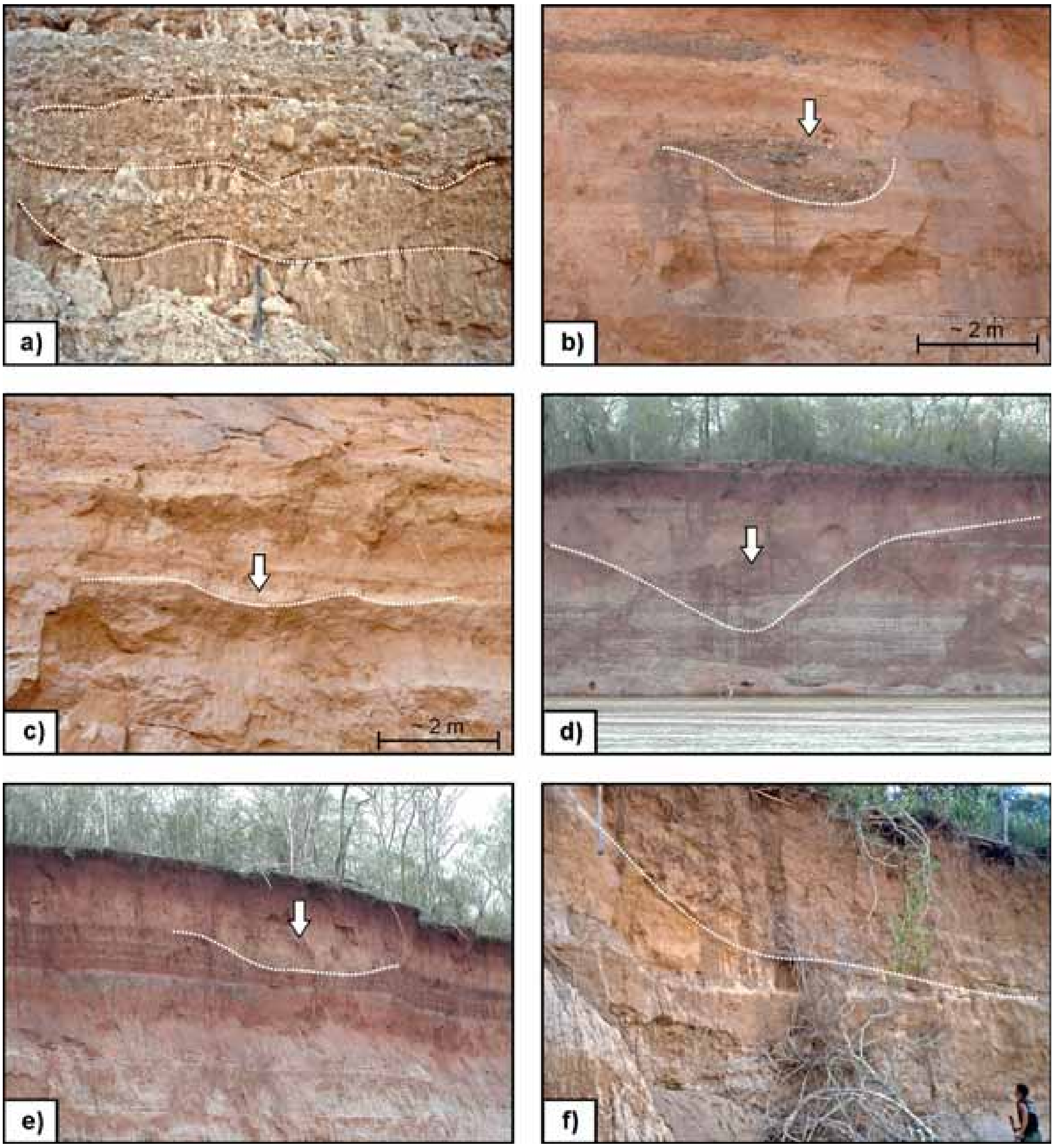
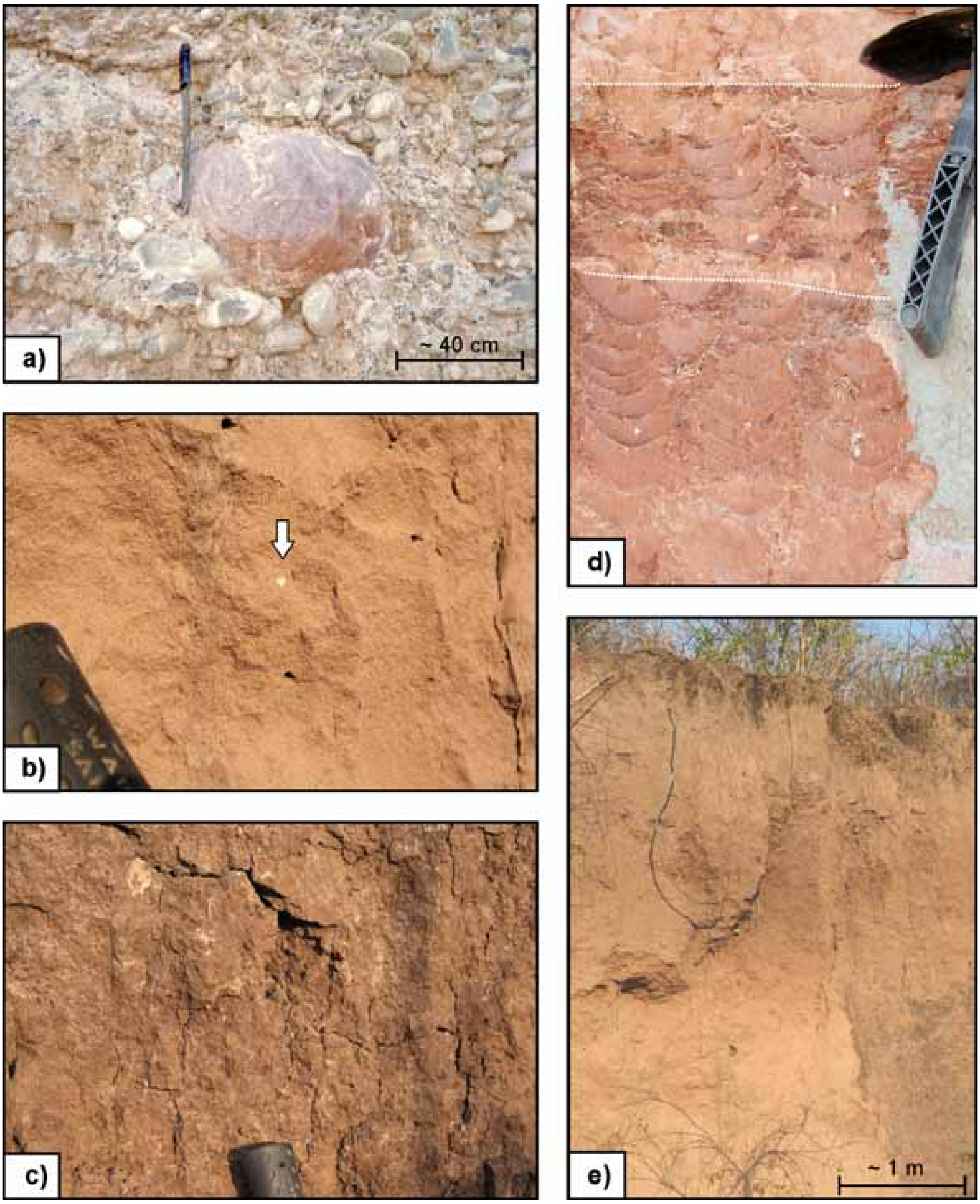
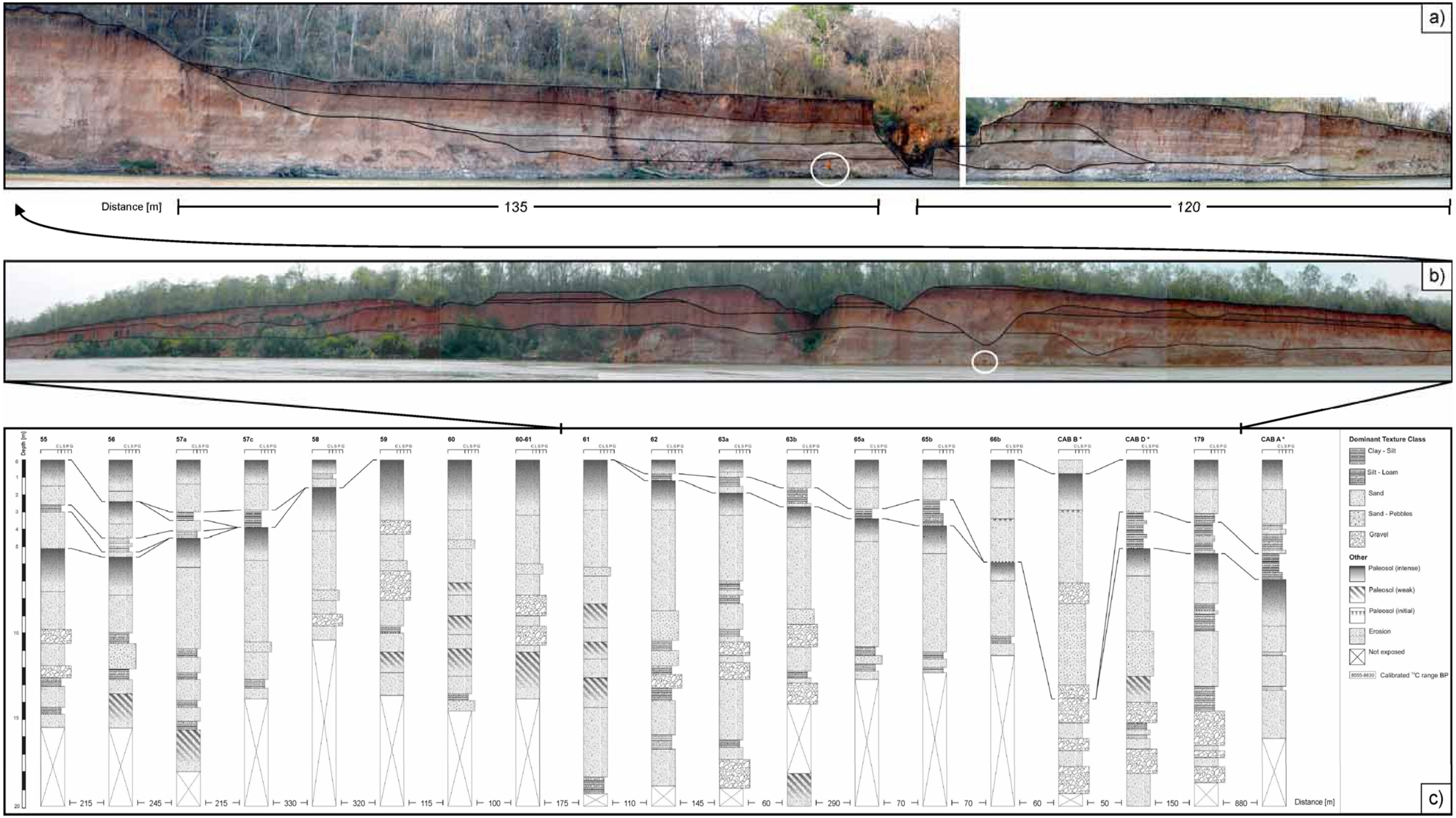
APPENDIX



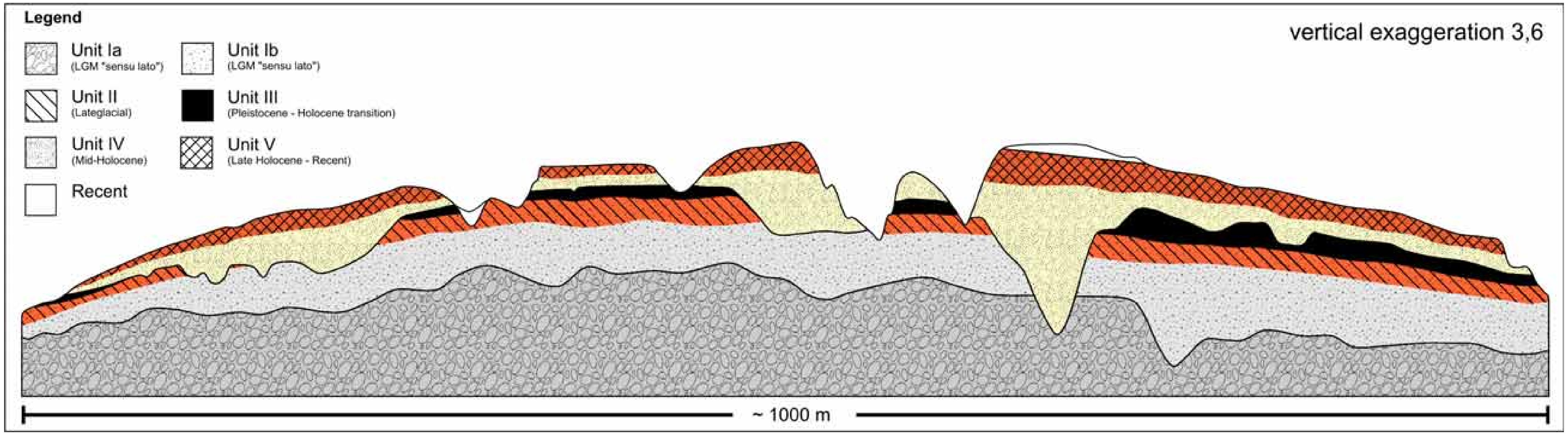
Supplementary Fig. 3-8: *Sedimentary architecture of the paleosol-sediment-sequences at Cabezas. a) Gravel trough beds and interlayered sands/silts of a gravel-bed river (unit Ia), b) paleochannel filled with gravel in dominantly sandy lithofacies (unit Ib), c) shallow paleochannel of a sand-bed braided river (unit Ib), d) deeply incised paleochannel at CAB-B, e) shallow paleochannel of sand-bed braided river (unit IV), f) erosional unconformity between piedmont sediments (lower half) and Río Grande sediments of the lower terrace at CAB-C1 and C2.*



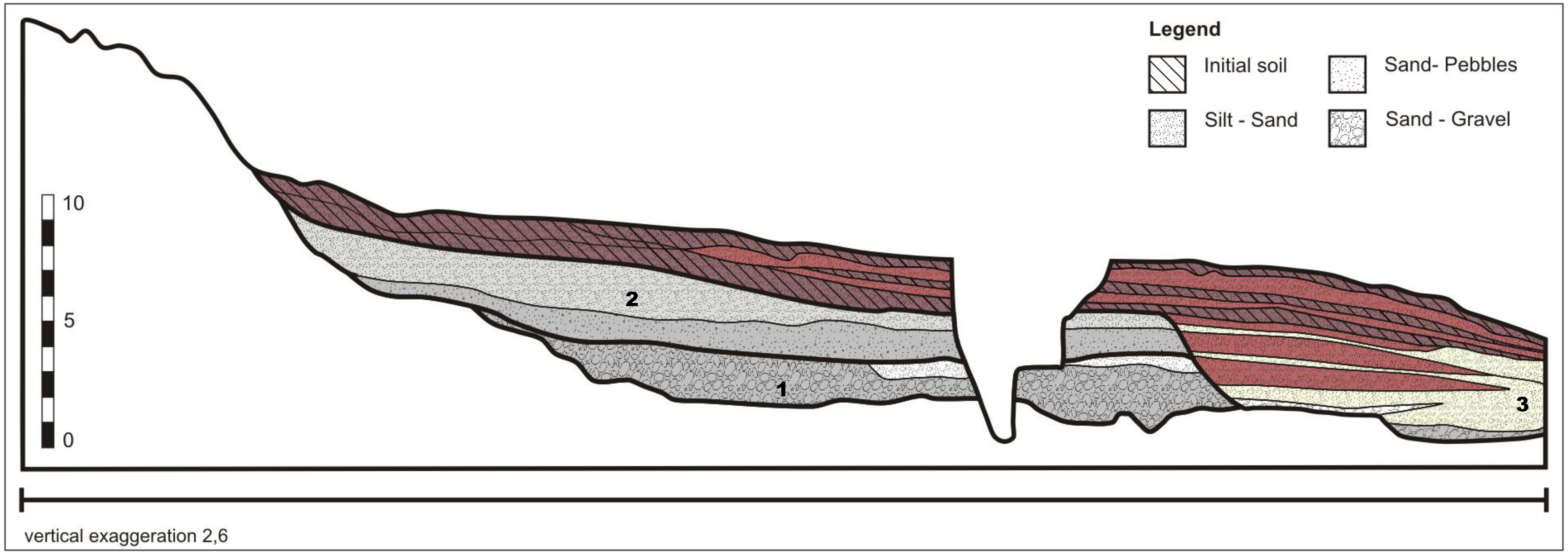
Supplementary Fig. 3-9: *Soils and sediments in the paleosol-sediment-sequences at Cabezas. a) Coarse fluvial gravel (CAB-B18), b) massive fluvial and/or fluvio-aeolian sands (CAB-A5, arrow depicts an incorporated fragment of terrestrial shell), c) fine-grained, organic rich silty clays (CAB-A10), d) two layers of overbank muds (PCN11, note the defined upper and lower boundaries and carbonate concretions as white spots), e) recent soil topping the sequences (CAB-A1-4).*



Supplementary Fig. 3-10: *Panoramic view of the paleosol-sediment-sequences at Cabezas. a) Lower terrace of Río Grande sediments resting unconformably on piedmont sediments (black lines delimit depositional units; circle marks person for scale), b) piedmont sequence along an outcrop of approximately 1000 m (black lines delimit the depositional units, see text for details; circle marks person for scale), c) detailed illustration of profiles documented along the entire outcrop width of ~3 km (black lines show tentative correlation).*



Supplementary Fig. 3-11: *Piedmont stratigraphy at CAB-B and CAB-D.*



Supplementary Fig. 3-12: *Stratigraphy of the lower Río Grande terrace at CAB-C1 and C2 (thick black lines delimit assumed depositional events I, II and III, which interrupt the overall tendency to erosion (note coarse fluvial gravel at the base of each depositional event, and the colluvial character of the reddish, initial soils topping event 3).*

Sample	pH	$CaCO_3$ [%]	Fe_o [mg/g]	Fe_d [mg/g]	Hue	Val.	Chr.	Calc. [%]	Dol. [%]	Kalif. [%]	Plag. [%]	Quartz [%]	Other [%]
CAB A-1	5.39	0.00	0.47	3.01	7.5	5	4	0.11	0.24	5.38	2.15	71.53	20.60
CAB A-2	5.38	0.00	0.35	3.73	5	4	6	0.17	0.32	11.72	3.83	62.07	21.89
CAB A-3	6.31	0.00	0.20	4.33	5	5	6	0.21	0.22	8.08	4.36	55.97	31.17
CAB A-4	7.68	6.21	0.09	3.96	7.5	6	4	4.62	0.09	9.82	3.74	51.33	30.41
CAB A-5	7.98	0.65	0.04	1.11	7.5	6	6	0.50	0.26	5.24	0.42	93.56	0.02
CAB A-6	7.96	3.33	0.21	4.30	7.5	6	4	2.79	0.30	7.83	4.65	50.31	34.12
CAB A-7	7.94	1.49	0.09	3.11	7.5	6	6	1.36	0.43	14.97	5.83	76.69	0.71
CAB A-8	7.95	1.53	0.22	5.78	7.5	5	4	1.91	0.09	6.57	2.65	33.57	55.21
CAB A-9	7.97	0.30	0.09	2.45	7.5	5	6	0.43	0.33	6.48	0.87	77.20	14.68
CAB A-10	7.59	0.00	0.18	5.46	7.5	5	4	3.34	0.15	5.84	1.23	34.23	55.21
CAB A-11	8.05	1.84	0.05	3.48	7.5	5	6	1.46	0.26	6.89	1.30	52.60	37.49
CAB A-12	7.09	0.00	0.13	2.76	5	5	6	0.40	0.50	10.92	2.13	82.21	3.84
CAB A-13	7.04	0.19	0.12	2.42	5	6	6	0.18	0.39	17.28	2.78	79.12	0.25
CAB A 14	7.78	5.94	0.09	2.61	7.5	6	6	4.19	0.23	9.33	1.66	75.88	8.71
CAB A-15	7.72	0.00	0.05	1.59	5	6	6	0.27	0.25	3.87	0.54	91.02	4.06
CAB A-16	7.78	6.21	0.15	4.89	7.5	6	4	6.89	0.15	10.63	2.38	47.66	32.28
CAB A-17	7.84	1.27	0.03	1.45	7.5	7	6	0.80	0.24	5.60	0.43	84.28	8.65
CAB A-18	7.73	0.78	0.02	0.82	7.5	7	4	0.54	0.27	3.92	0.00	95.26	0.01
CAB A-19	8.10	3.98	0.19	6.41	7.5	6	4	5.39	0.28	4.92	1.96	26.41	61.04
CAB A-20	7.86	0.00	0.09	1.88	7.5	5	8	0.13	0.29	6.28	0.85	87.31	5.14
PCN-1	7.14	0.19	0.91	3.55	7.5	4	4	-	-	-	-	-	-
PCN-2	7.12	0.00	0.81	3.19	2.5	4	6	0.20	0.34	8.13	0.40	82.70	8.27
PCN-3	7.74	0.70	0.53	2.69	7.5	5	6	0.54	0.31	4.80	0.14	93.57	5.79
PCN-4	7.91	0.00	0.62	1.62	7.5	7	4	0.16	0.28	3.67	0.27	96.90	3.84
PCN-5	7.82	1.21	3.20	7.33	7.5	5	8	-	-	-	-	-	-
PCN-6	7.63	0.00	1.50	4.71	7.5	5	2	-	-	-	-	-	-
PCN-7	7.77	3.23	1.40	6.83	5	4	4	3.12	0.34	7.49	1.24	61.80	12.19
PCN-8	7.80	0.00	0.77	2.95	2.5	4	6	-	-	-	-	-	-
PCN-9	7.77	0.00	0.76	1.41	7.5	6	4	0.10	0.14	0.42	0.13	84.82	0.53
PCN-10	7.96	0.00	0.59	2.01	2.5	4	6	-	-	-	-	-	-
PCN-11	7.89	6.72	0.97	7.14	7.5	6	4	-	-	-	-	-	-
PCN-12	7.83	0.00	0.94	3.83	7.5	5	8	-	-	-	-	-	-
PCN-13	7.83	4.34	1.14	9.84	7.5	6	4	3.55	0.27	8.95	3.94	45.96	16.71
PCN-14	7.82	0.19	0.72	3.69	7.5	5	8	0.19	0.24	3.21	0.35	83.85	3.99

Supplementary Table 3-3: *Data summary for pH, $CaCO_3$, iron fractions (Fe_o and Fe_d), Munsell soil colour (hue, value, chroma) and XRD measurements (calcite, dolomite, kalifeldspar, plagioklase, quartz and other minerals).*

Sample	SiO_2	TiO_2	Al_2O_3	Fe_2O_3	MnO	MgO	CaO	Na_2O	K_2O	P_2O_5	Ba	Cr	Cu	Nb	Ni	Pb	Rb	Sr	Y	Zn	Zr
	[wt.%]	[wt.%]	[wt.%]	[wt.%]	[wt.%]	[wt.%]	[wt.%]	[wt.%]	[wt.%]	[wt.%]	[ppm]	[ppm]	[ppm]	[ppm]	[ppm]	[ppm]	[ppm]	[ppm]	[ppm]	[ppm]	[ppm]
CAB A-1	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
CAB A-2	79.19	0.50	9.51	3.00	0.05	0.85	0.34	1.21	2.38	0.15	512	46	14	10	15	17	80	92	19	38	275
CAB A-3	83.93	0.59	10.67	3.30	0.05	1.03	0.47	1.41	2.75	0.17	532	34	13	12	17	15	90	110	19	38	279
CAB A-4	71.82	0.53	9.84	3.13	0.05	1.18	3.71	1.30	2.56	0.19	673	50	14	11	15	16	78	135	17	41	237
CAB A-5	92.34	0.16	2.67	0.60	0.01	0.27	0.50	1.65	1.12	0.05	170.22	13.86	< 5	5.94	3.96	10.89	24.74	44.53	11.88	3.96	293.93
CAB A-6	74.59	0.60	10.94	3.35	0.05	1.24	2.09	1.43	2.77	0.19	583	41	13	12	16	17	92	132	21	41	220
CAB A-7	79.76	0.49	7.52	2.16	0.03	0.71	1.06	1.12	2.39	0.11	358.21	30.79	< 5	10.75	10.75	16.13	68.42	91.87	28.34	29.81	325.96
CAB A-8	62.04	0.67	14.11	< 5	0.08	1.85	1.72	1.15	3.17	0.22	597	67	24	13	24	25	121	154	22	65	174
CAB A-9	87.37	0.34	5.91	1.76	0.03	0.62	0.59	0.51	1.84	0.07	365.32	< 5	< 5	7.86	9.82	14.73	54.01	74.64	20.62	27.50	260.24
CAB A-10	63.22	0.62	14.57	5.08	0.07	2.01	2.79	1.01	2.97	0.19	628	61	19	11	24	23	123	151	21	67	176
CAB A-11	75.53	0.45	9.81	2.99	0.05	1.22	1.42	1.05	2.31	0.16	470	44	15	10	13	17	82	120	13	43	230
CAB A-12	86.35	0.35	6.89	1.89	0.03	0.64	0.38	1.05	1.94	0.11	470	20	10	8	8	11	55	80	11	22	256
CAB A-13	86.96	0.40	6.73	1.90	0.03	0.64	0.29	1.11	1.98	0.12	453	17	17	9	8	13	57	78	10	24	286
CAB A 14	78.97	0.40	6.52	2.08	0.04	0.72	3.58	0.71	1.87	0.08	400.69	< 5	< 5	9.56	10.52	15.30	59.29	92.76	21.99	30.60	254.38
CAB A-15	91.32	0.23	3.59	1.04	0.02	0.35	0.25	1.18	1.28	0.02	296.40	10.90	< 5	5.95	6.94	10.90	32.71	46.59	13.88	12.89	268.64
CAB A-16	66.45	0.57	11.80	3.97	0.06	1.38	3.99	1.20	2.61	0.16	527	75	25	11	28	22	98	124	19	53	175
CAB A-17	90.79	0.22	3.22	0.82	0.02	0.30	0.69	0.74	1.38	0.06	389.50	< 5	< 5	5.93	< 5	10.87	35.59	51.41	14.83	11.86	341.06
CAB A-18	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
CAB A-19	55.41	0.59	15.99	5.71	0.07	2.31	3.38	1.58	3.14	0.21	597	60	20	12	28	25	127	148	19	76	135
CAB A-20	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
PCN-1	89.12	0.20	3.28	0.77	0.02	0.26	0.22	1.13	1.37	0.06	137.32	7.85	4.90	6.87	4.90	11.77	34.33	49.04	12.75	11.77	239.32
PCN-2	92.44	0.18	3.29	0.79	0.02	0.28	0.25	0.47	1.39	0.02	202.33	< 5	< 5	< 5	3.97	10.91	35.71	47.61	10.91	10.91	242.01
PCN-3	92.11	0.18	3.20	0.75	0.01	0.32	0.52	0.41	1.35	0.06	231.44	< 5	< 5	< 5	2.97	8.90	32.64	51.43	11.87	9.89	229.46
PCN-4	96.22	0.08	1.94	0.26	0.01	0.15	0.09	0.54	1.10	0.04	233.32	9.97	< 5	< 5	< 5	7.98	21.94	42.88	6.98	3.99	153.55
PCN-5	73.49	0.69	12.74	4.16	0.09	1.30	1.25	1.41	3.26	0.10	496.17	39.69	< 5	14.89	20.84	22.82	102.21	132.97	33.74	49.62	278.85
PCN-6	87.09	0.34	5.86	1.59	0.03	0.52	0.29	0.65	1.95	0.10	415.29	15.75	< 5	8.86	6.89	169.27	56.09	75.78	20.67	27.56	359.20
PCN-7	70.90	0.40	9.98	3.43	0.06	1.18	2.17	1.31	2.38	0.13	407.47	34.00	< 5	8.62	16.28	17.24	80.92	108.21	21.07	51.23	187.22
PCN-8	91.41	0.15	3.96	1.19	0.02	0.47	0.27	0.56	1.30	0.07	192.95	22.76	< 5	< 5	6.93	11.87	35.62	50.46	11.87	13.85	123.68
PCN-9	96.28	0.06	1.57	0.36	0.03	0.18	0.07	0.40	0.69	0.02	94.63	< 5	< 5	< 5	2.99	< 5	10.96	26.89	7.97	3.98	76.70
PCN-10	94.90	0.11	2.61	0.74	0.02	0.28	0.20	0.63	0.79	0.05	75.96	10.92	< 5	5.46	< 5	9.93	15.89	36.74	10.43	7.94	88.37
PCN-11	74.01	0.52	9.33	2.63	0.04	0.91	3.46	2.41	2.79	0.07	472.47	28.63	< 5	11.45	12.41	14.32	78.27	111.68	28.63	33.41	289.21
PCN-12	89.75	0.24	5.03	1.22	0.02	0.42	0.25	0.57	2.01	0.05	456.81	10.88	< 5	6.92	7.91	13.84	52.40	64.27	14.83	14.83	259.06
PCN-13	69.28	0.66	12.66	3.98	0.05	1.35	2.58	0.90	3.15	0.10	365.78	58.11	4.76	12.38	21.91	20.00	100.02	120.97	30.48	52.39	223.85
PCN-14	91.09	0.21	3.72	1.04	0.02	0.35	0.20	1.02	1.30	0.04	174.46	12.89	< 5	5.95	5.95	9.91	36.68	48.57	14.87	14.87	223.03

Supplementary Table 3-4: *Data summary for XRF measurements.*

4

HOLOCENE LANDSCAPE EVOLUTION ALONG THE ANDEAN PIEDMONT, BOLIVIAN CHACO

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Submitted: Palaeogeography, Palaeoclimatology, Palaeoecology

ABSTRACT

As part of the Gran Chaco, the Andean piedmont in Eastern Bolivia is characterized by a highly seasonal climate and large rainfall variability. It receives sediments from small drainage basins in the Subandean ranges. Therefore it should constitute a suitable sedimentary and geomorphic archive for the detection of past environmental changes. This study reconstructs Holocene landscape evolution along the Andean piedmont in the Bolivian Chaco by combining large-scale geomorphological analysis and the investigation of sedimentary sequences. Fluvial aggradation and channel avulsions are the dominant processes of piedmont construction, and were particularly pronounced during the Mid-Holocene. This is interpreted to reflect a generally active landscape characterized by reduced forest cover as result of increased aridity. Widespread soil formation and landscape stability in all investigated catchments starts after 4 cal ka BP indicating the onset of wetter conditions and successively denser forest cover in the Bolivian Chaco. Renewed sedimentation during the last millennium could imply a shift to more arid environmental conditions, probably in relation to larger-scale climatic phenomena such as the Little Ice Age (LIA). Particularly during the last centuries the fluvial system of the study area has undergone the most profound changes of the entire Holocene with sedimentation of very coarse sediments and subsequent incision. This reflects important changes both in discharge and sediment supply, and might be the result of either shorter-term climate changes or increasing human impact.

Keywords: Holocene; fluvial geomorphology; sedimentary sequences; paleo-environment; piedmont; Bolivian Chaco

4.1 INTRODUCTION

Geoecological research in the tropics and subtropics is important for the understanding of the climate and environmental system. In particular, the reconstruction of changes in the past is essential for the interpretation of modern observations and for future predictions. Apart from the investigation of global climate linkages, respective research should also focus on the analysis of regional environmental variability (Markgraf et al., 2000). There is a growing number of studies from the South American lowlands including various paleoenvironmental archives, for example the fluvial systems of the Amazonian lowlands (Latrubesse, 2003) or the aeolian and fluvial plains of northern Argentina and southern Brazil (Iriondo and Garcia, 1993; Iriondo, 1999; Stevaux, 2000). Additionally, palynological studies from the Amazon lowlands and adjacent regions (van der Hammen and Absy, 1994; Ledru et al., 1996; Behling, 1998; Ledru et al., 1998; Colinvaux and Oliveira, 2000; van der Hammen and Hooghiemstra, 2000; Behling, 2002) and high-resolution speleothem records from southern Brazil (Wang et al., 2004; Cruz et al., 2005; Wang et al., In Press) provide manifold evidence for major geomorphic, hydrological and ecological changes during the Late Quaternary. However, large regions in the South American lowlands still lack detailed paleoenvironmental studies. More regional investigations are needed to close the existing gaps and to supplement the spatially limited interpretations of the high-resolution proxy records (Coltrinari, 1993; Markgraf, 1998; Baker, 2000; Markgraf et al., 2000).

Due to its transitory position between the tropical humid climate to the north (Amazonia) and the semi-arid climate to the south-east (Gran Chaco) the Bolivian Chaco is characterized by a steep climatic gradient. Past changes in atmospheric circulation and resultant precipitation should therefore be sensitively recorded in suitable archives.

Up to now, the number of geomorphological and paleoenvironmental studies from the Bolivian Chaco is very limited. The large-scale geomorphic evolution has been discussed by Iriondo (1993), May (2006) and Werding (1977b; 1977a). Geyh et al. (1996), Kruck (1996), Barboza et al. (2000) and Pasig (2005) have investigated the Late Pleistocene and Holocene sedimentary and hydrogeological evolution of the adjacent Paraguayan Chaco. In addition, Servant et al. (1981) and May et al. (in press) used paleosol-sediment-sequences to reconstruct landscape evolution along the Andean piedmont. All of these studies show evidence for major environmental changes during the Late Quaternary, but none of them has combined extensive geomorphological mapping with a detailed regional stratigraphical analysis.

Therefore, the aim of this paper is to i) document the geomorphological landforms and processes along the Andean piedmont in the Bolivian Chaco, ii) establish a regional stratigraphy for the Late Quaternary sediments and iii) reconstruct and interpret landscape evolution in the study area based on the geomorphological and stratigraphical findings. Finally, the results are discussed in the regional context of the paleoenvironmental evolution of the Bolivian Chaco.

4.2 REGIONAL SETTING

The study area is situated around the town Charagua (Cordillera province) approximately 160 to 240 kilometers south of Santa Cruz de la Sierra (Fig. 4-1). It is part of the Andean piedmont and forms the western margin of the Gran Chaco.
The climatic conditions in the study area are mainly controlled by the South American Summer Monsoon (SASM), which is responsible for precipitation maxima during austral summer (Zhou and Lau, 1998; Nogues-Paegle et al., 2002). Cold polar air incursions can cause severe temperature drops and additional rainfall throughout the year (Garreaud, 2000). Total annual precipitation ranges from 529 mm/a (Coperé) to > 825 mm/a (e.g. Charagua, Tarenda) (AGTECA, 2005) with higher values near the easternmost Andean ranges. The pronounced seasonality, with a dry season of 5-7 months during austral winter, as well as the high interannual rainfall variability are responsible for potentially intensive erosion (Gerold, 1988). The Andean piedmont around Charagua is characterized by semi-deciduous Chaco forest (Navarro and Fuentes, 1999; Ibisch et al., 2004). Depending on small-scale differences in topography and parent material, arenosols, leptosols and regosols, but also cambisols and luvisols are the most common soil types in the study area (Guamán, 1981; Gerold, 2004).

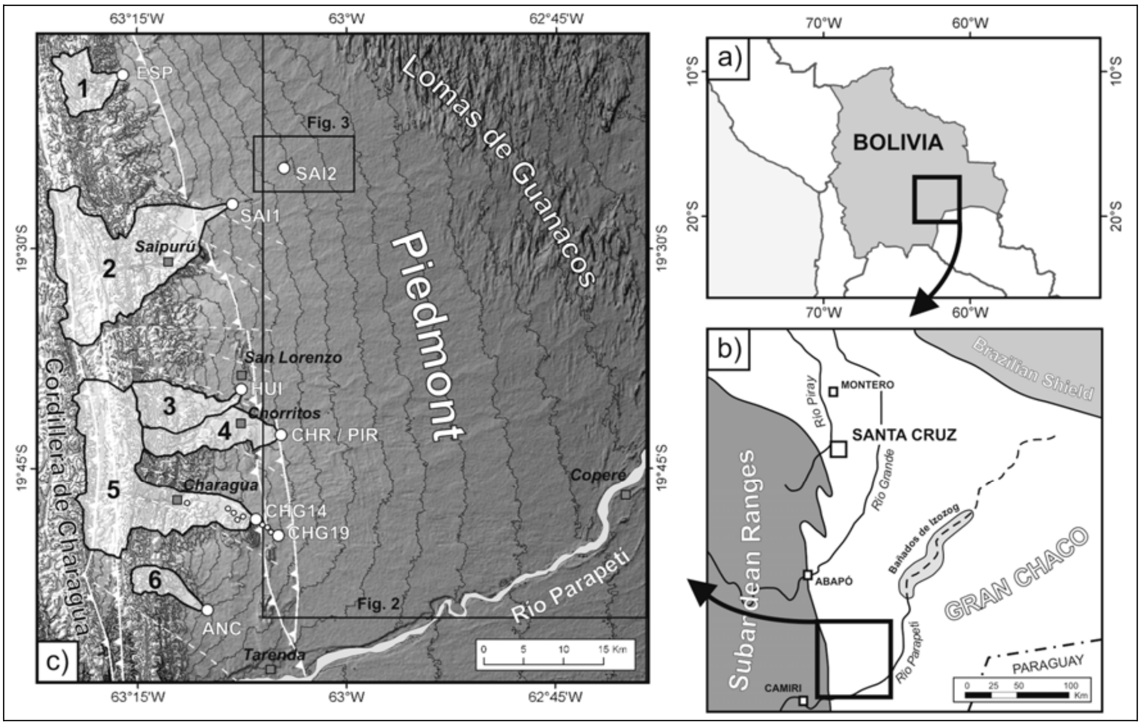

Fig. 4-1: *Location and regional setting of the study area. a) Political boundaries of Bolivia, b) Eastern Bolivian lowlands and the Subandean Ranges, c) Piedmont around the town of Charagua, including the main thrust faults (white lines), transcurrent faults (white dashed lines), the locations of the investigated sedimentary sequences (white dots) and their drainage basins in the Subandean Ranges (1=Quebrada Espino, 2= Quebrada Saipurú, 3=Quebrada Huirapucutí, 4=Quebrada Chorritos/Pirití, 5= Quebrada Charagua, 6=Quebrada Ancasoro). Black boxes indicate locations of Fig.4-2 and Fig.4-3.*

Geologically, the study area is situated at the transition between the morphostructural units of the Subandean Zone, which is affected by the Andean uplift and deformation throughout the Late Cenozoic characterized by fold-and-thrust belts (Cordillera de Charagua, Fig. 4-1), and the Chaco plain, which represents one of several Andean retroarc foreland basin systems (Sempere et al., 1990; Horton and DeCelles, 1997; Uba et al., 2006). Around Charagua, the transition between the Subandean Zone and the Chaco Plain is topographically expressed in the Subandean foothills, where Late Miocene to Pleistocene sedimentary rocks of the Guandacay and Emborozú formations crop out (Marshall, 1991; Moretti et al., 1996; Uba et al., 2006).

The uppermost sediments of the foreland basin system of the Bolivian Chaco consist of Late Quaternary fluvial and fluvio-aeolian deposits of the large megafans of the Río Grande, Río Parapetí and Río Pilcomayo (Werding, 1977a; Horton and DeCelles, 2001) or are part of the Andean piedmont (Horton and DeCelles, 1997; May, 2006).

Based on topography and structural-geological criteria, the piedmont in the study area can be subdivided into two distinct geomorphological zones (Fig. 4-1): (i) In direct vicinity to the Cordillera de Charagua, the Subandean foothills form the proximal part of the piedmont. As a consequence of the active foreland deformation and emergent thrust-faults, it is characterized by topographically elevated thrust blocks (cuestas, escarpments?), outcrops of Tertiary to Quaternary sedimentary rocks, dissected topography and slope gradients between 0.5 and >1.5°. (ii) Where topography becomes smooth and slope gradients are less than 0.5°, the proximal piedmont grades into the medial and distal piedmont. A complex array of parabolic dunes on the distal part of the piedmont constitutes the southernmost extension of the Lomas de Guanacos dunefield (Fig. 4-1). Further to the east and the south, the piedmont is eventually bordered by the Río Parapetí floodplain.

Several drainage channels of ephemeral streams (quebradas) with varying catchment sizes contribute discharge and sediment onto the piedmont, forming a series of coalescent fans (Fig. 4-1) (Horton and DeCelles, 1997). Note that the piedmont slope generally shows no cone-shaped alluvial fan morphology , pointing to channelled stream flow and frequent avulsions as the dominant processes of piedmont formation (Smith, 2000). The catchments of the smaller streams extend up the eastern slopes of the Cordillera de Charagua. Only the Quebrada Charagua and the Quebrada Saipurú have large enough catchments to cut through the Cordillera de Charagua, reaching into the Subandean ranges. Along the proximal to medial part of the piedmont the meandering drainage channels are incised up to more than 10 m, exposing paleosol-sediment-sequences, which document the sedimentary (hydrological, geomorphological) evolution of the piedmont during the Late Quaternary. Downslope of the incised channel segment, the channels widen into "floodouts" depositing large quantities of bedload.

4.3 METHODS

This study integrates two methodological approaches. First, a regional comprehension of geomorphic patterns and processes has been achieved by extensive field reconnaissance, analysis of remote sensing data and available regional cartography. Satellite imagery was pre-processed using basic procedures of image enhancement (Lillesand and Kiefer, 1994). Three sets of Landsat scenes (1975, 1986 and 2000) as well as Corona images (1966) were used for multi-temporal analysis. In combination, these data formed the basis for visual geomorphic interpretation, which makes use of colour, density and textural patterns, but also incorporates information inferred from elevation, vegetation and land-use patterns (Verstappen, 1977; Rosenfeld, 1984). Thus landforms, surface processes and their changes can be analysed for the investigated time period. The observed patterns were compared to soil-geomorphic reconnaissance maps (Guamán, 1981), contributing additional information regarding the distribution of vegetation, soils and surface sediments.

In order to establish a stratigraphy, which takes into account the high lateral variability inherent to each fluvial system, a total of ten natural outcrops were studied concerning their sedimentary sequences in the Quebrada Charagua watershed (=CHG). Six additional profiles from five further watersheds (ANC=Quebradas Ancasora, HUI=Huirapucutí, CHR/PIR=Chorritos (Pirití), SAI=Saipurú and ESP=El Espino) enable a more regional comparison. The sedimentary sequences were described based on AG Boden (1994). Specifically, macroscopic pedological characteristics, such as colour, pedogenic texture, cutans, redox characteristics and carbonate pseudomycelia and nodules were used to identify soil horizons. In addition, the determination of dominant grain sizes and basic sedimentary structures allowed defining various sedimentary facies. Two sequences (SAI2, CHG19) were sampled for more detailed grain size analysis. A bulk sample of ~500 g was taken from each horizon or layer, and analyses were carried out on dry and sieved (< 2 mm) samples. For all measurements, carbonates were removed with 10% HCl and organic matter was oxidized with 30% H_2O_2. In addition, microaggregates < 63 µm were dispersed with Na_2CO_3. The sand fractions (63-2000 µm) were separated by wet sieving and the silt (2-63 µm) and clay (< 2 µm) fractions were quantified using a Micromeritics SediGraph 5100.

The chronology of the sedimentary profiles is based on 15 AMS radiocarbon dates (Poznan Radiocarbon Laboratory) and four conventional radiocarbon measurements (Institute of Physics, University of Bern). All radiocarbon ages used and cited in this study have been calibrated using the online calibration software CALPAL (Weninger et al., 2006).

4.4. RESULTS

4.4.1. GEOMORPHOLOGY

Large-scale piedmont geomorphology

Analysis of the remote sensing data (Landsat imagery) reveals a patchy pattern of different colours and textures (Fig. 4-2A) reflecting the heterogeneity of the vegetation cover. Darker shades indicate a dense cover of semi-deciduous Chaco forest; lighter shades fewer and smaller trees. The spatial pattern is likely controlled by hydrologicalcriteria such as soil water balance (Navarro and Maldonado, 2002), which in turn depends on surface topography and soil properties. In general, shallow depressions tend to remain waterlogged for longer times, leading to accumulation of fine-grained sediments and salts upon desiccation. On the contrary, elevations consist of coarser sediments and are better drained, exhibiting more preferable conditions for tree growth. Our interpretation is in good agreement with findings of Guamán (1981), who combined air photography and extensive field work in order to map small-scale topography and basic soil properties along the medial part of the piedmont around Charagua (see Fig. 4-2B for details). The interrelation between geomorphology and soils versus vegetation is confirmed by independently compiled vegetation maps, which were classified from Landsat imagery (Museo de Historia Natural NKM, 2004).

The pattern of small-scale topography, soil and sediment type bears valuable information on the spatial activity of geomorphic processes, which have shaped the landscape, and their changes in the past. The coarser sediments of the topographic elevations, for example, imply sediment deposition in paleochannels, i.e. near the central parts of past floodplains. On the contrary, topographic depressions generally correspond to more distal parts receiving less sediment and finer grain sizes. Concerning the geomorphic evolution of the piedmont and the fluvial history of its contributory streams the following conclusions can be deduced:

- *The distribution of the soil-geomorphic units allows delimitating drainage divides and identifying paleo-floodplains on the piedmont.*
- *Only the largest streams (Quebrada Charagua, Quebrada Saipurú) have developed a morphological fan shape. This suggests that channel avulsion, as typical for alluvial and fluvial fans, has been an important process for piedmont construction, and was essentially controlled by sediment supplies.*
- *Within the individual catchments, areas of active fluvial activity (Fig. 4-2, "M") characterized by recent frequent flooding, can be distinguished from paleofloodplains (Fig. 4-2, "P").*
- *Deposition of coarser sediments (i.e. occurrence of sandy soils) has reached further downslope in the past compared to today (inferred from sandy soils of recent floodplains). Stream power of the individual discharge events thus changed over time, likely related to climate and environmental changes.*
- *The strong discharge events transported sediments onto the distal piedmont and provided material for aeolian activation there (Lomas de Guanacos, Fig. 4-1).*

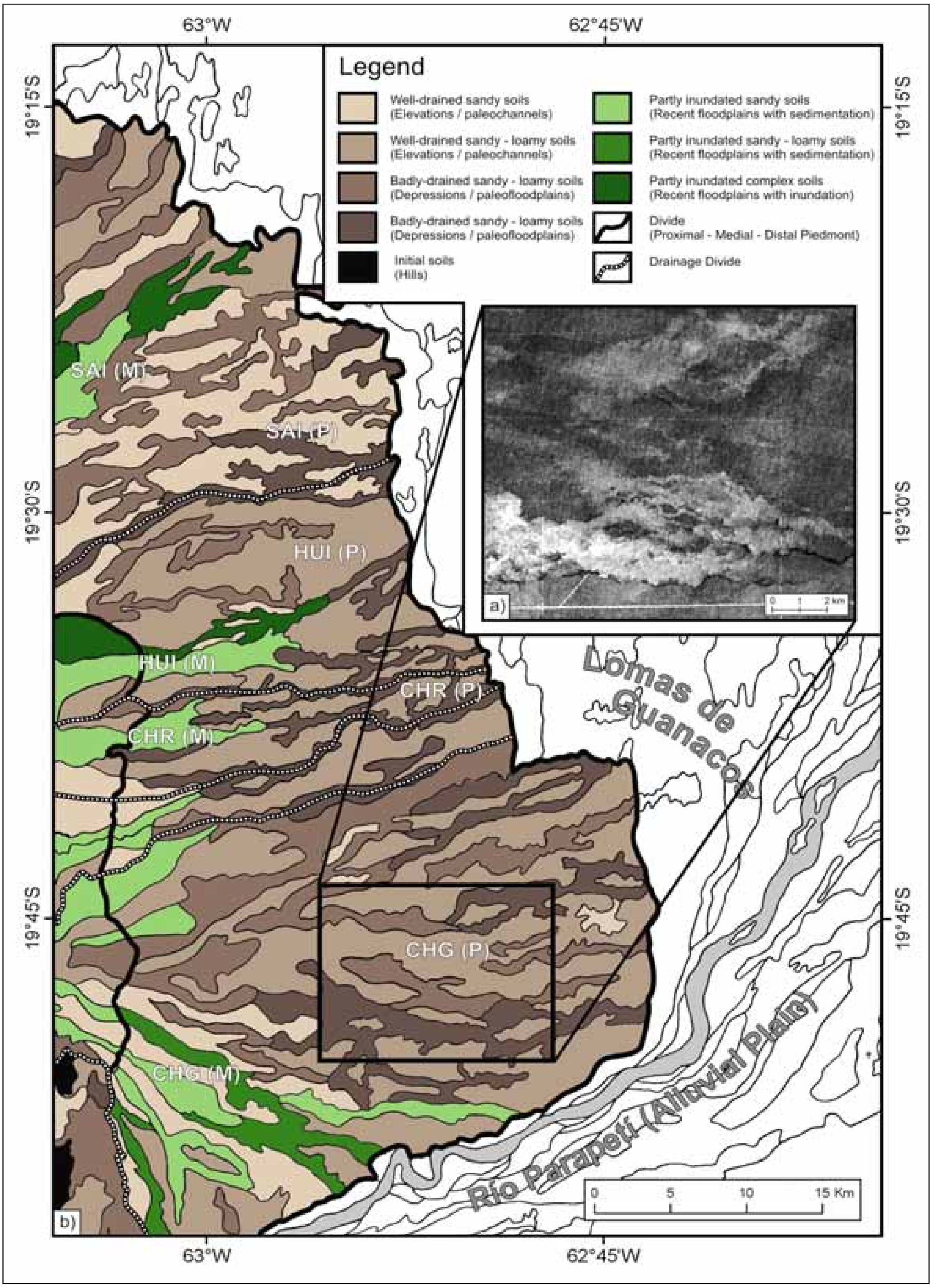

Fig. 4-2: *Piedmont geomorphology indicating a) active floodplains (M) and inactive paleofloodplains (P) as interpreted from the identification of vegetation patterns in remote sensing imagery, and b) large-scale soil-geomorphic maps (modified from Guamán (1981)).*

Recent channel changes

In the study area, lobes of sandy surface and little vegetation cover downstream of the incised channel reaches are readily distinguishable on satellite imagery, and have been identified as floodouts, where channelized flow ceases and the floodwaters spill across the adjacent alluvial surfaces (Tooth, 1999; May, 2006). Based on multi-temporal analysis of remote sensing data (Landsat 1975, 1986 and 2000, Corona 1966) a detailed inventory of geomorphological changes in the floodout zone along the lower Quebrada Saipurú during the past ~ 50 years has been established. The resulting map (see Fig. 4-3) illustrates the migration of the loci of sand deposition and successive channel incision through time.

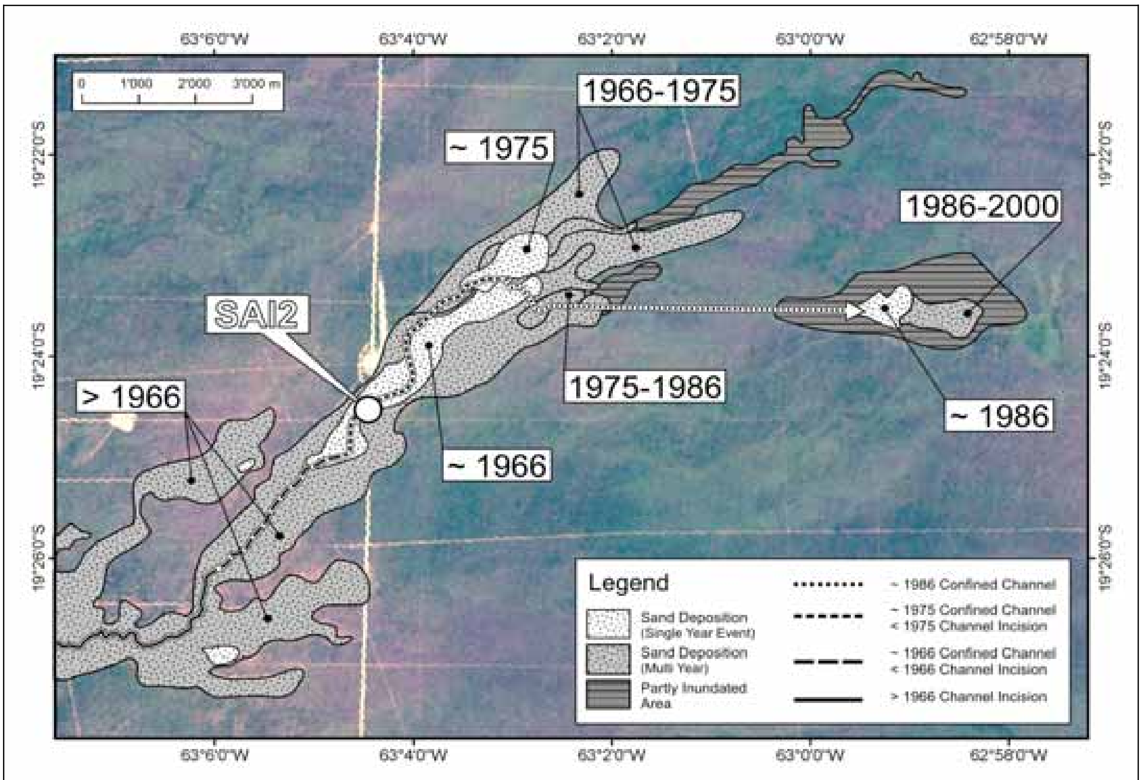

Fig. 4-3: *Floodout evolution and migration of sand deposition along the lower Quebrada Saipurú interpreted from Corona (1966) and Landsat (1975, 1986, 2000) imagery.*

Sandy floodout deposits older than 1966 are branching in different directions, likely reflecting multiple depositional events and frequent avulsions. Since 1966, the channel incised and the location of floodout deposition migrated downwards. In the course of time, active sand deposition decreased (1966 > 1975 > 1986) and eventually ceased after 2000. Channel incision successively migrated eastward as well, cutting into the young floodout sediments. The westernmost incised channel segments in the floodout have developed a highly sinuous channel planform, whereas the younger channel sections further downslope show low sinuosity. These differences are probably due to the longer time of active incision in the meandering segments and the resulting subsequent modifications of the channel banks by intensive floods. In its lower reach, the confined channel has advanced along a forest aisle and exhibits a perfectly straight pattern. The height of channel banks along the incised channels decreases downslope from > 10 meters in the proximal piedmont to < 3 meters shortly before the recent floodouts. Within the channel, remnants of a depositional terrace of varying height (3-5 meters) are preserved (Fig. 4-4A), implying that incision was not continuous but interrupted by at least one interval of decreased stream power and deposition of coarse grained sediments. For the recent dynamics of the piedmont fluvial system, the development of the Quebrada Saipurú floodout implies i) a relative increase in stream power (i.e. the energy of the individual discharge events / floods), and ii) a marked reduction of sediment load (bed load) since the pre-1965's.

4.4.2 THE SEDIMENTARY SEQUENCES

Field observations and general remarks

In the following, the 16 sedimentary sequences, which were studied along the mostly vertical banks of the incised stream channels, shall be described. Generally, the sequences consist of sandy material with intercalated layers of finer overbank deposits and paleosols. All sequences are topped by coarse sands or cobbles of varying thickness - sediments resembling those of the terrace segments, which are locally preserved within the channels (with maximum clast sizes of up to 80 cm in diameter).

Coarse sand and cobble deposits are often associated with distinct erosional lower contacts, sometimes developed as deep paleochannels (Fig. 4-4A). At other locations, shallow paleochannels form the lower contact of sandy layers (Fig. 4-4B), but erosional hiati can be absent at all as well. The internal architecture of the sandy units is mostly massive, homogeneous and laterally extensive (Fig. 4-4B, D). These general observations point to significant differences in stream power and channel architecture, ranging from shallow aggrading channels to linear channel incision (Miall, 1985).

Only in the sand units associated with recent floodout deposits (see 4.4.1.), individual sand banks of 40-70 cm thickness can be identified. They exhibit sharp, linear and mostly non-erosive contacts between the individual layers (Fig. 4-4C). Up to 4.5 meters of sand can thus be ascribed to 6-11 individual depositional events.

Paleosols that are developed in the sequences are generally characterized by darker, brownish to reddish colours than the surrounding sands. In contrast to the sometimes also dark fluvial layers of fine-grained silts and clays, the paleosols are usually thicker and show a gradual contact with the sediments in which they have developed (Fig. 4-4D, E). The paleosols as well as the fine-grained layers have sharp upper contacts, representing in both cases past surfaces. Well-developed paleosols, however, indicate long periods of landscape stability, whereas the finer-grained layers document a distal floodplain environment with an actively aggrading landscape with slow burial of leaves and soil fauna. In contrast, the preservation of tree trunks points to rapid and catastrophic sedimentation events (Fig. 4-4E, F).

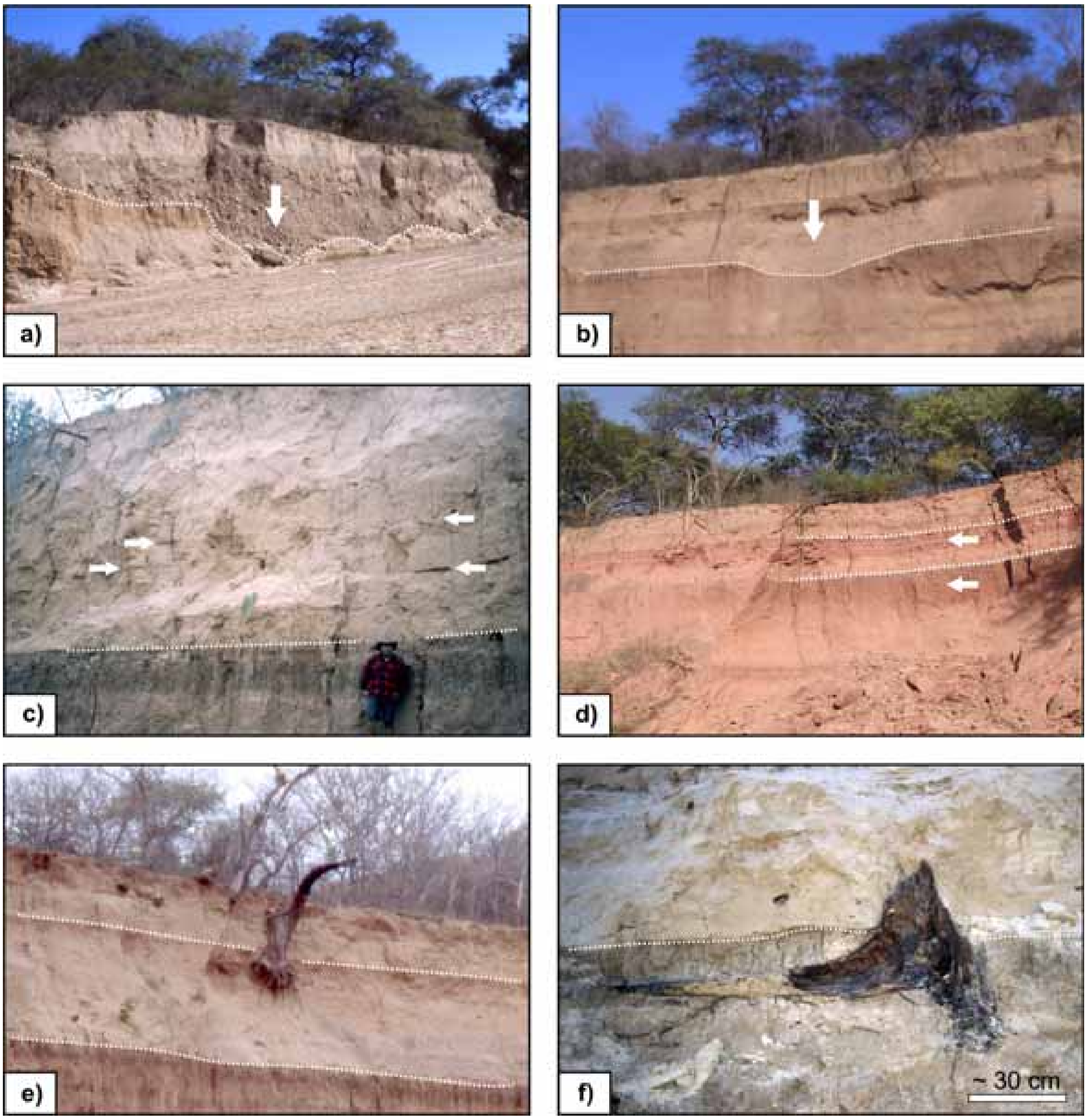

Fig. 4-4: *Field observations of from the investigated sedimentary sequences. a) Paleochannel filled with coarse sands and cobbles in a lower terrace segment preserved within the Quebrada Charagua, b) Shallow and laterally extensive paleochannel in the Quebrada Charagua indicating an aggrading (avulsive) fluvial system, c) Sand banks in floodout deposits in the lower Quebrada Saipurú corresponding to individual depositional events, d) Sedimentary sequence in the Quebrada Charagua exhibiting a well-developed paleosol (lower arrow) and overbank deposits (upper arrow), e) Buried tree rooted in a thin layer of overbank deposits in the Quebrada Charagua, f) Buried tree trunk in overbank muds in the Quebrada Saipurú.*

Grain size classes

Twenty-five samples from two selected profiles (SAI2, CHG19) were analyzed regarding their grain size frequency distribution, which contains information regarding the process energy during sediment transport and deposition (e.g. Folk and Ward, 1957; Visher, 1969; Kalicki, 2000). In combination with field observation, the grain size data provided the base for the definition of typical grain size frequency distribution classes (Fig. 4-5), and the interpretation of specific depositional environments for the classes (Miall, 1985). Silty clays have been interpreted as overbank deposits within a distal floodplain. The very fine grain sizes indicate slow water movement during deposition in a topographic depression in temporary lacustrine / palustrine environments resulting from extensive flooding events. Sandy loams and clay loams (Fig. 4-5) show very poor sorting. This is typical for fluvial muds, resulting from the incorporation of fine suspended sediment load into coarser bed load. These sediments have likely been deposited in more proximal overbank environment during high water stages of flooding events.

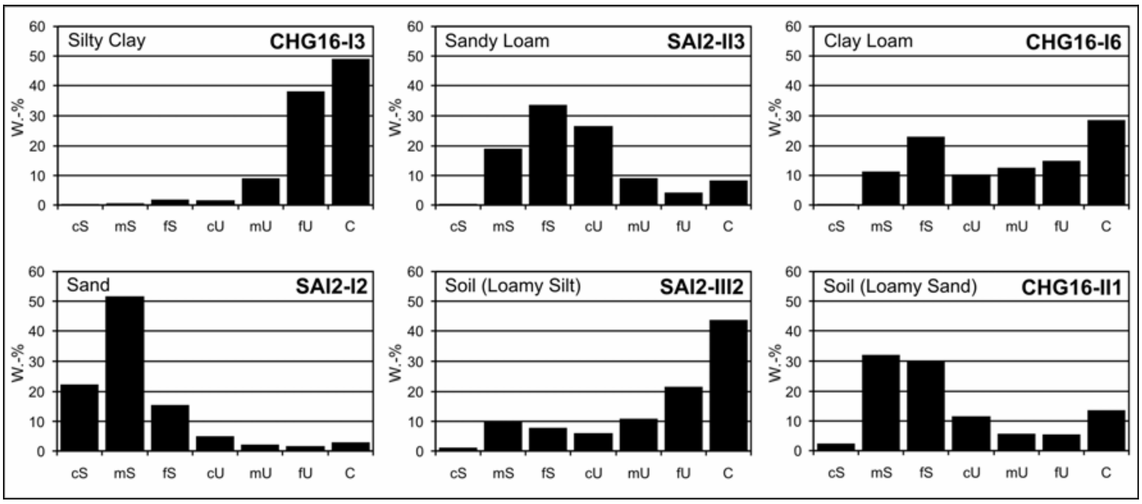

Fig. 4-5: *Typical grain size distributions of sediment and soils in two investigated sequences.*

Sandy sediments with little content of fine grained sediment indicate deposition in higher energy environments in close vicinity of or within the fluvial channel. Loamy silt and loamy sand as well as poor sorting is characteristic for samples, which have been associated with well-developed paleosols or soil horizons in the field. Commonly, these horizons have shown intense coloration, gradual lower boundaries and weakly developed clay cutans. Thus, increased amount of clay in the frequency distribution points to clay illuviation and or clay formation within the soil profile.

4.4.3 CORRELATION OF THE SEDIMENTARY SEQUENCES

The described sedimentary sequences can be illustrated as a vertical succession of texture classes (Fig. 4-6, 4-7), each of which has previously been associated with fluvial processes in a specific depositional environment. The reconstruction of landscape evolution and the detection of changes in the fluvial dynamics are mainly inferred from the interpretation of spatial and temporal changes in process type and intensity. In this regard, a well-developed paleosol implies stability over an extended period of time without essential sedimentation or erosion (Rohdenburg, 1970), whereas overbank muds and channel sands indicate sedimentation in different floodplain areas of an overall aggrading fluvial system. Erosion can be inferred from the existence of paleochannels and incised active channels. Thus, each sedimentary sequence can be regarded a succession of alternating phases of sedimentation, stability and erosion at a given location. For the correlation between the sequences, well-developed paleosols were used as marker horizons, reflecting regional instead of local landscape stability. In addition, overall grain size trends (e.g. fining upward sequences topped by distal overbank deposits) or the repetition of similar successions (e.g. loam – clay – loam – clay) were used for correlation within the Quebrada Charagua. Resulting from the correlation, sedimentary units (I to III) have been established as the base for the reconstruction of regional landscape evolution and the discussion of environmental interpretation.

Chronology of the sedimentary sequences

An absolute chronology has been established in order to corroborate the correlation of the sedimentary sequences and to integrate the results into a broader regional and chronological frame. For this purpose a total of 19 radiocarbon ages were obtained (Table 4-1).
The datings were conducted on wood, terrestrial charcoal and terrestrial shells, which were extracted from the sediments or buried tree trunks, respectively. In addition, humic acids and humins were dated from soil organic matter of a buried paleosol. Both ages correspond well, and should therefore reflect the approximate burial age of the respective paleosol.

Sample Name	**Lab.-Code**	**Material**	**Depth** [cm]	**^{14}C Age** [^{14}C yr BP]	**Calibrated Age** [cal. yr BP]	**Calibrated Age** [cal. yr AD]
SAI2 I-II C14W	B-8540	wood	450	100 ± 20	51 - 239	1805 ± 94
SAI2 II C14S	Poz-9939	terrestrial shell	550	140 ± 30	31 - 238	1811 ± 103
SAI2 III C14S	Poz-9940	terrestrial shell	800	7270 ± 40	8040 - 8147	-
HUI IIa NaOH	Poz-16793	soil (humic acid)	400	740 ± 30	674 - 704	1261 ± 15
HUI IIa RES	Poz-16795	soil (humins)	400	650 ± 30	575 - 657	1334 ± 41
HUI IIa C14K	Poz-10104	charcoal	350	165 ± 30	29 - 263	1804 ± 117
HUI IIb C14S	B-8535	terrestrial shell	550	4080 ± 50	4515 - 4768	-
HUI IIc C14S	Poz-9902	terrestrial shell	900	4220 ± 35	4702 - 4837	-
HUI IIIb C14K	Poz-10105	charcoal	1050	4700 ± 35	5351 - 5544	-
HUI IVa C14K	Poz-10106	charcoal	1180	4950 ± 35	5635 - 5718	-
CHR 2 C14S	Poz-9903	terrestrial shell	850	5295 ± 35	6020 - 6160	-
CHR 3 C14K	Poz-10107	charcoal	600	4525 ± 35	5092 - 5279	-
CHG19 I C14S	Poz-9904	terrestrial shell	200	420 ± 30	465 - 510	1462 ± 22
CHG19 II C14S	Poz-9941	terrestrial shell	300	985 ± 30	839 - 934	1063 ± 47
CHG19 III C14S	Poz-9942	terrestrial shell	1100	8560 ± 50	9508 - 9555	-
CHG14 I-II C14W1	B-8541	wood	150	100 ± 20	51 - 239	1805 ± 94
CHG14 I-II C14W2	B-8542	wood	150	90 ± 20	50 - 239	1805 ± 94
CHG1 C14K	Poz-10207	charcoal	400	215 ± 30	154 - 293	1726 ± 69
ANC C14S	Poz-10211	charcoal	450	1110 ± 30	983 - 1052	932 ± 34

Table 4-1: *List of radiocarbon ages obtained from the sedimentary sequences*

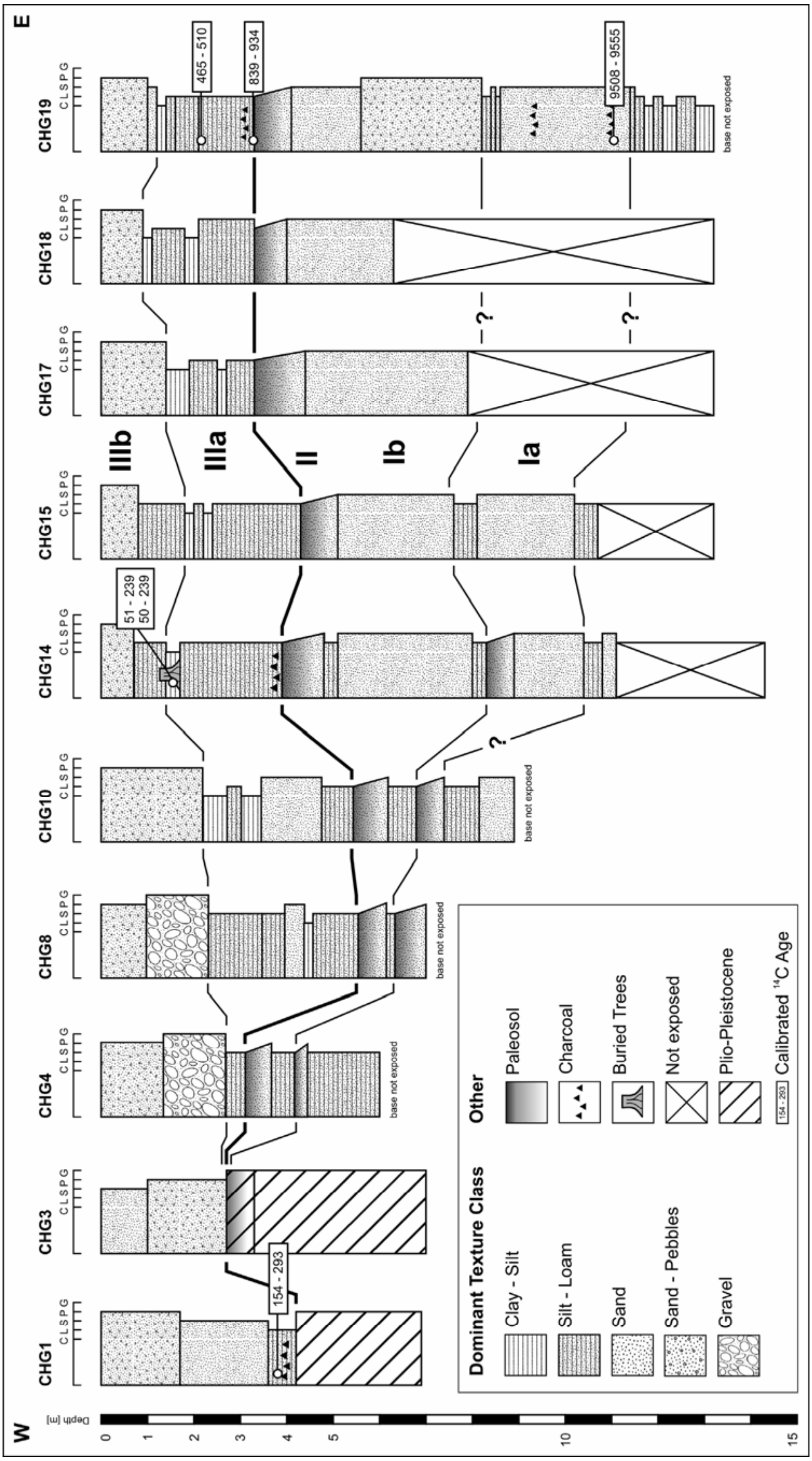

Fig. 4-6: *Correlation of the investigated sedimentary sequences in the Quebrada Charagua based on based on paleosols, the succession of grain size trends and calibrated radiocarbon ages (see text and table 4-1 for details). The interpretation of sedimentological units (I to III) is indicated by black lines.*

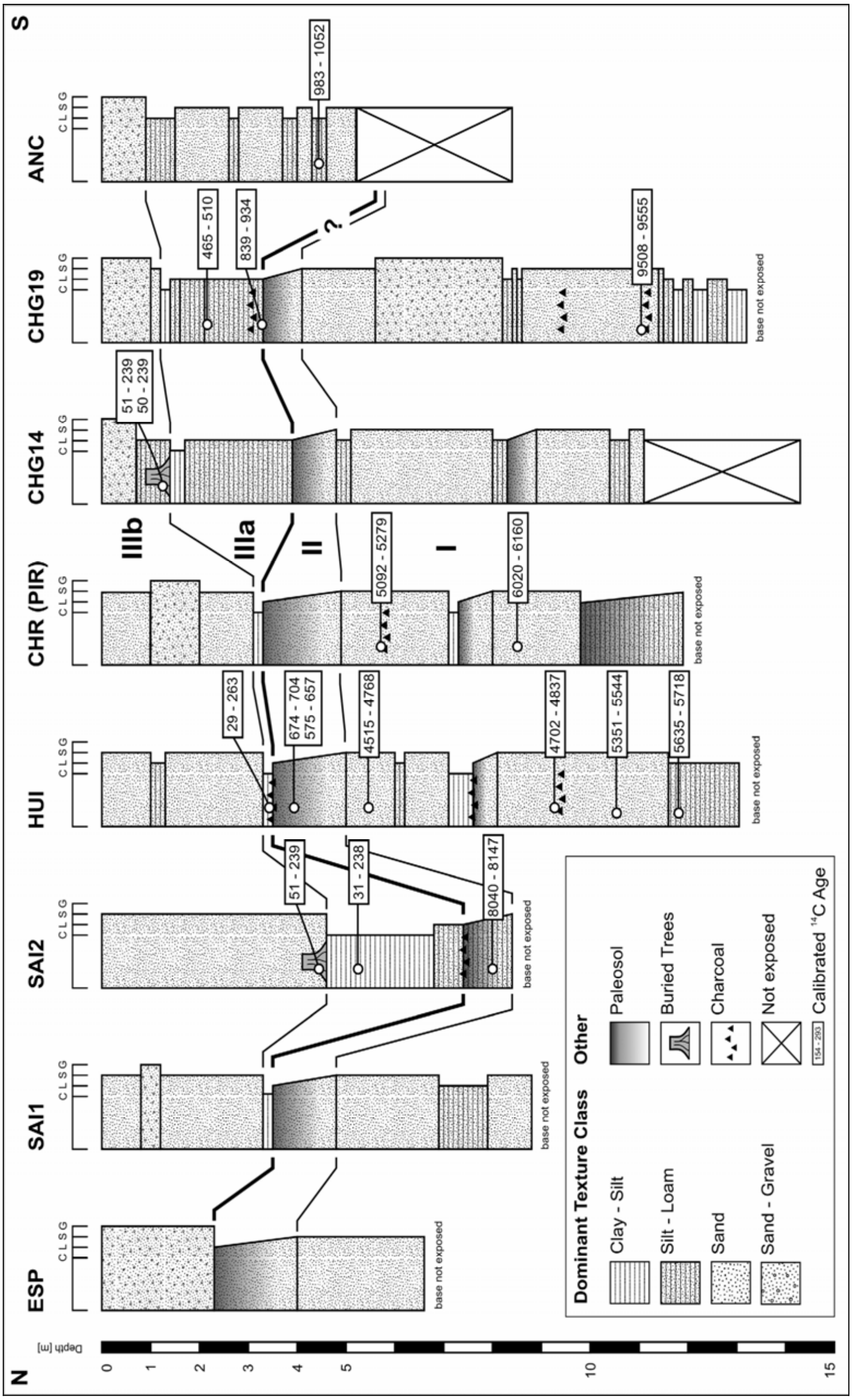

Fig. 4-7: *Correlation of the investigated sedimentary sequences along the piedmont at Charagua based on paleosols, the succession of grain size trends and calibrated radiocarbon ages (see text and table 1 for details). The interpretation of sedimentological units (I to III) is indicated by black lines.*

In addition, the calibration of young ages results in large temporal age frames (> 200 years). All other ages dates on terrestrial (snail) shells and charcoal likely reflect the approximate timing of sediment deposition. Radiocarbon dates of charcoal might overestimate the timing of deposition, as charcoal from forest fires is usually subject to reworking and transport within the catchment before its final sedimentation (e.g. Whitlock and Larsen, 2001). To a lesser extent, this might also be true for the transport of shells.

Correlation Quebrada Charagua

With the exception of CHG1, all sequences in the Quebrada Charagua are divided into an upper profile part (unit III) and a lower profile part (unit I) separated by a well-developed paleosol (unit II). At CHG1 and CHG3 the base of the sequences is formed by older sedimentary rocks of Pliocene-Pleistocene age, reflecting long persistence of soil formation and/or erosion along the proximal (tectonically active) piedmont. Overbank muds and silts, but also secondary paleosols, are abundant in unit I at CHG4 to 10 and grade into coarser floodplain sediments and channels sands further downstream (CHG14 to 19). Within the Quebrada Charagua, unit I can tentatively be subdivided into two distinct subunits (Ia and Ib) by a secondary paleosol (CHG4 to 14) or intercalated overbank muds (CHG15 and 19). Radiocarbon ages from CHG19 imply that deposition of unit I commenced > 9.5 cal ka BP, i.e. in the Early Holocene, and probably continued at least through the Mid-Holocene.
A well-developed paleosol (unit II) has formed within the sediments of unit I. It is overlain by the sediments of unit III, which are subdivided into two subunits (IIIa and IIIb). Subunit IIIa directly overlies the paleosol and generally consists of overbank muds, but also sands, showing a fining upward sequence and a sharp upper boundary with locally buried tree trunks. Subunit IIIb consists of extensive coarse sands to gravel, forming frequent erosional paleochannels particularly in the upstream locations (CHG4 and CHG8).

Regional correlation

The obtained results from the Quebrada Charagua were correlated to sequences of five different catchments (Fig. 4-7), generally confirming the distinction of two sedimentary units, which are separated by a well-developed paleosol. Unit I forms the base of the sequences and is mainly built by sands with few intercalated overbank deposits. Radiocarbon ages from four sequences place the entire unit in the Mid-Holocene between 9.5 cal ka BP and < 4.5 cal ka BP. An intercalated, weakly developed paleosol (CHR, HUI, CHG14) can not be correlated between the sequences.
Almost all the sequences exhibit a well-developed paleosol towards the top of unit I, confirming the existence of a significant time of relative landscape stability in the study area. The available radiocarbon ages from the sediments above and below the paleosol place the timeframe of soil formation between ~ < 4.5 cal ka and > 0.9 cal ka BP.

Locally, soil formation has persisted until < 0.6 – 0.7 ka BP as shown by a burial age of the paleosol (HUI).

At all locations the deposits of the overlying unit III are the coarsest sediments throughout the sequences. The onset of unit III deposition locally varies between > 0.9 cal ka BP and 0.2 cal ka BP. The subdivision of a finer grained unit IIIa, consisting of sands and overbank deposits, can only be established for the sequences located further downstream (SAI2, ANC, CHG14 and 19).

All sequences are topped by coarse sands and gravel, which are likely younger than 0.2 cal ka BP, sometimes in paleochannels.

4.5 DISCUSSION: RECONSTRUCTION OF THE HOLOCENE REGIONAL LANDSCAPE EVOLUTION

Changes in ephemeral fluvial systems can be attributed to changes in sediment load and discharge characteristics such as magnitude and frequency of flooding event (Wolman and Miller, 1960; Patton and Schumm, 1981; Knighton, 1998), which in turn essentially depend on climate. The rainfall amount in the study area shows large variability on seasonal and inter-annual timescales (Gerold, 1988). On centennial to millennial time scales, changes in climate (i.e. total annual precipitation and seasonality) as well as changes in the vegetation cover exert the dominant control on sediment load and discharge events (Langbein and Schumm, 1958; Wolman and Gerson, 1978). Thus, changes in the fluvial system as observed in the sedimentary and geomorphic record provide valuable information about past environmental and climate changes, but are discussed separately for the different timescales involved.

4.5.1 UNIT I (EARLY TO MID-HOLOCENE)

The Mid-Holocene unit I predominantly consists of sands with intercalated overbank deposits. If present at all, erosional contacts are very shallow. Although paleosols occur at some locations, no precise temporal correlation could be established between them. They could possibly indicate more or less random and probably frequent avulsions. The sediments of Unit I thus resemble the present proximal piedmont (Fig. 4-2, “P”). Paleochannels and -floodplains can be traced further to the distal parts of the piedmont. Additionally, a downstream thickening of unit I deposits can be observed.

In conclusion, the Mid-Holocene landscape was characterized by ongoing sand sedimentation in an aggrading and avulsive fluvial system. Sediment supply and flood magnitude were likely larger than today, transporting sands several tens of kilometres further down the piedmont than at present. The large torrentiality necessary for the long transport of sands was probably the direct result of increased aridity and seasonality, leading to a reduction in vegetation cover and intensive discharge events. An increase in aridity is also confirmed by the occurrence of macroscopic charcoal in the Mid-Holocene sediments, reflecting extensive forest fires.

Mid-Holocene aridity has also been reported from other parts of the Bolivian and Paraguayan Chaco. Sedimentation of fluvial sands was OSL/TL-dated between ~7.7 and 3.4 ka BP along the Pilcomayo river (Geyh et al., 1996; Kruck, 1996). Along the Andean piedmont south of Santa Cruz May et al. (in press) and Servant et al. (1981) reported fluvio-aeolian deposition commencing after ~7.5 cal ka BP. During the same time, the fluvial system of the Purús River in SW Amazonia was characterized by aggradation (Latrubesse and Kalicki, 2002). Corroborating the interpretations of the fluvial systems, paleobotanical studies provide evidence for the expansion of savannah vegetation and increased forest fires in SW Brazil and the Andean Cordillera (Pessenda et al., 1998; de Freitas et al., 2001; Mourguiart and Ledru, 2003; Pessenda et al., 2004). In general, increased Mid-Holocene aridity in central South America could be attributed to an orbitally induced northerly position of the ITCZ and a weakening of the SASM (Baker et al., 2001a; Baker et al., 2001b; Haug et al., 2001; Cruz et al., 2005).

4.5.2 UNIT II (LATE HOLOCENE)

Well-developed paleosols (unit II) formed in the Mid-Holocene sediments at almost all locations in the study area. This indicates the transition from a landscape of active sedimentation to stability and soil formation. No erosional channels are evident in the sedimentary sequences, implying that the mostly confined streams were characterized by very low sedimentation rates and significantly reduced flood magnitudes. Soil formation and the overall stable landscape were likely the consequence of the onset of overall wetter and less seasonal climate conditions at the transition from the Mid- to the Late Holocene, resulting in a dense vegetation cover along the entire piedmont and reduced sediment supplies. The timing of this transition varies and may reflect a gradual change towards stability since ~4 cal ka BP.

These results corroborate geomorphological and pedological records from the Argentinean and Paraguayan Chaco reporting soil formation and stable landscapes since ~3.8 cal ka BP with a peak after ~2 cal ka BP (Barboza et al., 2000; Pasig, 2005). Along the Andean piedmont north of the study area, soil formation might have commenced as early as 5.8 cal ka BP (Servant et al., 1981), but an overall stable landscape had only been established by ~2.9 cal ka BP (May et al., in press). Paleobotanical studies place the onset of modern, wetter conditions at ~4.5 cal ka BP in the Eastern Cordillera (Mourguiart and Ledru, 2003) and ~3.2 cal ka BP in the adjacent lowlands of NE Bolivia and SW Brazil (Pessenda et al., 1998; Mayle et al., 2000; de Freitas et al., 2001; Burbridge et al., 2004). The establishment of modern, more humid environmental conditions in central South America coincides with a southward shift and intensification of the SASM during the Late Holocene (Baker et al., 2001b; Wang et al., 2004; Cruz et al., 2005; Wang et al., In Press).

4.5.3 UNIT III (< ~1 CAL KA BP)

At all locations, the Late Holocene paleosol is overlain by unit III sediments. This unit can been divided into a generally finer lower unit IIIa and a very coarse upper unit IIIb. Within the Quebrada Charagua the onset of unit IIIa sedimentation can be estimated from a basal radiocarbon age to ~0.9 cal ka BP (~1060 cal yr AD). However, at other locations the end of unit II soil formation and the beginning of renewed sedimentation vary by several hundreds of years from > 1.02 cal ka BP (~930 cal yr AD) in the Quebrada Ancasora to 0.6-0.7 cal ka BP (~1260-1330 cal yr AD) in the Quebrada Huirapucutí. This might be due to different response times of the individual catchments to a simultaneous forcing. The unit IIIa deposits tend to be thicker at locations further downstream (Fig. 4-2, CHG8-19, SAI2, ANC), indicating that the channels along the upper reaches generally remained confined. However, in contrast to the preceding phase of restricted sedimentation, sediment supply and flood magnitude increased at the turn of the millennium, possibly as the result of increased aridity and/or seasonality.

In many tropical and subtropical regions in South America, environmental changes occurred at the beginning of the last millennium: a climatic deterioration towards more arid and colder conditions took place around 1200 AD in Central Argentina (Carignano, 1999; Cioccale, 1999; Iriondo, 1999). A cold event of more than six centuries also occurred after ~1000-1250 AD in Venezuela (Polissar et al., 2006) and ~1300 AD in the Cariaco basin (Haug et al., 2001). Dry conditions were reported to have started after ~900 AD in the Peruvian Andes (Chepstow-Lusty et al., 2003) and ~1100 AD in the Altiplano at Lake Titicaca (Abbott et al., 1997; Binford et al., 1997; Wolfe et al., 2001). These climatic shifts could be due to a decrease in solar activity, leading to a gradual transition into the cooler atmospheric conditions of the LIA (Little Ice Age) (Rabatel et al., 2005; Polissar et al., 2006).
Anthropogenic environmental impacts since Pre-Incan times have been documented from both the Andean highlands (Erickson, 2000; Abbott and Wolfe, 2003), the Eastern Cordillera (Kulemeyer, 2005) as well as the South American lowlands (Denevan, 1992; Balée, 2000; Erickson, 2006). Significant human presence in Eastern Bolivia has started as early as 2.4 cal ka BP (~400 BC) around Santa Cruz, (Prümers, 2000), but has not yet been proved before ~900 AD in the Bolivian Chaco (Dames & Moore Inc., 2001). The marked change from soil formation and landscape stability towards renewed sedimentation in the study area might therefore be alternatively explained by the onset of pre-Hispanic anthropogenic impacts such as deforestation and forest fires (Riveros, 2004).

Sands and gravels of unit IIIb constitute the uppermost and coarsest sediments in all investigated sequences. At some locations, trees are buried (e.g. SAI2, CHG14) and several radiocarbon ages tentatively date the beginning of unit IIIb into the 18th or 19th centuries. Based on multi-temporal analysis (compare Fig. 4-3), the sediments of unit IIIb could clearly be linked to floodout processes, indicating increased sediment loads. This suggests that profound changes in the fluvial system occurred, either as a result of climatically induced changes of sediment supply and flood regime or due to anthropogenic activity. The volume of sand deposition has, however, ceased again at least since the late 1960's. Simultaneously, incision and sand deposition have propagated downstream.

A significantly altered fluvial regime and rapidly increasing sediment loads might have been the result of increased human activities such as cattle farming and deforestation in the Bolivian Chaco following the Spanish conquest during the late 16th century. However, the common response of all investigated watershed of different size might point to a climatic and regional cause for the observed changes. Particularly for the waning 19th century, manifold proxy evidence has accumulated in South America for a significant climatic shift related to the end of the LIA (Thompson et al., 1985; Thompson et al., 1986; Villalba et al., 1998; Liu et al., 2005; Polissar et al., 2006). Concerning the fluvial processes in Bolivia and NW Argentina increased flood frequencies have been reported for the period following the LIA between the late 19th century and the 1960's (Maas et al., 1999a; Maas et al., 1999b), possibly correlated with La Niña conditions of the Southern Oscillation (ENSO) (Maas et al., 1999a; Maas et al., 1999b; Aalto et al., 2003).

6. CONCLUSIONS

The investigation of geomorphology and sedimentary sequences along the piedmont near Charagua has revealed major changes of the fluvial system since the Early Holocene. An aggrading and avulsive fluvial system reflects drier and probably more seasonal environmental and climate conditions during the Mid-Holocene. Soil formation in an overall stable landscape gradually replaced sedimentation around 4 cal ka BP, likely due to the onset of wetter climate conditions and a dense vegetation cover. Renewed sedimentation has characterized the course of the last millennium. Particularly during the last centuries the fluvial system has been subject to the most profound changes of the entire Holocene. Without further age dates, however, it is difficult to decide, whether this change is due to increased aridity going along with larger scale climatic changes, or resulted from regional anthropogenic impact in the study area. In summary, sedimentary and stratigraphical investigations combined with a thorough analysis of the geomorphological characteristics of the study area has enabled a more detailed documentation of the temporal and spatial variations of geomorphological processes in the Bolivian Chaco during the Holocene.

ACKNOWLEDGEMENTS

The authors would like to thank the Museo de Historia Natural Noel Kempff Mercado, Santa Cruz, for scientific and logistical support in Bolivia. In addition, we thank Bernhard Vogt and Daniel Tristram for field assistence. All conventional 14C-measurements at the Institute of Physics, University of Berne, are gratefully acknowledged. This study contributes to the SNF-funded projects "Paleoclimate and landscape evolution in the tropical Andes of Bolivia and the adjacent lowland rainforest" (SNF 200020-105228/1) and "Paleoecology of Eastern Bolivia" (SNF 21-067937.02/1).

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Used remote sensing data

Landsat ETM 2000-12-07 (Path 230, Row 74), Landsat TM 1986-01-07 (Path 230, Row 74), Landsat MSS 1975-07-23 (Path 247, Row 74). Source: Global Land Cover Facility (http://www.landcover.org)

Corona 1966-03-13 (1030-1, 61-051). Source: United States Geological Survey (http://edcsns17.cr.usgs.gov/EarthExplorer)

5

PALEOSOL-SEDIMENT-SEQUENCES ALONG THE ANDEAN PIEDMONT OF SANTA CRUZ AND THEIR IMPLICATIONS FOR LATE QUATERNARY LANDSCAPE EVOLUTION

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ABSTRACT

The Andean piedmont of Eastern Bolivia is situated at the southern margin of Amazonia characterized by an overall humid climate regime with marked rainy and dry season. The nearby Subandean foothills deliver abundant sediment to the piedmont, leading to a complex array of sediments and paleosol horizons. In this context, the presented study analyzes four paleosol-sediment-sequences along incised ephemeral streams near Santa Cruz by combining geomorphological, sedimentological and paleopedological methods. The results are interpreted in order to reconstruct the Late Quaternary landscape evolution.

Based on field observations, micromorphological analysis, geochemical and clay mineralogical data five classes of paleosol horizons could be distinguished and were interpreted regarding their environmental significance. The formation of well-developed Bt horizons result from dominant clay illuviation under wet conditions similar to today. More arid and seasonal conditions lead to strong seasonal contrasts in soil water flow causing the formation of initial Bwt horizons. Bw horizons ("red beds") imply dominantly dry and desert like conditions.

As evident from coarse fluvial gravel and sands in association with Bw and Bwt horizons point to generally dry conditions and significantly reduced forest cover in the study area before and during the LGM (>18.4 cal ka BP). Sedimentological and paleopedological evidence reflect a subsequent shift towards substantially wetter climate, probably during the Pleistocene-Holocene transition. Active landscapes and formation of intial Bwt horizons in the study area represent a dry and likely seasonal Mid-Holocene. After ~5.5 cal ka BP, the onset of wetter conditions similar to today causes the initiation of fluvial incision and formation of moderately and well-developed Bt horizons. Incision, however, likely propagated stepwise down the ephemeral streams and was interrupted several times by intervals of increased sediment load, which may be interpreted in relation to larger-scale atmospheric phenomena such as El Niño Southern Oscillation (ENSO) frequencies or the Little Ice Age (LIA).

Keywords: piedmont; Amazonia; pedogenesis; incision; paleo-environment; fluvio-aeolian geomorphology

5.1 INTRODUCTION

The ongoing discussion of past, present and future climate changes has brought about the necessity for intensified paleoenvironmental research. Marginal ecoregions and/or transitions between contrasting climatic regimes respond particularly sensitive to climatic changes and should therefore be suitable for paleoenvironmental studies. The Eastern Bolivian lowlands around Santa Cruz are characterized by the marked transition from tropical wet climate to the north (Amazonia) and subtropical semi-arid climatic to the south (Gran Chaco).

Most of the paleoenvironmental studies in South America have traditionally come from the Andean highlands (e.g. Servant and Fontes, 1978; Clapperton et al., 1997; Argollo and Mourguiart, 2000; Baker et al., 2001a). Only during the last decades the research focus was increasingly set on the South American lowlands. Besides a number of paleobotanical investigations (e.g. Colinvaux and Oliveira, 2000; van der Hammen and Hooghiemstra, 2000; Behling, 2002), paleoenvironmental research started to make use of the large potential inherent to the geomorphological and sedimentological archives of the extensive fluvial and aeolian systems (Baker, 2000). Important fluvial evidence for Late Quaternary climate and environmental changes from Amazonia, Brazil and the fluvio-aeolian plains of northern Argentina and Paraguay was summarized by Latrubesse (2003). Eastern Bolivia has only been subject to very limited paleoenvironmental research. The large-scale geomorphology of the Eastern Bolivian lowlands has been discussed by (Werding, 1977; Iriondo, 1993; May, 2006). Servant et al. (1981) and May et al. (in review) have contributed first insights regarding the Late Quaternary climate and environmental evolution based on paleosol-sediment-sequences of the Andean piedmont. These studies mainly focus on the stratigraphical analysis of the sequences but contain only limited pedological and/or paleopedological information. Regional paleoenvironmental investigations, however, should make use of the regional paleopedological archives as well. Therefore this study aims at i) the analysis of paleosol-sediment sequences integrating geomorphological, sedimentological and paleopedological methods, and ii) the interpretation of these results regarding Late Quaternary environmental and climate changes along the piedmont at Santa Cruz de la Sierra.

5.2 REGIONAL SETTING

The study area is situated ~10-15 km southwest of Santa Cruz de la Sierra in the Eastern Bolivian lowlands (Fig. 5-1A, B, C). Climate conditions are largely controlled by the South American Summer Monsoon system (SASM) (Zhou and Lau, 1998; Nogues-Paegle et al., 2002). A strong northerly wind – the South American Low Level Jet (SALLJ) – is responsible for moisture transport from the Amazon basin into the study area (Berri and Inzunza, 1993; Marengo et al., 2004). Total annual precipitation exceeds 1000 mm/a at Santa Cruz de la Sierra (Gerold, 1985; AGTECA, 2005).

However, a high seasonality and inter-annual variability characterize the temporal distribution of precipitation, which predominantly falls during the wet season in austral summer, whereas austral winter is essentially dry. Throughout the year, incursions of polar air may lead to significant temperature drops and occasional rain (Garreaud, 2000).

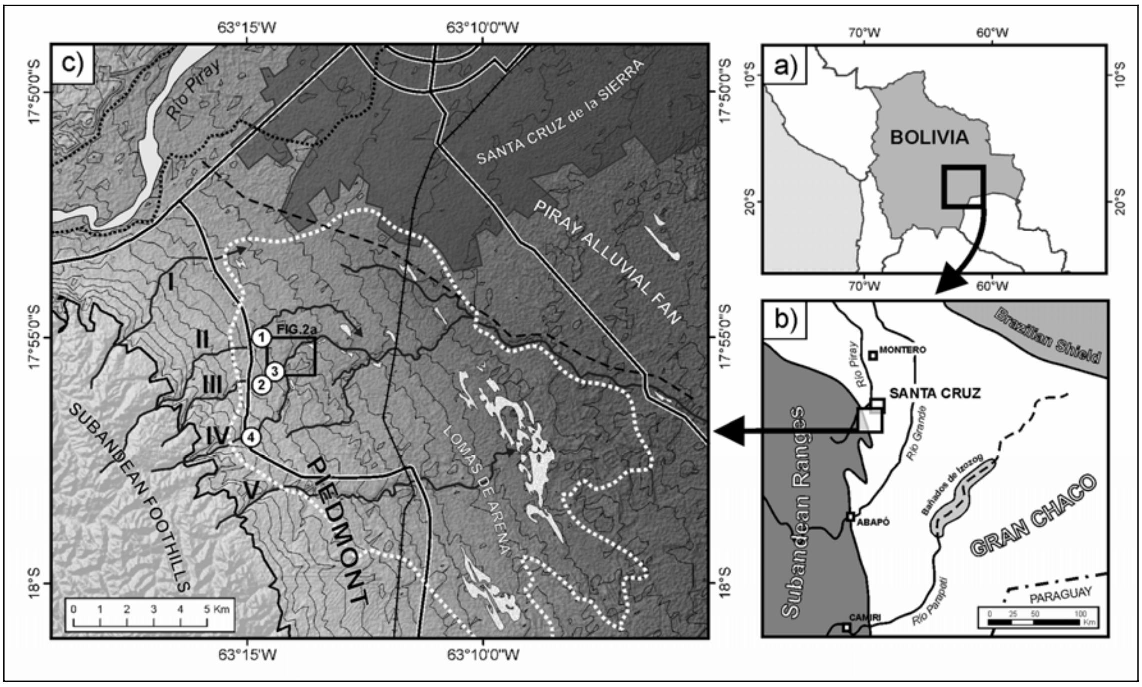


Fig. 5-1: *Location and regional setting of the study area. a) Political boundaries of Bolivia, b) Eastern Bolivian lowlands and the Subandean Ranges, c) Location of the most important ephemeral piedmont streams (I=Quebrada Mapaiso, II=Quebrada Seca, III=Quebrada Coronada, IV=Quebdrada Pedro Lorenzo, V=Río Peji) and the location of the investigated paleosol-sediment-sequences (1=SEC, 2=COR1, 3=COR2, 4=PLZ).White dotted line denotes the Lomas de Arena dunefield, black dashed line divides the piedmont and the Río Piray alluvial fan.*

Within the study area, humid Amazonian forest to the north grades into the semi-deciduous Chaco dry forest to the south, largely reflecting the transition between the two climatic regimes (Ibisch et al., 2004). Around Santa Cruz, savannah type vegetation is common, and expresses sandy subsurface lithologies as well as an increasing anthropogenic influence (Museo de Historia NKM, 2003). Under humid to subhumid climatic conditions, clay illuviation is reported as the dominant pedogenic process in the study area producing Acrisols, Luvisols and Nitisols (Cochrane, 1973; Gerold, 2004).

Geologically, the Andean piedmont is part of a foreland basin receiving sediments from the adjacent Eastern Andean Cordillera and Subandean foothills (Horton and DeCelles, 1997; Uba et al., 2006). The Subandean foothills are regarded the outermost topographic expression of Andean deformation and are built from uplifted and slightly tilted Tertiary and Pleistocene fluvial sediments (Marshall and Sempere, 1991; Moretti et al., 1996; Hinsch, 2001).

The Andean piedmont is a gently inclined (< 0.5 – 2°) alluvial slope, forming the transition between the Subandean foothills and the fluvial megafans of the large lowland rivers (Horton and DeCelles, 2001; May, 2006). In the study area, small, incised ephemeral streams deliver sediment from the Subandean foothills onto the piedmont. Here, aeolian deflation and reworking by the strong northerly winds of the SALLJ has produced the dunefield of the Lomas de Arena (Fig. 5-1C), which consists of inactive and presently active dunes (Jordan, 1982; May, 2006).

5.3 METHODS

This study integrates three main methodical approaches.
i) Firstly, the geomorphological context of the study area was assessed by thorough field reconnaissance. Field observations were complemented by the analysis of multi-temporal Landsat imagery and high-resolution data in Google Earth. These data formed the basis for the visual interpretation of the regional and local geomorphological setting (Verstappen, 1977; Rosenfeld, 1984).
ii) In a second step, four profiles of paleosol-sediment-sequences at natural outcrops along three incised ephemeral streams (*quebradas*) were selected for sedimentological and paleopedological analysis in order to identify soil horizons and characterize the existent sedimentary facies (see Fig. 5-1 C, 1-4). The pedological field description was based on FAO (2006) with particular focus on macroscopic pedological characteristics such as colour, pedogenic texture, cutans and redox characteristics. In each profile, oriented micromorphological samples were taken from selected horizons. Micromorphological analysis was conducted using a Leica DM LP polarization microscope in combination with a Leica DFC 280 camera device. The soil micromorphological interpretation was based on Bullock et al. (1985; 1993) and FitzPatrick (1993). A bulk sample of ~500 g was taken per horizon or layer for laboratory analysis. All analyses were carried out on dry and sieved (< 2 mm) samples. For grain size measurements, organic matter was oxidized with 30% H_2O_2. In addition, micro-aggregates < 63 µm were dispersed with Na_2CO_3. The sand fractions (63-2000 µm) were separated by wet sieving and the silt (2-63 µm) and clay (< 2 µm) fractions were quantified using a Micromeritics SediGraph 5100. The chronological framework for the investigated profiles was established using radiocarbon dating on organic material preserved within the sediments and by optically stimulated luminescence (OSL) dating on the mineral grains themselves. While radiocarbon dating determines the age when the once living organism was last in ^{14}C-exchange with the atmosphere, OSL-dating allows define the time when the mineral grains were last exposed to daylight during a former cycle of sediment reworking. Thus, the ages of both methods are gained independently of each other. A total of eleven conventional radiocarbon measurements (Institute of Physics, University of Bern) and eight AMS radiocarobon measurements (Poznan Radiocarbon Laboratory) were conducted. All our radiocarbon ages as well as other published radiocarbon ages were calibrated using the program CALIB 5.0.1 and the "intcal04" data set (Stuiver and Polach, 1977; Reimer et al., 2004). Samples for OSL-dating were taken

from freshly prepared profile walls in steel cylinders (ø 10 cm, 12 cm long). The possibly light-influenced outer rims were eliminated in the luminescence dark laboratory and retained for water content and dose rate determination. OSL dose determination was performed on quartz coarse grain (125-212 µm) using small aliquots with a limited number of mineral grains (ca. 20-50). Measurements were carried out at the Max-Planck-Institute for Nucleclear Physics in Heidelberg on a Risø TL/OSL Reader DA15 using the blue-light stimulated (BLSL) quartz UV-emission around 340 nm for palaeodose determination. Further experimental details are given in Kadereit et al. (in preparation). Here, the so far available age margins of 12 samples are presented in figure 5-3.

iii) For the Pedro Lorenzo profile, additional laboratory analyses were conducted. The Munsell Conversion 7.0.1 software (WallkillColor, 2007) was used to determine Munsell colour (hue, chroma and value) on dry and moist samples. PH-values were measured with a glass electrode in 0.01M $CaCl_2$ with a soil:solution ratio of 1:2.5. Pedogenic iron (Fe_o and Fe_d) was extracted with oxalate and dithionite following standard procedures (Mehra and Jackson, 1960; Schwertmann, 1964) and measured using a Hach Spectrophotometer. X-ray fluorescence (XRF) was performed to determine the elemental composition. Clay mineralogy of selected samples was analyzed by X-ray diffractometry (XRD, Phillips PW 3710). The diffractograms of Mg^{2+} saturated specimens were obtained for normal conditions, after solvation with ethylene glycol and after heating to 550°C. Then, amounts of clay minerals were measured semi-quantitatively by XRD peak height.

Pedogenic iron is formed during soil formation (Schwertmann and Taylor, 1989) and can thus be used to assess the intensity of soil development and weathering (Torrent et al., 1980). Additional information regarding weathering processes and intensities was deduced from several paleopedological indices: i) the weathering index of Kronberg and Nesbitt (1981), which indicates chemical weathering intensity and feldspar breakdown; ii) the Redness Rating Index (RR-Index) after Torrent et al. (1983), which correlates with the hematite content; and iii) a salinization index, which estimates salt accumulation in soils by evaporation from the soda to potash ratio (Retallack, 2001).

5.4 RESULTS

5.4.1 GEOMORPHOLOGICAL SETTING

From analysis of remote sensing data, the piedmont surface in the study area appears highly heterogeneous. Patches of forest alternate with natural and anthropogenic grassland (savannah), and several ephemeral lakes spot the landscape (Fig. 5-2A). This pattern is partly the result of intense human impact such as deforestation and cattle farming. More importantly however, the pattern of vegetation is controlled by the geomorphological and sedimentological characteristics of the piedmont surface. Forest occupies the sandy elevations of inactive sand dunes and sand sheets, whereas grassland and savannah is found preferentially in the (waterlogged) depressions and plains, which resemble an overall young and badly-integrated drainage net. All paleodunes are oriented ~NW-SE, largely corresponding to the strong winds of the SALLJ and the dominant wind direction in the study area. The paleodunes were described as longitudinal dunes (Jordan, 1981; Servant et al., 1981), but analysis of remote sensing data suggests them to represent the limbs of parabolic and/or blowout dunes (May, 2006). Thus, they must have formed under intense influence of vegetation, and continue to do so at several locations in the study area (Fig. 5-2A). The dunes and paleodunes are exclusively found to border the SE banks of ephemeral streams. This implies that deflation from these streams has been responsible for dune formation, instead of a more distant sediment source.

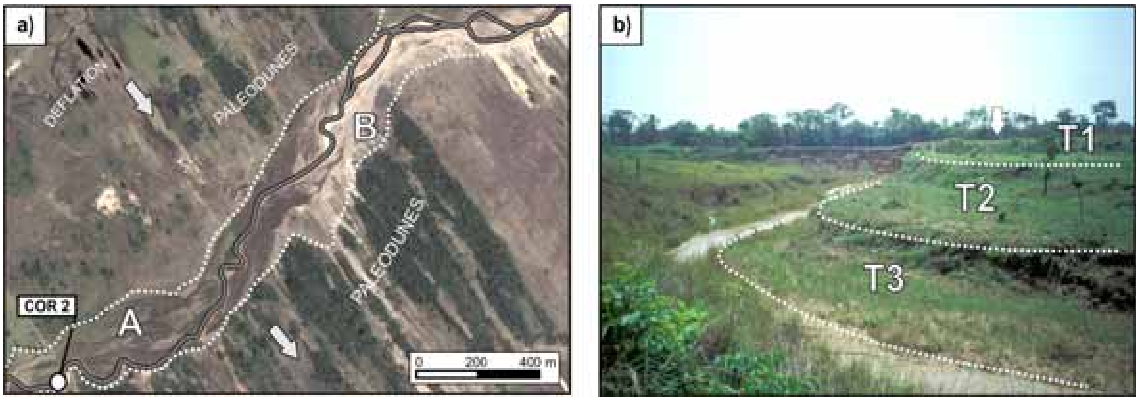


Fig. 5-2: *Geomorphological context of the paleosol-sediment-sequences. a) High-resolution satellite image of the upper Quebrada Coronada, showing the transition from a narrow, incised floodplain (A) to a wide, sandy floodplain (B) with active deflation (See Fig. 5-1 for location; image source: Google Earth) b) sequence of erosional terraces in the Quebrada Coronada.*

Essentially all ephemeral streams in the study area have incised into the piedmont surface. Incision is deepest upstream close to the foothills (~ 8m) and decreases downstream to < 2m. In the upper reaches up to three individual terraces have formed (Fig 5-2B). The terraces are erosional features covered only by thin accumulations of fluvial sands and gravels, indicating a stepwise instead of gradual progression of incision. Downstream, incision depth and floodplain width change relatively abruptly, and the narrow floodplain channel is substituted by a wide sand-braided floodplain, where active deflation is going on (Fig. 5-2A). The location and extent of these wide sandy floodplain reaches should be controlled by the decreasing stream gradient (Jordan, 1982), but also by stream discharge and sediment load, which eventually depends on environmental parameters such as precipitation and vegetation cover. In the study area, where strong wind and sufficient sediment supply are provided, the formation of dunes is not regarded a direct indicator of dry past climate. Rather, spatial and temporal changes of past aeolian activity (deflation and dune formation) on the piedmont surface are indirectly linked to the streams fluvial history and thereby provide paleoenviron-mental information.

5.4.2 GENERAL DESCRIPTION AND GRAIN SIZE DATA

All four investigated paleosol-sediment-sequences are located along the banks of incised stream channels, and thereby expose sequences of fluvial piedmont sediments and different paleosols with overlying aeolian sediments of inactive paleodunes (Fig. 5-3).

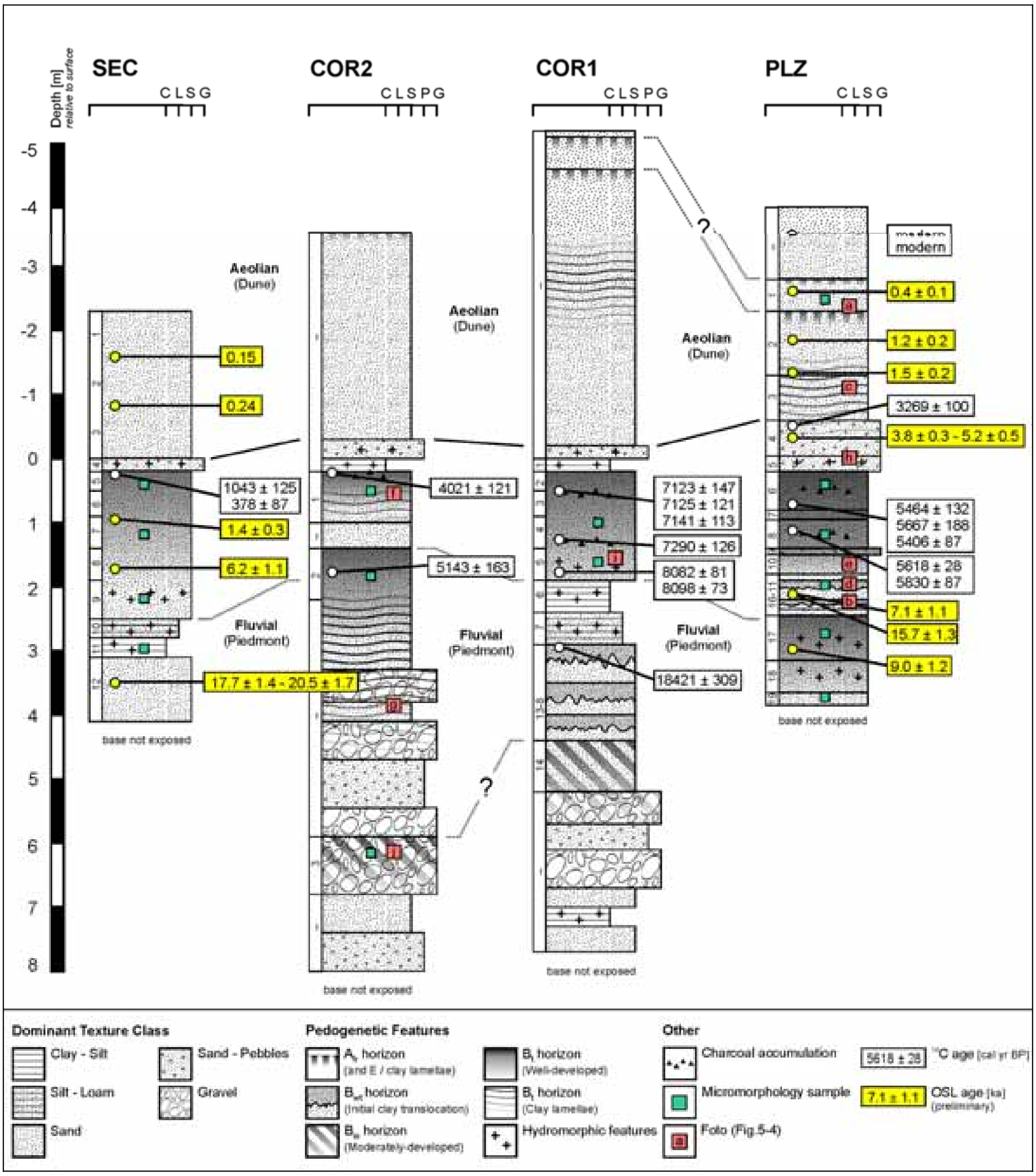


Fig. 5-3: *Illustration of the investigated paleosol-sediment-sequences and the tentative correlation between them (thin, dotted lines) based on field observation, micromorphological analysis and chronology (note that OSL-ages are only preliminary ages).*

From field examination, fine to medium sands appear to be the dominant grain size in all sequences. Nevertheless, large sedimentological variability characterizes the fluvial sediments in the lower parts of the sequences, ranging from coarse fluvial cobbles up to 25 cm in diameter to fine grained silts and clay silts. Particularly the coarser sediment layers are laterally extensive and no paleochannels were observed, pointing to an overall aggrading fluvial system. Generally, the boundaries between the individual layers are sharp and well-defined, indicating the potential presence of minor sedimentary hiati and limited erosion. At some locations, accumulations of macroscopic charcoal within fluvial sands are interpreted to reflect widespread fires (Gardner and Whitlock, 2001; Whitlock and Larsen, 2001; Reneau et al., 2007).

Sediment samples < 2 mm from three profiles were analyzed regarding their grain size frequency distribution, which contains information on process energy during sediment transport and deposition (Folk and Ward, 1957; Visher, 1969). These grain size data provided the base for the definition of typical grain size frequency distribution classes (Fig. 5-4, Supplementary table 5-2), and the interpretation of specific depositional and/or pedogenic environments for the classes (Miall, 1985; Miall, 1996).

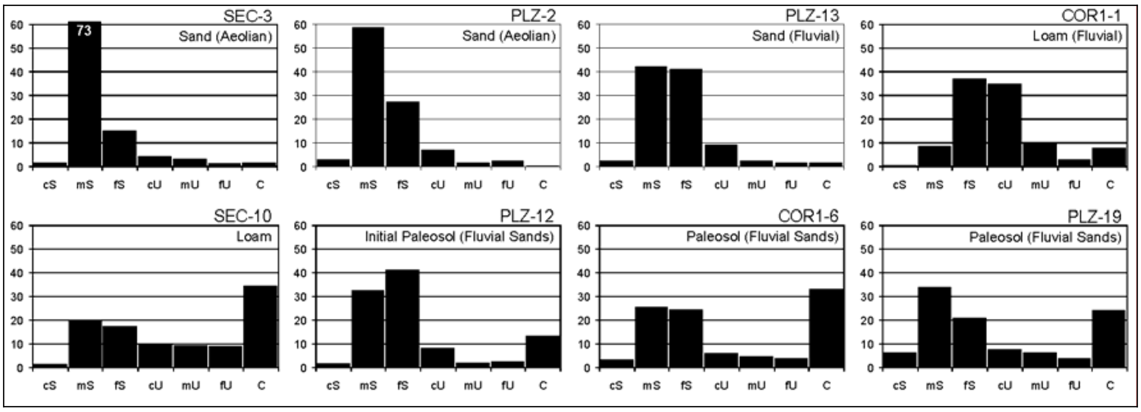


Fig. 5-4: *Typical grain size distributions of different sediments and paleosol horizons.*

As typical for aeolian origin, the sediments from inactive paleodunes mainly consist of medium and fine sands with low silt and/or clay content and very good to good sorting (Fig. 5-4; SEC-3, PLZ-2). Moderately-sorted sands with some silt content are interpreted to represent channel bedforms or accretionary macroforms of sand-braided rivers (Fig. 5-4; PLZ 13). These sediments are the most abundant in the investigated sequences. Badly-sorted sediments of variable grain sizes can have various origins. Loams with considerable content of silt are interpreted as fluvial muds, documenting the incorporation of fine suspended sediment into coarser bedload during waning flood stages (Fig. 5-4; COR1-1). Particularly the finer loams with high content of clay imply deposition from significantly reduced flow velocities, likely in a low energy environment of inundated distal floodplains (Fig. 5-4; SEC-10). Several paleosols have been identified within the fluvial sediments and are readily recognized in the field from their intensively reddish colour and the occurrence of other pedogenic features. Elevated clay contents of up to >30 weight percent in otherwise dominantly sandy sediments typically correspond to paleosol horizons and are the result of weathering, formation of secondary clay minerals and clay enrichment (Fig. 5-4; PLZ-12, PLZ-19, COR1-3).

5.4.3 PALEOSOL HORIZONS

Aside from sedimentological data, field examination of colour, type and intensity of pedogenic features and shape of horizon boundaries, forms the base for the differentiation of several types of paleosol horizons. In addition, 15 thin sections from paleosol horizons were analyzed regarding their micromorphological characteristics in order to extract additional information with particular focus on paleopedological processes and intensities (Supplementary table 5-3).

A_h horizons (and initial clay lamellae)

Up to 10 cm thick brownish to dark greyish horizons were identified within the aeolian sands in the uppermost parts of the investigated sequences (Fig. 5-5A). In some cases these horizons contain macroscopic organic material. They are patchy and have irregular upper and lower horizon boundaries. Based on these characteristics these horizons are interpreted to reflect buried A-horizons (A_h) of initial soils, which represent past vegetated surfaces of short duration and/or soil formation of little intensity. Below, the A_h horizons grade into light brownish unweathered sands, which may represent horizons of initial clay formation and eluviation (E-horizons). At some locations, thin clay lamellae of few mm in the deeper subsoil are associated with the A_h- and E-horizons. These lamellae likely indicate translocation of newly formed clay by a wetting front in descendent soil water regimes, leading to initial development of a banded illuvial (B_t) horizon (Bond, 1986; Rawling, 2000). Infrequently, the A-horizons are distorted and partly eroded, which might indicate (anthropogenic) interference and rapid destruction of vegetation cover and subsequent local displacement of sand (Fig. 5-5A).
The thin sections of the aeolian sands, in which the A_h horizons (and initial E horizons and clay lamellae) have formed, show very little fine grained matrix (Fig. 5-6A). The grains are arranged in single grain structure, indicative of a high porosity. Surface alteration of mineral grains and neoformation of clay is observed occasionally, but is likely inherited where no clay coatings are visible (Fig. 5-7A). Coatings are rare, but generally thin and reddish-brown with frequent grey and black granular inclusions. This is interpreted to reflect an initial clay translocation, which incorporates considerable amounts of organic material from A_h horizons.

B_{wt} horizons

Reddish and brownish-red horizons of variable thickness (~5-50 cm) are found in sandy fluvial sediments in the lower part of some investigated profiles (Fig. 5-5B, D, E). The soil structure is granular, and the sand grains are dominantly coated by a clayey matrix,

which is responsible for the overall coloration of the horizons. The lower horizon boundaries are highly irregular, fringy and blotchy (Fig. 5-5B, D), whereas the upper boundary tends to be sharp. Very often, these horizons are separated by light brown to whitish sands, and several horizons can by closely stacked onto each other (Fig. 5-5B, D). In some cases, the individual horizons show internal differentiation into subhorizons (Fig. 5-5B, D). Bioturbation, mostly in the form of burrows, is typical for these horizons (Fig. 5-5B). Their overall appearance and pedogenic characteristics indicate a shallow paleosol horizon of moderate weathering and formation of clay minerals. Particularly the fine clayey matrix and the internal zonation are indicative of a certain translocation of clay within the horizon. However, the lack of clay lamellae implies that the clay illuviation process (as initially observed in the aeolian sands) is significantly modified in these horizons. The irregular and fringy lower boundaries point to pitting and disintegration of the horizon from below (Fig. 5-5D), for example due to the temporal presence of sodium rich ascending soil water, which enables rapid instant dissolution and dissipation of clay. Thus, these horizons may be interpreted as the result of strong seasonal contrast of weathering, clay formation and clay illuviation with descendent soil water, and pitting and destruction by ascending and evaporating soil water.
Changing environmental conditions towards the dominance of clay formation and illuviation can lead to the accretion of several stacked horizons, and the gradual masking of the intercalated sands (Fig. 5-5E). Probably, this tendency is accompanied by gradually decreasing sediment delivery due to changes within the fluvial sytem.
The thin sections of these horizons exhibit a bridged to alveolar structure containing small and variable amounts of reddish-brown matrix (Fig. 5-6B, C). Bridges are typical structures in coarse sandy sediments with clay translocation, and alveolar structures are often associated with upper horizons of desert environments, pointing to trapping of gases during wetting and drying cycles (FitzPatrick, 1993). Abundant clay coatings without orientation or lamination can be observed (Fig. 5-7C). The coatings tend to form initial laminations only where matrix amount increases (Fig. 5-7B). Otherwise, frequent to abundant surface alteration, but also linear alteration, characterize the individual mineral grains.
These characteristics corroborate the field observations and indicate moderate weathering intensities with formation of iron rich clay minerals and limited clay translocation, leading to moderately weathered initial illuvial horizons (B_{wt}). Seasonally changing environmental conditions – expressed by the changing directions of soil water flow – seem to enable weathering and initial soil formation (illuviation) on one hand, but inhibit the development of a mature B_t horizon and formation of clay lamellae on the other hand.

B_w horizons ("red beds")

Reddish to orange horizons of ~50-75 cm thickness occur in the lowermost parts of two sequences (Fig. 5-5J). They have formed in coarse sands and gravel, and appear highly indurated in the field. In general, their lower horizon boundaries are sharp (Fig. 5-5J).

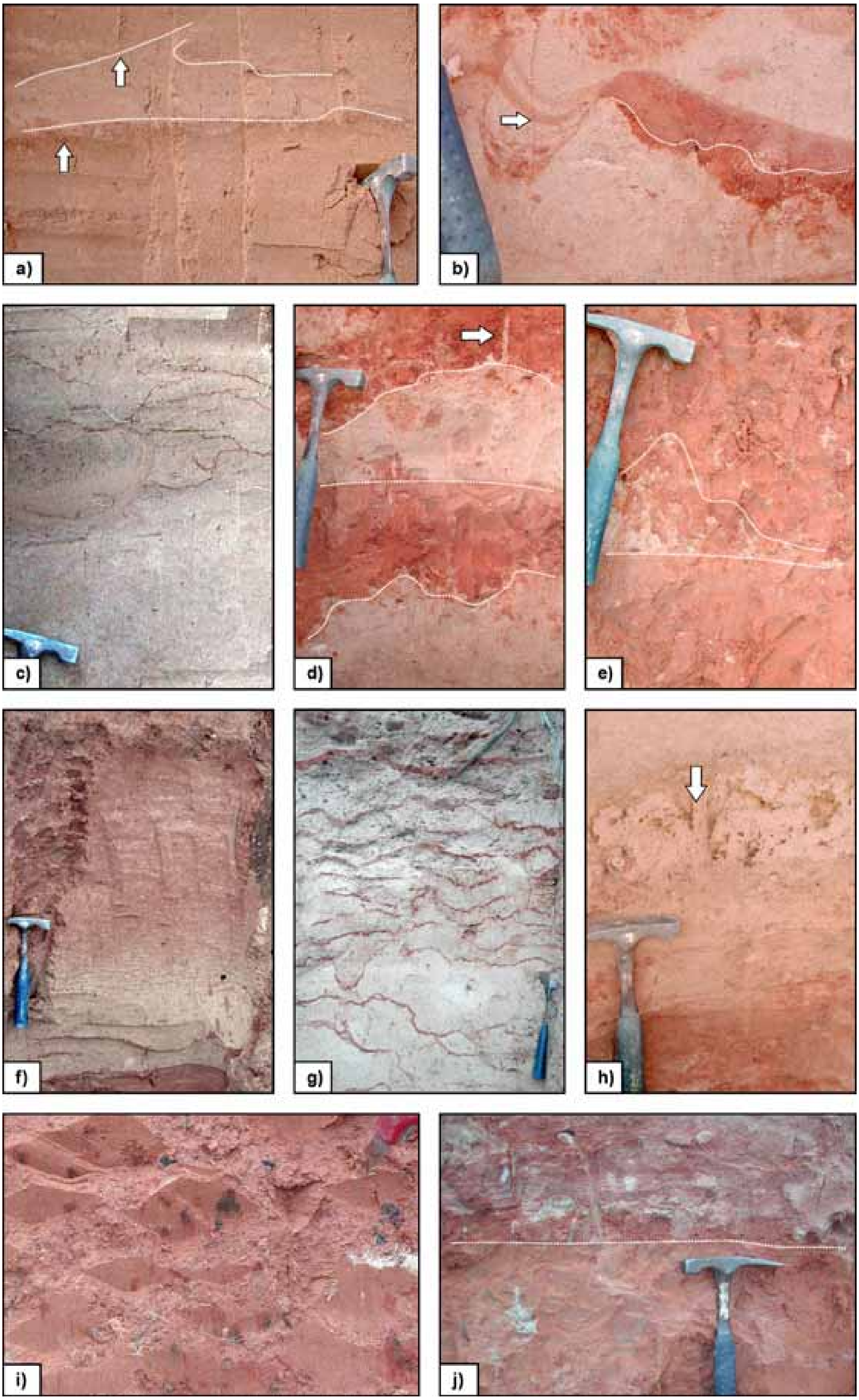
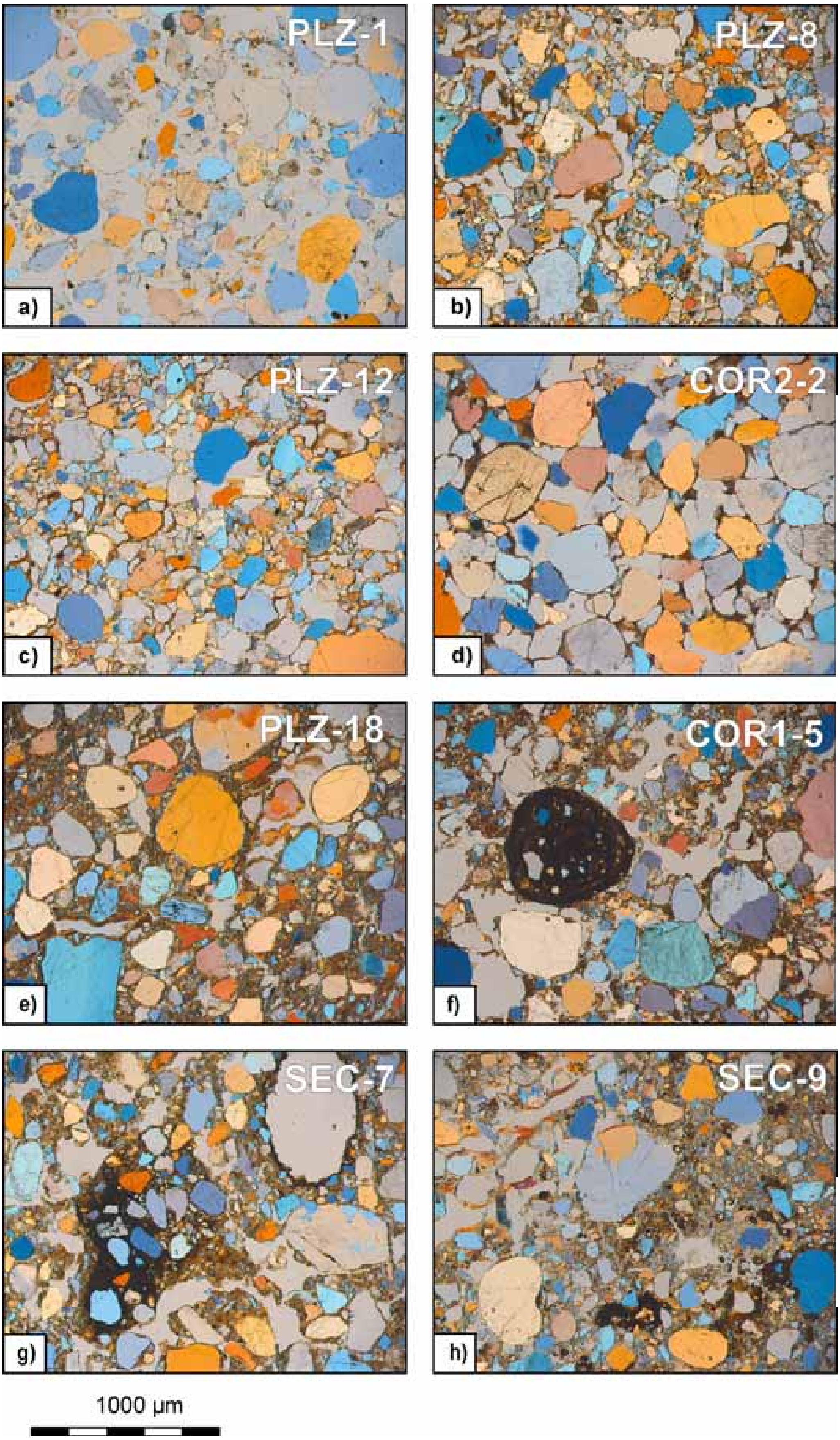

a)
b)
c)
d)
e)
f)
g)
h)
i)
j)

Fig. 5-5: *Characteristic pedogenic horizons of the study area (see Fig. 5-3 for location in the sequences). a) buried initial Ah horizon (lower arrow) and distortion due to interference (upper arrow) in aeolian sands, b) initial Bwt horizon with internal differentiation (white dotted line) and burrow (arrow), c) initial clay lamellae in aeolian sand, d) initial Bwt horizons in fluvial sands with irregular lower boundary and evidence for ascendant pitting, e) fluvial sands largely overprinted by development of a Bwt horizon above, f) moderately developed Bt horizon with gradual lower boundary and the formation of clay lamellae, g) well-developed clay lamellae in fluvial gravels and sands, h) hydromorphic mottles and concentrations (pseudogleyzation) in fluvial sands over a paleosol horizon, i) well-developed hydromorphic mottles and concretions within a Bt horizon, j) indurated "red beds" in fluvial gravel (reddish, above) and sands (orange, below) divided by sharp boundary (dotted line).*

The horizon structure is granular and somewhat porous with small amounts of fine grained matrix bridging between the individual grains. Around some clasts, the matrix colour is greyish to whitish, likely because of minor local redox depletions. Particularly the reddish to orange colour and the presence of fine grained matrix between the grains point to reddening without essential translocation of clay (B_w).
The thin sections of these horizons exhibit relatively well-sorted medium sands with a well-developed coat and bridge structure, which probably explains the distinct indurations (Fig. 5-6D). The small amounts of reddish-brown to brown clay matrix are developed as coatings of no internal orientation or lamination (Fig. 5-7C). Alteration of the mineral grains is abundant, confirming moderate weathering intensities and formation of clays and/or iron oxides with varying participation of hematite as indicated by orange to reddish colours of the soil and the soil matrix.
From field observations and micromorphology, these horizons may be interpreted as "*red beds*", indicating dehydration and transformation of goethite to hematite common in alluvial sediments of desert environments (Berner, 1969).

B_t horizons (and clay lamellae)

Thick reddish to brownish horizons of up to 2 m with gradual lower boundaries were identified at some locations (Fig. 5-5F, G). The soil structure is granular, and a clayey matrix fills the spaces between the grains, sometimes coating them. In these thick-developed horizons, the clay content can be significantly higher than in the initial paleosol horizons described above.
In the lower solum, these horizons partly grade into thin clay lamellae (Fig. 5-5F, G). In some cases, these clay lamellae can extend several meters into light brownish or whitish sands below the upper horizon boundary. The individual clay lamellae have higher clay content than the surrounding sands. They are very irregular and contorted in shape and have variable thickness, usually not exceeding a few centimetres in thickness (Fig. 5-5G). Their lower boundary is rather diffuse and fringy, whereas the upper boundary is relatively sharp. The association of a thick reddish to brownish and clay enriched horizon (B_t) with a clay lamellae in the lower solum implies an advanced state of pedogenesis. Aside from the formation of clay minerals, this refers to the translocation of clays within the profile, resulting in an overall gradual lower horizon boundary, which is frequently characterized by formation of clay lamellae.


PLZ-1
a)
PLZ-8
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COR2-2
d)
PLZ-18
e)
COR1-5
f)
SEC-7
g)
SEC-9
h)
1000 µm

Fig. 5-6: *Sorting, pores, structure type and matrix characteristics illustrated from thin sections of characteristic pedogenic horizons of the study area (see Fig. 5-3 for location in the sequences). a) single grain structure in porous aeolian sands, b) alveolar and bridge structure of a Bwt horizon, c) bridge structure of an initial Bwt horizon, d) coat and bridge structure of an indurated Bw horizon ("red bed"), e) alveolar structure of a well-developed, clay rich Bt horizon, f) hydromorphic Fe/Mn concretion (redeposited?) in a Bt horizon, g) in-situ hydromorphic Fe/Mn mottle and coating, h) hydromorphic secondary clay illuviation (upper left , rainbow coloured) and Fe/Mn mottles.*

In combination, this is interpreted to indicate soil formation with episodic (seasonal?) changes between dry intervals with clay flocculation, and wetting with deep translocation of clays by wetting fronts (Schaetzl and Anderson, 2005).

The thin sections of these clay enriched horizons clearly show a high amount of reddish brown to brown clay matrix compared to the above described horizons (Fig. 5-6E, F). The overall structure varies with grain size of parent material, but tends to be alveolar (Fig. 5-6E), likely resulting from the trapping of air in the dense matrix during desiccation. The clay matrix is dominantly developed as coatings, which frequently show moderate laminations ("cutans", Fig. 5-7G, H). This clearly identifies clay translocation and illuviation as an essential process in these horizons. In several places, a certain degree of fragmentation is indicated by irregular, mamillated boundaries and fragmentation of the clay coatings (Fig. 5-7F, G). Pore spaces are generally smaller than in the above describes horizons (Fig. 5-6E, F) and sometimes even infilled by clay cutans (Fig. 5-6H). The individual mineral grains show evidence for intense weathering and formation of clay regarding both surface and linear alteration (Fig. 5-7D, E).

Resuming these observations, the formation of clay minerals and their translocation into lower parts of the solum, characterizes the most intensively developed paleosols in all the sequences. Particularly the association with frequent clay lamellae requires sustained and deep wetting and somewhat acidic conditions in the parent sediment. Formation of these horizons thereby indicates seasonal but generally wet environmental conditions similar to today.

Hydromorphic horizons

In all investigated sequences, hydromorphic features are present (Fig. 5-5H, I). In most cases, these features are black mottles of spherical, irregular or platy shape, or diffuse masses of a few mm in diameter, which are interpreted as iron and manganese concentrations. In addition, nodules of different shapes and diameters are found locally. The nodules are mostly black and have spherical to irregular shapes. Reddish accumulations of iron-rich clay tend to form around them (Fig. 5-5I). Due to their well-defined, sharp surface morphology, some of these nodules may be regarded as sedimentary features, which formed elsewhere and were incorporated into the fluvial sediment during the transport.

In the thin sections, the hydromorphic features are easily identified by their opaque, black appearance, likely indicating the predominance of manganese oxides instead of iron (Fig. 5-6F, G, H).

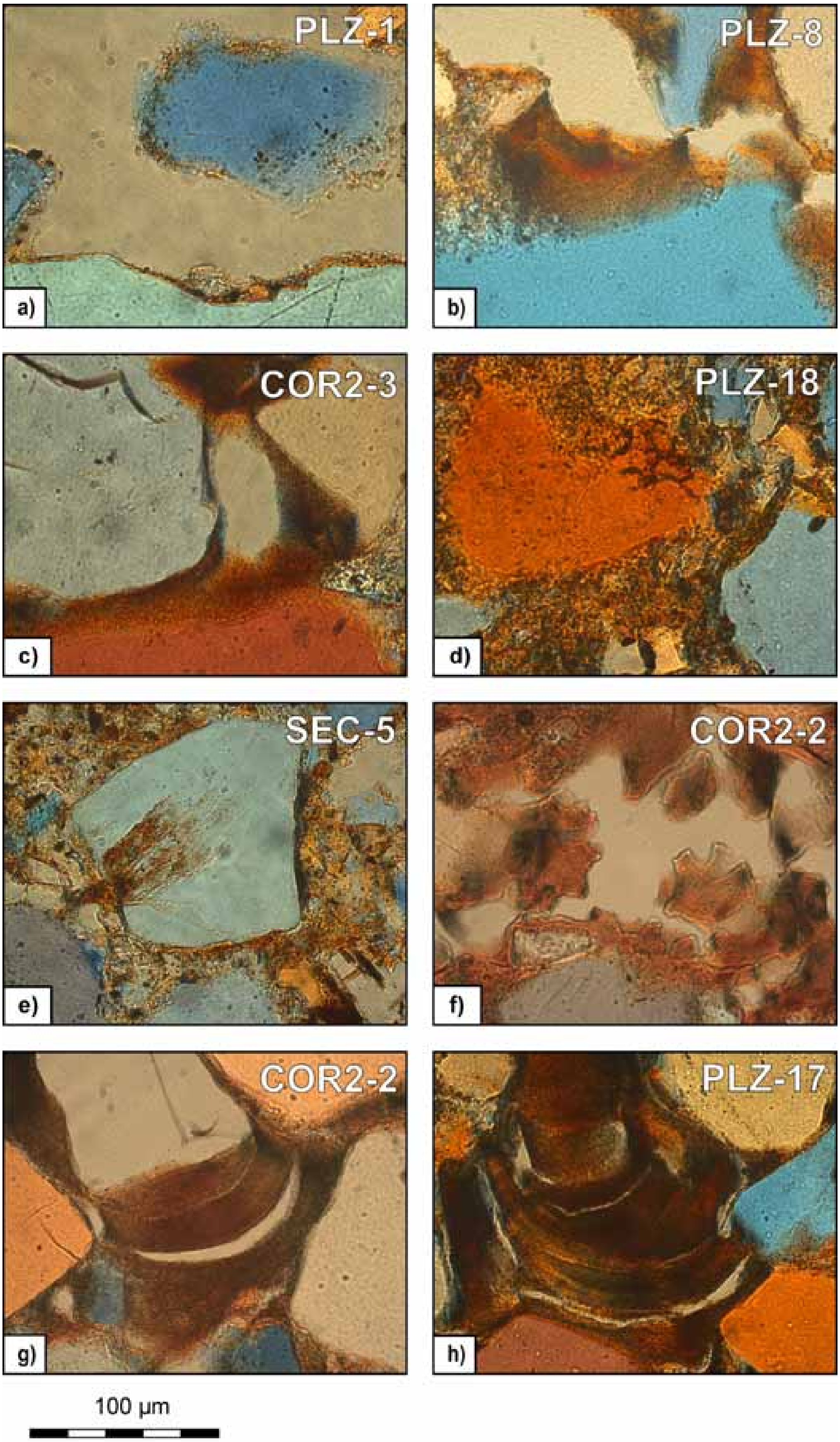
PLZ-1
a)
PLZ-8
b)
COR2-3
c)
PLZ-18
d)
SEC-5
e)
COR2-2
f)
COR2-2
g)
PLZ-17
h)
100 µm

Fig. 5-7: *Mineral alteration, weathering and coatings illustrated from thin sections of characteristic pedogenic horizons of the study area (see Fig. 5-3 for location in the sequences). a) surface alteration (above) and initial clay coating (below) of quartz grains in aeolian sand, b) neoformation of clay and initial formation of laminated clay coating in a Bwt horizon, c) clay matrix between unaltered (above) and altered quarz grain (below) in a Bw horizon ("red bed"), d) clay matrix around a intensely altered quartz grain in a well-developed Bt horizon, e) linear alteration of quartz grain in Bt horizon, f) irregular, mamillated illuvial clay coatings around a pore in Bt horizon, g) laminated and partly fragmented illuvial clay coatings in Bt horizon, h) pore infilled with laminated illuvial clay coatings in well-developed Bt horizon.*

Sharply bounded and spherical nodules may be the result of redeposition (Fig. 5-6F), probably implying the onset of erosion of formerly developed concretions in the upper catchment. Diffuse nodules and concentrations rather point to in-situ formation (Fig. 5-6G). They can be developed as coatings and hypocoatings of manganese and iron along pores as well (Fig. 5-6G, H), likely indicating their ongoing formation. In addition, whitish to rainbow coloured clay coatings were found in association with hydromorphic concentrations, nodules and depletions (Fig. 5-6H) and may be the result of increased acidification and subsequent hydromorphic clay illuviation (Fernández et al., 2004).
All hydromorphic features are interpreted as the result of intense redox reactions. They are particularly present in and above fine-grained silts, clay silts and well-developed paleosol horizons, pointing to gleyzation due to impeded drainage of soil water (german: *pseudogleyzation*) rather than direct influence of the fluctuating ground water table. Therefore, stream incision into the piedmont surface may have reduced the formation of hydromorphic horizons in sediments (C_g horizon). Where strong enough, pseudogleyzation can potentially mask and alter pre-existing soil horizons through the increased solution, translocation and alteration of iron and clays (B_g horizon).

5.4.4 CORRELATION AND CHRONOLOGY OF THE SEQUENCES

Each of the four investigated paleosol-sediment-sequences can be described as a succession of sediments and paleosols, exhibiting some sedimentological variability and a large pedological complexity (Fig. 5-3). In overall similar sediments, very different types of pedogenic horizons are developed, pointing to temporal and environmental parameters as the dominant controls on type and intensity of soil formation. As described above, five different types of paleosol horizons were classified and serve as reference for the interpretation of pedogenic processes in subsequent chapters (5.4.5, 5.5):

- *A_h horizons (and initial clay lamellae)*
- *B_{wt} horizons (initial)*
- *B_w horizons ("red beds")*
- *B_t horizons (and clay lamellae)*
- *Hydromorphic horizons (B_g/C_g)*

Generally, the correlation between the sequences is based on well-developed paleosols. In addition, similarities of grain size trends were used as additional information.

However, the large sedimentological and, more importantly, pedological variability within the investigated sequences, complicate the correlation between them to some extent (Fig. 5-3).
Therefore, an absolute chronology has been established in order to enable regional comparison of the results. For this purpose 19 radiocarbon ages were obtained predominantly from charcoal, and used as a rough estimate for sediment deposition (Table 5-1). In one case, humic acids and humins were extracted from soil organic matter. In general, the radiocarbon ages are stratigraphically consistent and show only minor age inversions. However, radiocarbon dates of charcoals may slightly overestimate the time of deposition as the result of reworking and transport of the charcoal particles within the catchment after a fire event (Gardner and Whitlock, 2001; Moody and Martin, 2001). On the other hand, the inconsistent radiocarbon ages obtained for the humic acids and humins of sample SEC-5 probably indicate contamination of the more mobile humic acid fraction. In order to complement the radiocarbon chronology, a total number of 12 OSL samples were extracted from the Quebrada Seca (SEC) and the Quebrada Pedro Lorenzo (PLZ). Details on the dating procedure and the resulting interpretation of the preliminary ages are given in Kadereit et al. (in preparation).

Sample	**Lab.-Code**	**Material**	**Depth** [cm]	**^{14}C Age** [^{14}C yr BP]	**Calibrated Age*** [cal. yr BP]
PLZ-4	Poz-6624	Charcoal	335	3065 ± 35	3269 ± 100
PLZ-1 B	Poz-6626	Plant remains	110	154.6 ± 0.4 pMC**	modern
PLZ-1 A	Poz-6625	Bone	65	135.9 ± 0.4 pMC**	modern
PLZ-8 A	B-8348	Charcoal	510	4880 ± 20	5618 ± 28
PLZ-8 B	B-8335	Charcoal	510	5090 ± 40	5830 ± 87
PLZ-6 A	B-8336	Charcoal	500	4780 ± 40	5464 ± 132
PLZ-6 B	B-8337	Charcoal	505	4900 ± 60	5667 ± 188
PLZ-6 C	B-8338	Charcoal	500	4710 ± 60	5406 ± 87
COR1-4 A	B-8339	Charcoal	520	6240 ± 20	7141 ± 113
COR1-4 B	B-8340	Charcoal	520	6230 ± 60	7123 ± 147
COR1-4 C	B-8341	Charcoal	520	6210 ± 40	7125 ± 121
COR1-5	B-8524	Charcoal	590	6330 ± 50	7290 ± 126
COR1-6 A	B-8525	Charcoal	660	7250 ± 30	8082 ± 81
COR1-6 B	B-8526	Charcoal	660	7290 ± 30	8098 ± 73
COR1-8	Poz-10108	Charcoal	780	15140 ± 70	18421 ± 309
COR2-3	Poz-10110	Charcoal	420	3675 ± 35	4021 ± 121
COR2-6	Poz-13536	Charcoal	510	4500 ± 40	5143 ± 163
SEC-1 NaOH	Poz-10275	Soil (humic acid)	280	1080 ± 50	1043 ± 125
SEC-1 RES	Poz-10194	Soil (humins)	280	300 ± 35	378 ± 87

Table 5-1: *List of radiocarbon ages obtained from the four investigated paleosol-sediment-sequences (*2σ-range; cal. = calendar, calibrated with CALIB 5.0.1. and intcal04 data set (Stuiver and Reimer, 1993; Reimer et al., 2004), ** in pMC > 100 = modern).*

5.4.5 PEDOGENESIS AT PEDRO LORENZO

Geochemistry data (total element data, pH-value and iron fractions), colour and clay mineral composition were measured for the Pedro Lorenzo sequence in order to deduce additional information regarding the paleoenvironmental conditions of pedogenesis, and refine the results discussed above (Supplementary Table 5-4, 5-5). The Pedro Lorenzo sequence is built mainly from sands. A well-developed paleosol horizon (B_t) has formed at the base of the profile, overlain by a succession of initial B_{wt} horizons, which are stacked onto each other and grade into a second B_t horizon. The overlying sediments are fluvial sands and gravel, and predominantly aeolian sands, in which initial A_h horizons have developed. The sequence is topped by aeolian sands showing some evidence for (anthropogenic?) disturbance.

Geochemistry

The ratio of titanium and zirconium is generally constant throughout the paleosol-sediment-sequence at Pedro Lorenzo (Fig. 5-8). As both elements are essentially unaffected by pedogenesis, the constant Ti/Zr ratio points to a relatively uniform sediment source area, emphasizing the significance of the geochemical analysis (Milnes and Fitzpatrick, 1989; Schaetzl and Anderson, 2005). Near the base of the sequence, however, a peak of the Ti/Zr ratio might indicate a change in source area, probably related to erosion and/or the evolution of the drainage net.

The pH-value is moderately acidic and ranges between 4 and 5 for most of the profile. It shows reduced values within the two paleosols, particularly towards the top of the upper paleosol, even though post-burial processes are likely to have altered pH-values within the paleosols. Two marked peaks characterize the fluvial sands, which separate the initial B_{wt} horizons. This tendency to less acidic values might be explained by the presence of essentially unaltered, fresh parent sediment, or even an additional increase in pH-value by salt enrichment.

The iron fractions (Fe_o, Fe_d, Fe_t) were plotted against a common scale, illustrating their relative abundances. All fractions show elevated values within the two paleosols. Amorphous iron (Fe_o) is only contained in traces, and most of the pedogenically formed iron summarized by Fe_d is crystalline. The total iron content (Fe_t) exceeds the pedogenically formed iron by far, most likely due to the presence of unweathered iron-bearing silicates. Total iron values are highest within the well-developed B_t horizon at the base of the sequence. Here, they might be additionally elevated as the result of enhanced hydromorphic processes. The presence of relatively little total iron in the upper part of the sequence should be linked to aeolian sorting and the preferential deposition of quartz minerals over iron bearing minerals.

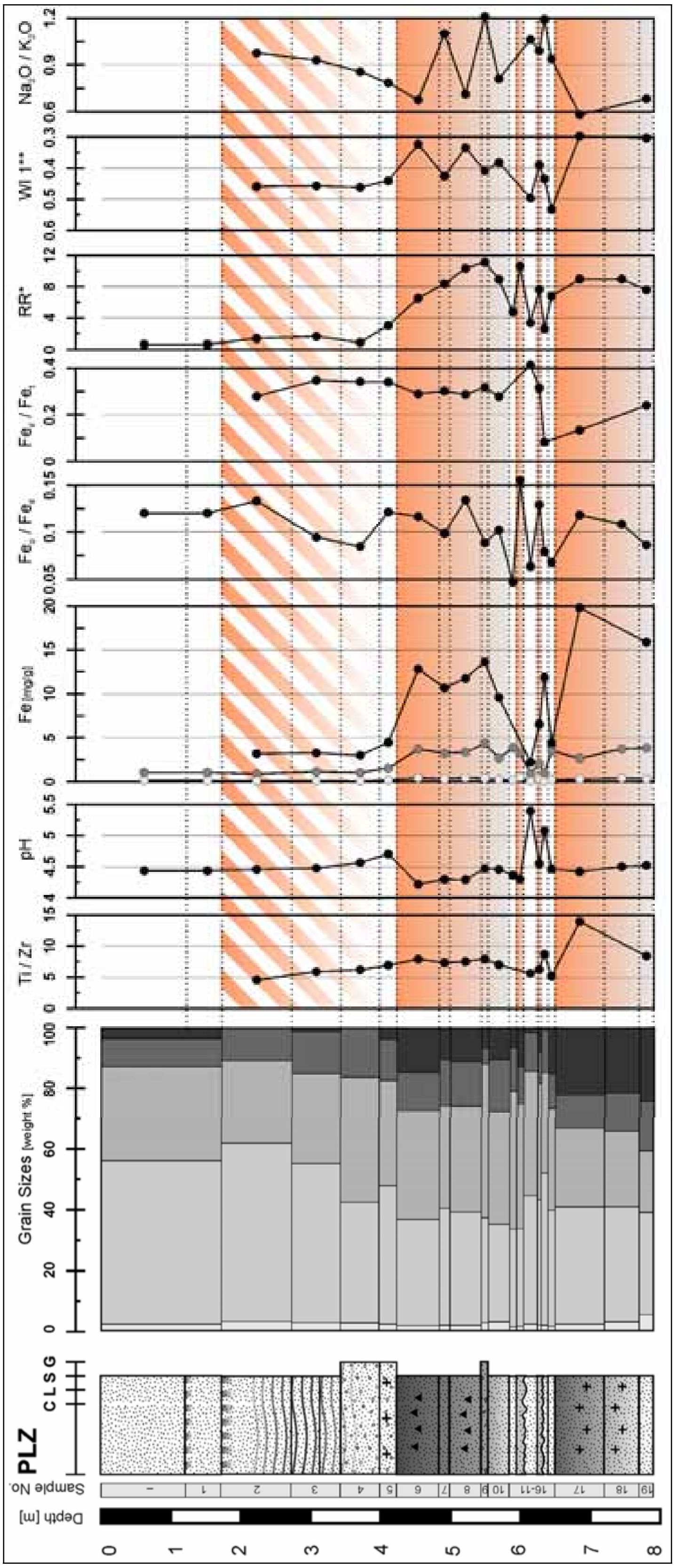

Fig. 5-8: *Grain size composition and selected geochemical parameters in the Pedro Lorenzo paleosol-sediment-sequence, interpreted regarding soil formation processes and overall weathering intensity in the profile; orange shading highlights the individual paleosol horizons described in the text (Legend is the same as in Fig. 5-3).*

The ratio of amorphous to overall pedogenic iron (Fe_o/Fe_d) is generally relatively low (around 0.1), due to low overall Fe_o values. However, it shows slightly elevated values towards the top of all individual paleosol horizons, particularly within the initial B_{wt} horizons. The Fe_o/Fe_d ratio estimates the crystallization grade of the iron oxides, and is thereby inversely related to the maturity of a soil. The highest Fe_o/Fe_d ratios should therefore identify the least mature paleosol horizons. This corroborates the initial character of these B_{wt} horizons.

The ratio of pedogenic to total iron (Fe_d/Fe_t) is relatively uniform throughout most of the sequence and can not be used as a parameter for overall weathering grade. The ratio of the upper well-developed B_t horizon corresponds to that of the initial soil horizons (A_h, minor clay lamellae) developed in the aeolian sands. This may be explained by high total iron values *and* intense formation of pedogenic iron in the paleosol, whereas the dune is characterized by low total iron content *and* little intense formation of pedogenic iron, resulting in an overall similar ratio. Only within the lower paleosol, Fe_d/Fe_t values decrease significantly, probably as the result of hydromorphic iron precipitation.

The Redness Rating Index, which can be used to approximate the hematite content (Torrent et al., 1983), shows clearly elevated values in all soil horizons, particularly in the B_{wt} horizons in the middle of the sequence. This might indicate xeric soil environments for these units and suggests overall more dry and seasonal environmental conditions. Upwards, the RR-values decrease, implying the dominance of goethite over hematite in the pedogenically formed iron oxides, possibly implying overall increased soil moisture where the initial B_{wt} horizons grade into the upper B_t horizon.

The weathering index of Kronberg and Nesbitt (1981) decreases with increasing weathering intensity and feldspar breakdown. It shows the lowest values within the lower B_t horizon, and thereby indicates the highest weathering intensities. However, this observation might be biased by possible differences in original mineralogical input, as shown by the Ti/Zr ratio. The WI is highest in the fluvial sands between the initial B_{wt} horizons. These sands have particularly high pH-values and can therefore be regarded as virtually unweathered, corroborating the initial character of the intercalated B_{wt} horizons. The index values within the upper B_t horizon are generally low, indicating moderate weathering intensities. Nevertheless, in the same horizon the WI shows significant variations similar to the previously described Fe_o/Fe_d ratio. Therefore, this upper B_t horizon might reflect the accretion of several individual initial B_{wt} horizons as the result of decreasing sediment accumulation and changing soil moisture regimes.

In order to prove xeric soil environments, a salinization index (soda/potash ratio) was applied to the sequence (Retallack, 2001). Values are particularly elevated in the sands between the initial B_{wt} horizons. This may be the result of insufficient dissolution of the generally highly soluble sodium, implying subsurface enrichment of salts within the sediments largely unaffected by soil formation. This enrichment might partly be due to ascending soil water, which may be responsible for the highly irregular and pitted lower boundaries of the overlying intial B_{wt} horizons. In turn, ascending soil water points to strong evaporation and thereby indicates pronounced aridity, possibly under highly seasonal environmental conditions.

Clay mineralogy

The composition of main clay mineral fractions throughout the sequence shows large variability (Fig. 5-9). Illite is the main clay component throughout the sequence but varies between 44% and >65%. Kaolinite content shows lesser variations between 21% and 37%. On the contrary, there is a marked difference between the smectite-rich upper and lower sequences parts of the sequence, and the smectite-poor medium part. In addition, a measurable chlorite peak was only determined in two samples within the middle part of the profile. Aside from variability of parent material, weathering and clay mineral formation generally depend on environmental parameters, such as temperature, rainfall and seasonality, which control soil moisture and soil temperature (Folkoff and Meentemeyer, 1987). Kaolinite, as an extremely widespread clay mineral, is interpreted to be mostly inherited from parent materials within the investigated sequence, because its formation is mainly restricted to very intense weathering under tropical wet climate conditions (Dixon, 1989; Velde, 1992).

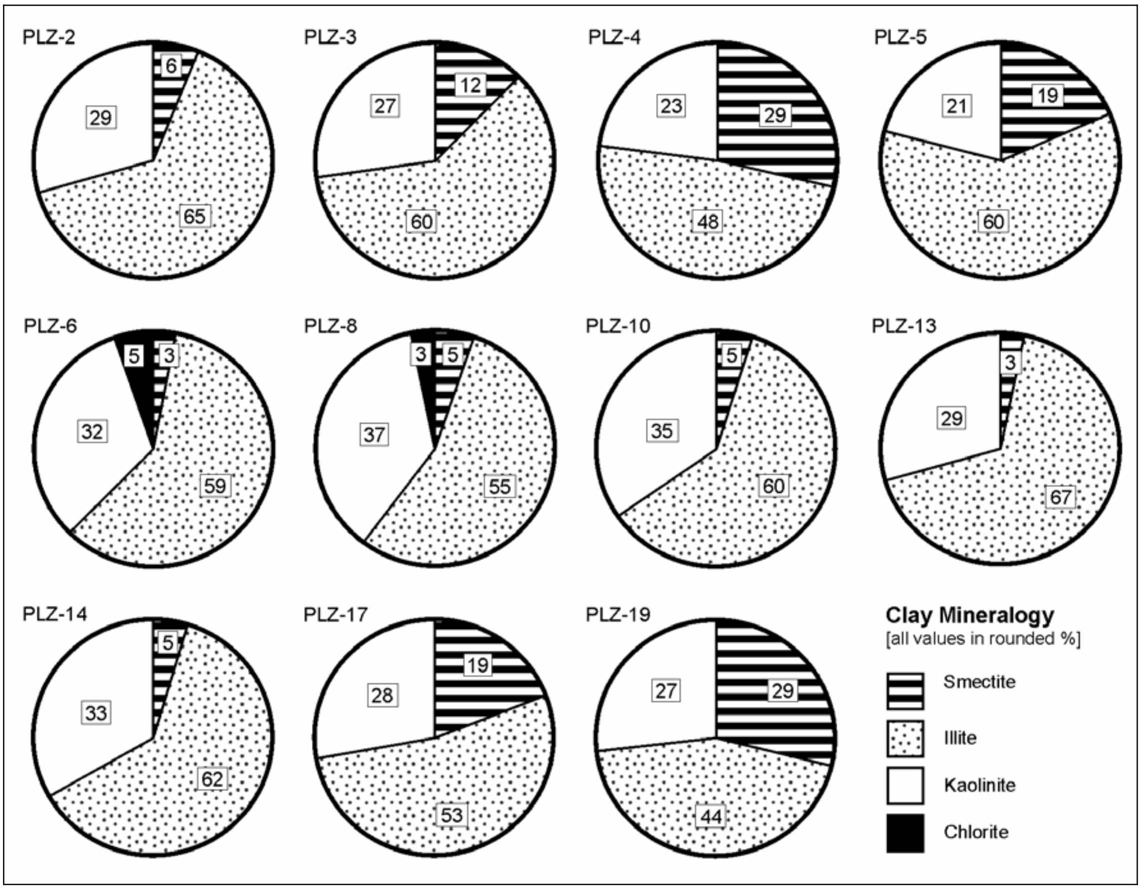

Fig. 5-9: *Clay mineral composition in the Pedro Lorenzo paleosol-sediment-sequence (from top PLZ-2 to bottom PLZ-19).*

Illite content is often inherited from parent materials as well (Allen and Hajek, 1989; Fanning et al., 1989). However, it might indicate semi-arid to arid soil environments when formed from expanding clays (such as smectite), whereas smectites tend to form pedogenically under warm temperate to tropical wet-dry climates under the influence of intermittent soil water (Allen and Hajek, 1989; Schaetzl and Anderson, 2005). High smectite content in combination with relatively low illite content is particularly characteristic for the lower B_t horizon (Fig. 5-9, PLZ-17 and 19) and the aeolian sediments showing initial pedogenesis (Fig. 5-9, PLZ-2 to PLZ-5). This observation might be indicative of a reduction in aridity during soil formation and clay mineral formation. On the contrary, markedly low smectite content and dominance of illite clay minerals in the middle part of the profile (Fig. 5-9, PLZ- 6 to 14) characterizes the initial B_{wt} horizons and the upper B_t horizon, and may thereby reflect much more xeric soil environments, likely resulting from overall increased aridity. This assumption is possibly corroborated by the presence of chlorites within the middle part of the profile, because chlorites are very unstable and usually inherited clays, which preferentially preserve in dry desert conditions (Allen and Hajek, 1989; Velde, 1992).

5.5 DISCUSSION AND INTERPRETATION

5.5.1 LANDSCAPE EVOLUTION AND PEDOGENESIS

In order to deduce information on landscape evolution from the paleosol-sediment-sequences, the presence of well-developed paleosols has traditionally been interpreted to reflect sustained landscape stability, reflecting a dense vegetation cover and reduced activity of extensive sedimentation or erosion under generally wetter environmental conditions (Rohdenburg, 1970). On the contrary, more arid conditions lead to increased sediment loads and torrentiality with higher sedimentation rates and more frequent displacements of the fluvial channels. However, the large complexity inherent to the investigated sequences, as well as their different spatial location in three catchments of different size probably complicates this approach (Fig. 5-1, 5-3). In addition, the chronological data seems not yet sufficient to establish an unambiguous correlation between all profiles. Therefore the paleoenvironmental interpretation of the sequences and the deduction of landscape evolution are mainly based on the paleoenvironmental significance of the different paleosol horizons in the study area (Fig. 5-10), and the temporal succession of sediments and paleosol horizons within the *individual* sequences.

The sequences at COR1 and COR2 expose the coarsest sediments found in all sequences (Fig. 5-3). Near the base, fluvial gravels are intercalated with sands, pebbles and overbank muds. Indurated B_w horizons ("*red beds*") have developed. At COR2, the deposition of coarse fluvial gravel seems to persist longer than at COR1 even though no age dates are available to determine the exact timing. Upwards, the gravel grade into sand and a well-developed B_t horizon. At COR1, initial B_{wt} horizons have formed in fluvial sands. In combination, these observations point to relatively dry environmental conditions (B_w, B_{wt}), probably interrupted by sedimentation of fluvial sands and gravel by high-magnitude floods. Based on a single radiocarbon date, this succession is older than 18.4 cal ka BP. A similar, preliminary OSL age of ~17.7-20.5 ka from the sandy base of the SEC profile may corroborate this date.

This interpretation is reinforced by several studies of fluvial systems in SW Amazonia (Madre de Díos, Ucayali, Juruá and Purús rivers) which have shown sedimentological evidence for intervals of significant hydrological changes towards increased torrentiality and aridity during the time before ~24 ka BP (Dumont et al., 1992; Räsänen et al., 1992; Latrubesse and Ramonell, 1994; Latrubesse and Rancy, 1998; Latrubesse and Kalicki, 2002).

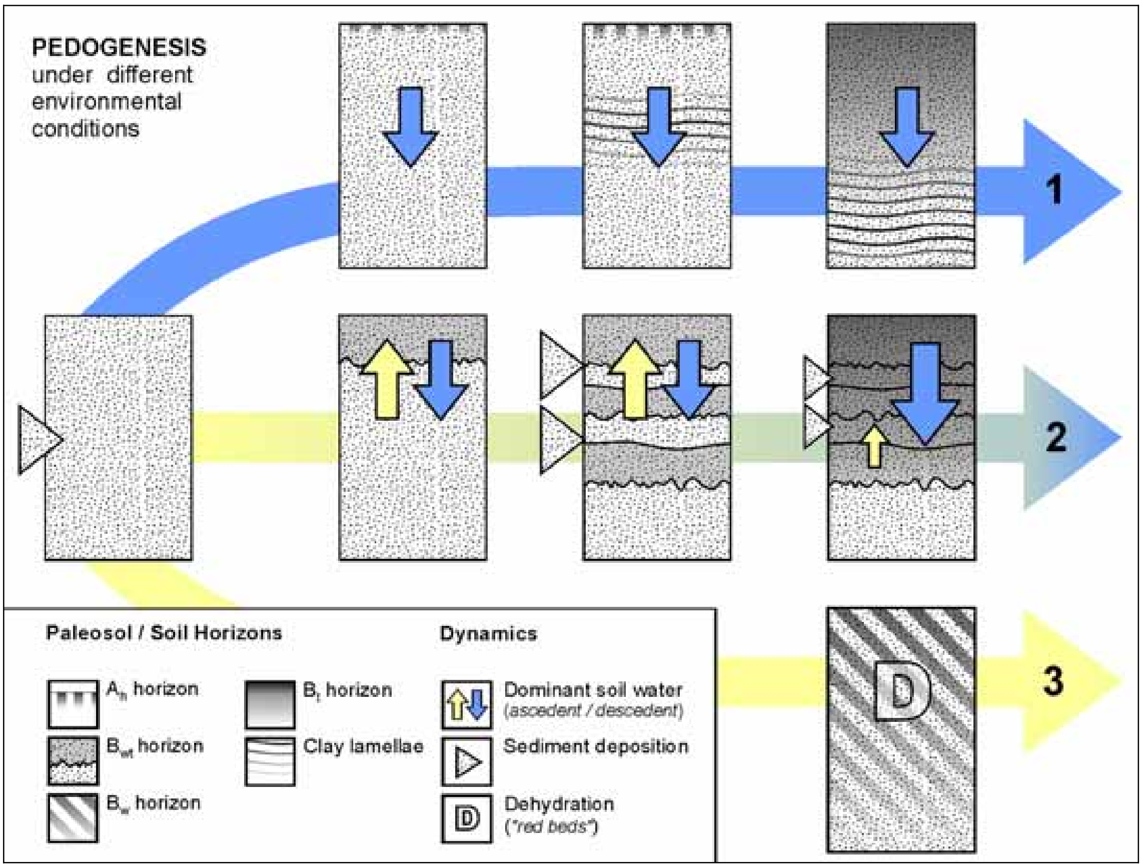

Fig. 5-10: *Conceptual model of pedogenesis under different environmental settings in the study area based on pedological and geochemical data; 1) formation of well-developed Bt horizons resulting from dominant clay illuviation under wet conditions, 2) formation of initial Bwt horizons resulting from contrasting soil water flow under highly seasonal conditions and 3) the formation of "red beds" under dominantly dry environmental conditions.*

Drier environmental conditions and landscape activity with sediment deposition and avulsion also seem to have prevailed in middle Amazonia until ~20 ka (TL age) (Latrubesse and Ramonell, 1994; Latrubesse, 2000) and the Bolivian Chaco (May et al., in review). Further evidence for increased aridity in Southern Amazonia and Brazil before ~20 ka is contributed by palynological studies (Mayle et al., 2000; Behling,

2002; Burbridge et al., 2004) and the analysis of speleothems in S Brazil (Cruz et al., 2005; Wang et al., In Press).
Active sedimentation of sands (and gravel) is replaced by fine grained overbank sediments at SEC and COR1, probably pointing to generally more stable fluvial systems. Although sufficient age dates do not exist to test whether the well-developed B_t horizons in COR2 and PLZ correlate with these fine grained sediments, both observations are interpreted to reflect a significantly increased vegetation cover under wetter conditions.
In the literature, the onset of generally wetter environmental conditions due to a southward shift and/or intensification of the SASM is reported to have commenced shortly after 18 ka in the Bolivian Altiplano (Argollo and Mourguiart, 2000; Baker et al., 2001b; Placzek et al., 2006) and the Eastern Andean cloud forest (Mourguiart and Ledru, 2003). During the same interval, stability of the fluvial systems has been reported from SW Amazonia (Dumont et al., 1992; Latrubesse and Kalicki, 2002) and the Eastern Andean piedmont of the Bolivian Chaco (Kruck, 1996; Pasig, 2005; May et al., in press). Similarly, wetter conditions at the turn from the Pleistocene to the Holocene were interpreted from the widespread deposition of very fine-grained, sometimes paludal sediments in the Eastern Bolivian Cordillera (Servant and Servant-Vildary, 2003) and the Gran Chaco (Kruck, 1996; Pasig, 2005; May et al., in review). Without further age dates, however, the fine grained sediments and paleosol formation in the study area can only tentatively be related to these records.

Overbank sediments as well as the well-developed B_t horizons are overlain by fluvial sands frequently containing charcoal. At Pedro Lorenzo, a succession of initial B_{wt} horizons likely developed under a soil moisture regime characterized by seasonal changes between descendent and ascendant soil water flow. In general, the obtained ages indicate sand deposition between ~ 8 cal ka BP to < 5.5 cal ka BP. Ages are consistent within the profiles but differ between the sequences, probably indicating a shifting (avulsive) fluvial system of predominantly sand deposition. In combination, these results point to pronounced seasonality during the Mid-Holocene, probably going along with a reduction in vegetation cover, increased evaporation and high-sediment supplies.
Similar results are summarized by Servant et al. (1981), who documented aggradation of the Río Piray as well as frequent forest fires and fluvio-aeolian sedimentation between ~ 7.8 and 5.8 cal ka BP in the study area around Santa Cruz. In addition, increased aridity and/or seasonality are corroborated by several records from Amazonia, where the Mid-Holocene was characterized by the expansion of savannah and grassland vegetation (Pessenda et al., 1998; de Freitas et al., 2001) and aggradation of the fluvial systems (Latrubesse and Kalicki, 2002; Latrubesse, 2003). Widespread aggradation of the fluvial systems during the Mid-Holocene is also reported from the Gran Chaco of S Bolivia and Paraguay (Geyh et al., 1996; Kruck, 1996; May et al., in review; May et al., submitted).

Moderately to well-developed B_t horizons have developed within the Mid-Holocene fluvial sands at COR1, COR2 and PLZ, likely reflecting a shift towards more stable and wetter environmental conditions starting after ~5.5 cal ka BP. On top, a moderately developed B_t horizon has formed at COR2 within fluvial sands after 4 cal ka BP before renewed fluvial sedimentation of coarser grain sizes (sands, pebbles) ends the soil formation sometime between ~4 cal ka BP and 3.2 cal ka BP. These observations point to an increase of fluvial energy, likely corresponding to an upstream onset of stream incision, which must have progressed successively downstream with time. This assumption is corroborated by the available age dates at SEC, indicating persisting sedimentation until ~1 cal ka BP. In any case, the moderately to well-developed B_t horizons conflict with comparatively short duration of pedogenesis (0.4 to 1 ka at SEC, ~1 ka at COR2 and < 1.6 ka at PLZ). In the absence of further age dates the exact timing and duration of pedogenesis at the four investigated locations remains unsolved.

The return to generally wet conditions and landscape stability is also reported from the lowlands of NE Bolivia and SW Amazonia at ~3.2 cal ka BP (Pessenda et al., 1998; Mayle et al., 2000; de Freitas et al., 2001; Burbridge et al., 2004). The onset of soil formation in the Bolivian and Paraguayan Chaco at ~4 - 3.8 cal ka BP is interpreted similarly (Barboza et al., 2000; May et al., submitted). On the base of relatively few radiocarbon dates Servant et al. (1981) suggest stable landscapes and soil formation in the study area already since 5.8 cal ka BP.

5.5.2 GEOMORPHOLOGICAL MODEL OF LATE HOLOCENE PIEDMONT EVOLUTION

All investigated paleosol-sediment-sequences are topped by aeolian sands. At Pedro Lorenzo (PLZ) these sands seem to exhibit a more complex architecture including at least three phases of aeolian deposition and evidence for initial soil formation, whereas at Quebrada Seca (SEC) the dune sands appear homogeneous and do not contain buried A_h horizons. A model of successive stepwise fluvial incision may explain this apparent paradox by integrating geomorphological, sedimentological and pedological observations (Fig. 5-11).

The *incision process* itself is the expression of excess fluvial energy (stream power) due to the relative increase of available runoff in relation to bedload (e.g. Bull, 1979; Simon and Darby, 1999). Along the longitudinal stream profile, however, these variables may vary significantly due to a decline in topographical gradient and runoff infiltration losses. Generally, this leads to the typical geomorphological division of upstream erosion, midstream transport and downstream deposition with significant widening of the floodplain (Bull, 1979).

The location of *sediment deposition* – mostly sands – occurs where the fluvial energy (stream power) falls short of threshold values regarding topographic gradient, discharge and sediment supply. Over the time scales involved, tectonic changes in longitudinal stream gradient are negligible. Therefore the location of sediment deposition depends largely on the prevailing climatic/hydrological variables. Furthermore, the spatial extent of the depositional stream reaches is influenced by the time, over which similar conditions persist. Particularly within incised and confined stream valleys sediment

deposition is likely to propagate upslope due to gradient lowering, ultimately filling up the valley.
Efficient *deflation* requires sustained conditions of available sediment as provided by the wide floodplains of dominant sediment deposition during a markedly prolonged dry season. Under environmental conditions still wet enough to sustain a dense vegetation cover, the persistence of increased sediment supply and marked seasonality may eventually lead to the formation of extensive *parabolic paleodunes* in the study area (Lomas de Arena, Fig. 5-1, 5-2).

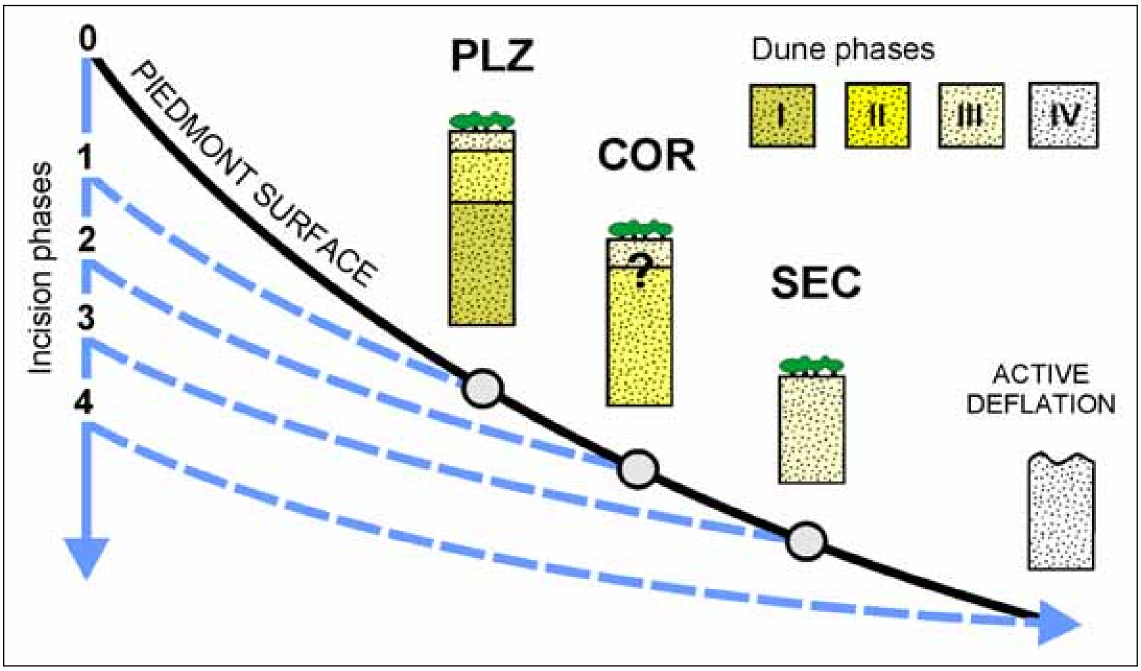

Fig. 5-11: *Schematic model of the landscape evolution of the piedmont in the study area since ~5.5 cal ka BP, illustrating the stepwise incision of the ephemeral piedmont stream interrupted by intervals of increased sediment load and the formation of dunes.*

In this model, the repeated cycles of environmental change may, however, produce spatially different results because the geomorphological (and topographical) preconditions change with each repeated cycle. Specifically the narrowing of the channel through incision and the modified longitudinal stream profile through sediment deposition and/or incision are hold responsible for the generally progressing downstream migration of active sediment deposition and deflation during the dry season, emphasizing the fluvio-aeolian interactivity as an important geomorphological concept in regions of seasonal contrasting environments (e.g. Langford, 1989). While this model explains the landscape evolution in the local and regional piedmont setting, it might well be applied to similar geomorphological and environmental piedmont areas in other parts of the world.

In the study area, environmental conditions did apparently not allow for significant incision during the Mid-Holocene, likely due to pronounced aridity and large sediment supplies. No Mid-Holocene aeolian sediments were documented either, which may be due to a reduced forest cover not able of fixating airborne sand.

Only since ~5.5 cal ka BP, environmental conditions in the study area allow for incision of the ephemeral streams, reflecting a marked change towards wetter conditions going along with denser vegetation and a reduction in sediment supply. Considerable vegetation cover is also necessary for the formation of parabolic dunes. The effect of a climatic change from wetter climate, generally characterized by downstream progressing incision, towards drier and more seasonal climate should lead to preferential deposition where the floodplain broadens and deflation with downwind formation of parabolic dunes sets in. Three intervals of aeolian sand deposition separated by initial A_h horizons were identified based on preliminary OSL age dates and two radiocarbon ages. These data suggest intervals of increased aridity and sediment supply after ~1.5 ka, between ~0.4 and ~0.1 ka and within the last ~60 years (post 1950).

The existence of a first phase of landscape activity around ~1.5 ka is generally corroborated by the regional investigation of Río Piray terraces and paleosol-sediment-sequences by Servant et al. (1981), who assume a drier interval between ~3.6 and 1.3 cal ka BP followed by and a renewed change towards wetter conditions. In this context, aggradation of the Río Grande between ~1.7 and <1.4 cal ka BP may be interpreted as the result of increased aridity (May et al., in review). Intervals of landscape activity during the second half of the millennium have also been reported from NW Argentina, SW Bolivia and the Bolivian Chaco (Maas et al., 1999a; Maas et al., 1999b; May et al., in review; May et al., submitted). Thus, they may be considered the expression of decadal to centennial environmental changes in relation to larger scale climatic phenomena such as the Little Ice Age (LIA) or frequency changes of the El Niño Southern Oscillation (ENSO) known from the Andean highlands (Thompson et al., 1986; Liu et al., 2005; Rabatel et al., 2005; Polissar et al., 2006). A return to wetter conditions within the last ~50 years has likely caused concentration of runoff, thereby leading to renewed incision and formation of lowermost erosional terrace in study area. In addition, the formerly active parabolic dunes are colonized by vegetation due to restricted aeolian sediment supply from the floodplains, ultimately leading to dune fixation and initiation of pedogenesis.

5.6 CONCLUSION

This study of paleosol-sediment-sequences at the Andean piedmont around Santa Cruz in Eastern Bolivia integrates several methodical approaches. Particularly the detailed analysis of the complex paleopedological data has proved necessary in order to corroborate and expand the results from geomorphological and sedimentological observations.

Although a complete and reliable chronology of the investigated sequences has not been established yet, the sequences constitute pedological and sedimentological archives extending well back into the Pleistocene. The available data suggest dry environmental conditions with sedimentation of coarse fluvial sediments and largely restricted soil formation for the time > 20 cal ka BP. Subsequently, the results indicate a change towards wetter conditions with formation of well-developed B_t horizons (characterized by clay illuviation) and/or deposition of fine grained overbank deposits, which possibly correlate to Lateglacial to Early Holocene records elsewhere. During the Mid-Holocene, renewed deposition of fluvial sands and substantially changed processes of soil formation (characterized by ascendant soil water and evaporation) reflect environmental conditions of marked seasonality and dominant aridity. The development of B_t horizons and subsequent incision in the study area imply a shift to wetter conditions of the Late Holocene after ~5.5 cal ka BP. Since then, however, significant changes of runoff and sediment supply have occurred on shorter time scales, probably in relation to larger-scale atmospheric phenomena. Shifts towards increased aridity interrupted the incision, ultimately leading to the formation of fluvial terraces and several intervals of dune formation in the study area.

In the outer tropics, where high rainfall amounts combine with a marked dry season, the environmental conditions seem to provide sufficient moisture to maintain an intensive, although altered pedogenesis through times of significant aridity and overall landscape activity. The resulting high pedological complexity and the difficulties to obtain a reliable chronology complicate the establishment of a regional stratigraphy. Here, particularly paleopedological investigations and their paleoenvironmental interpretation have shown to provide additional information.

ACKNOWLEDGEMENTS

The authors would like to thank the Museo de Historia Noel Kempff Mercado, Santa Cruz, for logistical support in Bolivia. We gratefully acknowledge the conventional radiocarbon dating at the Institute of Physics (University of Bern). In addition, Urs Eggenberger, Ivan Mercolli and Matthias Trachsel offered valuable help with XRF- and XRD measurements and interpretation of the results. Soil micromorphological analysis was assisted by Jana Ilgner.

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APPENDIX

Sample	gS	mS	fS	gU	mU	fU	T
PLZ-1	2.02	53.95	31.54	7.09	1.29	0.60	3.51
PLZ-2	3.02	58.85	27.13	7.06	1.49	2.23	0.22
PLZ-3	2.74	52.34	29.71	10.31	2.53	1.08	1.29
PLZ-4	2.59	39.76	41.10	11.78	2.78	1.79	0.21
PLZ-5	2.37	45.39	34.70	9.16	1.74	2.83	3.83
PLZ-6	1.67	34.97	35.81	8.90	2.70	1.18	14.76
PLZ-7	1.93	38.35	33.92	10.14	2.97	2.19	10.50
PLZ-8	1.84	37.20	35.06	9.89	2.43	2.18	11.40
PLZ-9	2.81	34.44	50.70	3.20	1.57	0.74	6.56
PLZ-10	2.88	32.24	37.02	11.31	3.65	2.53	10.36
PLZ-11	1.24	32.56	45.25	9.89	2.49	1.97	6.60
PLZ-12	1.54	32.24	41.01	8.19	1.84	2.22	12.96
PLZ-13	2.23	42.39	40.99	9.11	2.29	1.42	1.57
PLZ-14	2.04	41.14	38.34	6.69	2.00	1.46	8.33
PLZ-15	1.98	50.08	33.06	11.66	0.71	1.82	0.69
PLZ-16	1.60	38.14	33.55	6.60	2.78	1.92	15.41
PLZ-17	2.39	38.40	25.91	5.29	3.60	2.10	22.31
PLZ-18	2.95	37.93	24.71	6.47	3.30	3.03	21.61
PLZ-19	5.39	33.57	20.27	7.34	5.79	3.34	24.30
SEC-1	3.66	61.76	28.34	2.61	-0.75	1.12	3.26
SEC-2	4.36	60.87	27.99	2.55	2.23	1.73	0.27
SEC-3	1.63	77.25	18.08	4.31	3.78	-6.79	1.75
SEC-4	7.30	53.26	28.76	5.58	0.68	1.57	2.85
SEC-5	2.43	46.78	19.58	6.90	3.50	4.37	16.45
SEC-6	2.67	37.39	25.71	8.39	4.35	3.18	18.31
SEC-7	4.38	35.97	26.56	7.84	4.50	3.04	17.71
SEC-8	3.02	33.35	28.96	10.22	4.85	3.19	16.39
SEC-9	2.14	28.65	24.45	10.12	7.83	4.75	22.07
SEC-10	1.09	19.64	17.38	9.59	9.28	8.73	34.29
SEC-11	1.84	41.81	37.98	9.17	3.00	1.95	4.26
SEC-12	2.59	49.05	36.44	4.30	1.37	1.01	5.23
COR1-1	0.38	8.57	36.82	34.60	9.22	2.60	7.81
COR1-2	0.54	23.54	48.58	11.32	3.58	1.86	10.58
COR1-3	1.83	35.55	31.90	10.97	4.92	3.75	11.09
COR1-4	1.85	31.36	24.89	11.06	5.74	3.69	21.41
COR1-5	1.66	26.90	24.71	11.07	6.22	4.35	25.09
COR1-6	3.22	25.47	24.07	5.72	4.58	3.87	33.07
COR1-7	3.93	46.60	24.83	4.85	1.77	2.12	15.89
COR1-8	6.47	41.44	35.09	7.60	1.96	1.51	5.93
COR1-9	4.55	38.37	34.33	6.17	2.05	1.37	13.18
COR1-10	4.86	30.16	48.78	9.51	1.44	1.65	3.60
COR1-11	4.25	37.47	30.23	9.23	3.17	1.54	14.11
COR1-12	3.57	30.76	38.33	11.02	4.76	2.76	8.80
COR1-13	6.35	35.10	40.55	7.33	3.85	3.19	3.64
COR1-14	5.98	40.97	37.43	2.78	1.33	1.22	10.30

Supplementary table 5-2: *Grain size data for the Pedro Lorenzo (PLZ), Quebrada Seca (SEC) and Quebrada Coronada (COR1) profiles.*

Sample Nr.	**Structure Type**	**Pores**	**Matrix Color**	**Ratio** *(Pores : Grains : Matrix)*	**Concretions** *(Fe/Mn)*	**Nodules** *(Fe/Mn)*	**Coatings**	**Laminated Cutans**	**Organics**	**Surface Alteration**	**Linear Alteration**	**Sorting**	**Dominant Minerals**	**Soil Horizon**
SEC-5	alveolar granular	medium irregular	black – reddish brown	30:40:30	A	VR	O	VR	A	O	A	–	quartz	Bt
SEC-7	alveolar	large irregular	brownish – grey	30:35:35	A	VR	O	VR	O	F	F	~	quartz	Bt
SEC-9	alveolar	small irregular	brownish – black	20:30:50	D	O	F	VR	VR	O	A	~	quartz	Bg Cg
SEC-10	massive	medium irregular elongate	greyish – brown	20:10:70	VA	O	O	R	VR	O	F	+	quartz	Bg Cg
COR1-2	alveolar granular	medium irregular	brownish	20:40:40	F	VA	R	VE	A	F	O	~	quartz feldspar	Bt
COR1-3	alveolar granular	small irregular	brownish	10:40:50	VA	O	R	VR	A	F	A	+	quartz	Bt
COR2-1	alveolar	medium irregular	dark greyish	20:30:50	A	R	VR	VR	A	O	A	~	quartz	Bt
COR2-2	alveolar coat & bridge	large irregular	reddish brown	35:35:30	F	R	VA	F	VR	F	A	~	quartz	Bt
COR2-3	coat & bridge	medium irregular	reddish brown – brown	40:50:10	R	R	A	VR	A	A	A	+	quartz	Bw
PLZ-1	single grain granular bridge	continuous	greyish	40:50:10	VR	VR	R	VR	F	O	F	~	quartz	Ah
PLZ-6	alveolar bridge	large irregular	reddish brown	30:40:30	R	VR	A	O	VR	F	F	~	quartz	Bwt
PLZ-8	alveolar bridge	medium irregular	reddish brown	30:50:20	VR	VR	A	O	VR	F	A	~	quartz feldspar	Bwt
PLZ-12	bridge	medium irregular	reddish brown	40:50:10	VR	VR	A	VR	VR	F	F	~	quartz	Bwt
PLZ-17	alveolar	medium irregular	reddish brown	20:50:30	F	O	A	F	VR	F	F	–	quartz	Bt
PLZ-18	alveolar	small irregular sinuous	reddish brown – brown	10:40:50	O	R	A	F	VR	F	A	–	quartz	Bt

Supplementary table 5-3: *Summary of selected paleopedological elements, based on micromorphological analysis of 15 thin sections from the investigated paleosol-sediment-sequences (sorting and frequency classes are based on FitzPatrick (1993): VR=very rare, R=rare, O=occasional, F=frequent, A=abundant, VA=very abundant, D=dominant; +=well-sorted, ~= moderately sorted, -=badly sorted).*

Sample	FE o [mg/g]	FE d [mg/g]	pH	HUE moist	VAL moist	CHR moist	RR moist
PLZ-1	0.13	1.04	4.44	9.00	5.80	3.60	0.62
PLZ-2	0.12	0.89	4.46	8.00	5.70	3.90	1.37
PLZ-3	0.11	1.14	4.48	8.00	5.20	4.20	1.62
PLZ-4	0.09	1.02	4.57	8.80	6.00	4.30	0.86
PLZ-5	0.19	1.53	4.71	6.80	5.30	5.00	3.02
PLZ-6	0.43	3.71	4.22	5.00	4.30	5.60	6.51
PLZ-7	0.32	3.23	4.30	3.90	4.60	6.30	8.35
PLZ-8	0.45	3.38	4.29	3.70	3.90	6.40	10.34
PLZ-9	0.38	4.34	4.47	3.90	3.50	6.40	11.15
PLZ-10	0.27	2.67	4.46	5.10	3.40	6.20	8.94
PLZ-11	0.18	3.88	4.37	6.40	4.80	6.30	4.73
PLZ-12	0.51	3.29	4.30	3.80	3.90	6.70	10.65
PLZ-13	0.06	0.91	5.40	7.00	5.10	5.70	3.35
PLZ-14	0.27	2.06	4.55	4.10	4.40	5.70	7.64
PLZ-15	0.08	0.99	5.08	7.60	5.30	5.70	2.58
PLZ-16	0.24	3.51	4.47	4.40	4.80	5.80	6.77
PLZ-17	0.31	2.66	4.42	4.20	4.40	6.80	8.96
PLZ-18	0.40	3.74	4.50	4.20	4.40	6.80	8.96
PLZ-19	0.33	3.83	4.52	5.40	3.70	6.10	7.58

Supplementary table 5-4: *Pedogenic iron fractions (Feo and Fe d), pH-value, Munsell soil colour and Redness Rating index in the Pedro Lorenzo (PLZ) profile.*

Sample	SiO_2 [wt.-%]	TiO_2 [wt.-%]	Al_2O_3 [wt.-%]	Fe_2O_3 [wt.-%]	MnO [wt.-%]	MgO [wt.-%]	CaO [wt.-%]	Na_2O [wt.-%]	K_2O [wt.-%]	P_2O_5 [wt.-%]	Ba ppm	Cr ppm	Cu ppm	Nb ppm	Ni ppm	Pb ppm	Rb ppm	Sr ppm	Y ppm	Zn ppm	Zr ppm
PLZ-1	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
PLZ-2	98.57	0.14	2.04	0.32	<0.01	0.18	0.06	0.83	0.85	0.11	233.28	21.93	<3	<3	<3	7.98	13.96	29.91	<5	<5	306.05
PLZ-3	98.47	0.20	2.39	0.33	0.01	0.20	0.07	0.94	1.01	0.12	164.24	<5	<3	4.98	<3	10.95	17.92	35.83	<5	<5	338.43
PLZ-4	98.46	0.20	2.32	0.30	0.01	0.18	0.07	0.89	1.04	0.08	191.52	17.95	<3	6.98	<3	<5	17.95	36.91	<5	<5	322.19
PLZ-5	96.85	0.24	2.54	0.45	0.02	0.23	0.10	0.84	1.07	0.10	642.18	14.93	<3	5.97	<3	9.96	22.90	37.83	<5	5.97	344.49
PLZ-6	90.03	0.26	4.66	1.28	0.03	0.37	0.09	0.86	1.27	0.11	358.12	13.81	<3	6.91	4.93	10.85	39.46	40.45	7.89	13.81	324.58
PLZ-7	91.69	0.27	3.71	1.07	0.02	0.25	0.07	1.41	1.28	0.06	307.78	33.65	4.95	6.93	5.94	12.87	37.61	38.60	16.82	11.88	363.20
PLZ-8	92.25	0.26	4.35	1.18	0.02	0.31	0.09	0.87	1.23	0.09	551.44	39.25	<3	6.87	5.89	10.79	37.29	37.29	6.87	9.81	352.25
PLZ-9	90.59	0.28	4.54	1.37	0.02	0.34	0.08	1.67	1.38	0.04	171.69	26.64	4.93	7.40	5.43	12.33	44.40	40.95	18.25	13.81	353.25
PLZ-10	92.43	0.24	3.76	0.96	0.02	0.27	0.07	1.01	1.25	0.10	353.90	20.76	<3	5.93	2.97	9.89	32.62	38.55	5.93	5.93	339.07
PLZ-11	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
PLZ-12	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
PLZ-13	97.83	0.13	2.02	0.22	0.02	0.16	0.05	1.00	0.94	0.10	391.73	27.98	<3	6.00	<3	7.99	15.99	31.98	<5	<5	230.84
PLZ-14	84.38	0.17	3.36	0.65	0.02	0.32	0.12	1.01	1.02	0.15	231.79	17.83	<3	<3	<3	10.90	22.78	30.71	<5	8.91	269.43
PLZ-15	92.72	0.27	4.02	1.19	0.02	0.28	0.08	1.64	1.38	0.04	167.58	8.98	4.99	7.98	5.49	11.97	40.90	42.89	14.46	10.47	315.21
PLZ-16	93.19	0.16	1.77	0.24	0.02	0.13	0.05	0.95	1.02	0.03	142.34	13.34	4.94	6.42	4.94	12.85	21.25	32.62	10.87	4.45	314.82
PLZ-17	84.33	0.30	6.15	1.98	0.02	0.56	0.19	0.88	1.52	0.12	426.11	29.45	18.65	6.87	7.85	14.73	50.07	53.02	5.89	30.44	217.97
PLZ-18	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
PLZ-19	77.04	0.25	5.15	1.59	0.01	0.46	0.16	0.84	1.24	0.13	455.11	12.46	6.71	5.75	6.71	6.71	41.20	38.33	5.75	21.08	296.06

Supplementary table 5-5: *Total element composition in the Pedro Lorenzo (PLZ) profile.*

6

SYNTHESIS AND OUTLOOK

6.1 SYNTHESIS

Following the outline of this dissertation, the synthesis gives a short summary of the results from large-scale geomorphological analysis and the detailed investigation paleosol-sediment-sequences at three different localities.

6.1.1 LARGE-SCALE GEOMORPHOLOGICAL ANALYSIS

Since a few years, the growing number and variety of *remote sensing data* with comparatively high temporal and spatial resolution offers a huge potential for modern, large-scale geomorphological analysis. In combination with field work interpretation of remote sensing data provided evidence for periods during the Late Quaternary in Eastern Bolivia that were characterized by extensive landscape activity (chapter 2).
Large-scale channel shifts on all *fluvial megafans* (Río Piraí, Río Grande, Río Parapetí) and along the piedmont, for example, reflect significant changes in sediment load and/or torrentiality. Similarly, the existence of numerous inactive *paleodunes and paleodune systems* suggests past climatic conditions favorable for higher sediment loads and/or enhanced mechanisms of deflation (longer dry season, reduced vegetation). However, the interpretation of the aeolian record of Eastern Bolivia is probably not that straightforward, owing to the high complexity of the existing forms and their interaction with the fluvial system. Large, inactive dune fields and smaller-scale, mostly inactive riverine dunes can be distinguished. For the dune field of the Lomas de Guanacos at least three different morphological generations of dune activity were identified. Particularly the evolution of the oldest generation is probably closely tied to the evolution of the Río Grande megafan. Most of the smaller dunes and paleodunes are directly coupled to deflation from adjacent active river channels. Smaller-scale paleodunes are also found in association with numerous *paleolakes* in the Bolivian Chaco, where they are interpreted to reflect pronounced seasonality allowing for sufficient sediment input and effective deflation. The formation of the paleolakes probably required hydrological conditions much wetter than today during the rainy summer season. Eventually, evidence for relict but also active fluvial dissection was observed at several locations of the study area. Particularly along the Andean piedmont ephemeral streams have deeply incised into the piedmont.

6.1.2 PALEOSOL-SEDIMENT-SEQUENCES ALONG THE ANDEAN PIEDMONT AS PALEOENVIRONMENTAL ARCHIVES

Along the incised stream channels, but also along the banks of the Río Grande, unique outcrop conditions were documented and investigated in more detail. In virtually all cases, the outcrops expose sequences of fluvial and partly aeolian sediments as well as intercalated paleosols. Occasionally, paleochannels and sedimentary hiati are observed and indicate erosion.

The paleosol-sediment-sequences reflect the local changes between active sedimentation, erosion and pedogenesis. For the *interpretation of the sequences*, paleosols are assumed to have formed under overall stable landscape conditions characterized by dense vegetation cover and sufficient precipitation. On the other hand, extensive deposition, transport and/or erosion of sediment generally indicate dry conditions. Well-developed paleosols of regional significance (marker horizons) form the base for correlation. For this thesis, the general concept of landscape stability and activity (Rohdenburg, 1970) was supplemented by integrating geomorphological, sedimentological and – to a lesser extent – paleopedological observations, in order to take into account smaller-scale variations of geomorphological processes (e.g. interpretation of terraces, dune generations, lithofacies etc.).

Regional extrapolation and validation of local results, and comparison to other existing records require integrating a large number of investigated sequences from different catchments. Therefore paleosol-sediment-sequences were investigated with more detail at three different locations along a ~200 km *north-south transect* (Santa Cruz – Cabezas – Charagua, Fig. 6-1). All locations are potentially covered by continuous forest. However, the climatic conditions at each location differ significantly from each other, grading from subhumid climate at Santa Cruz to semi-arid climate at Charagua.

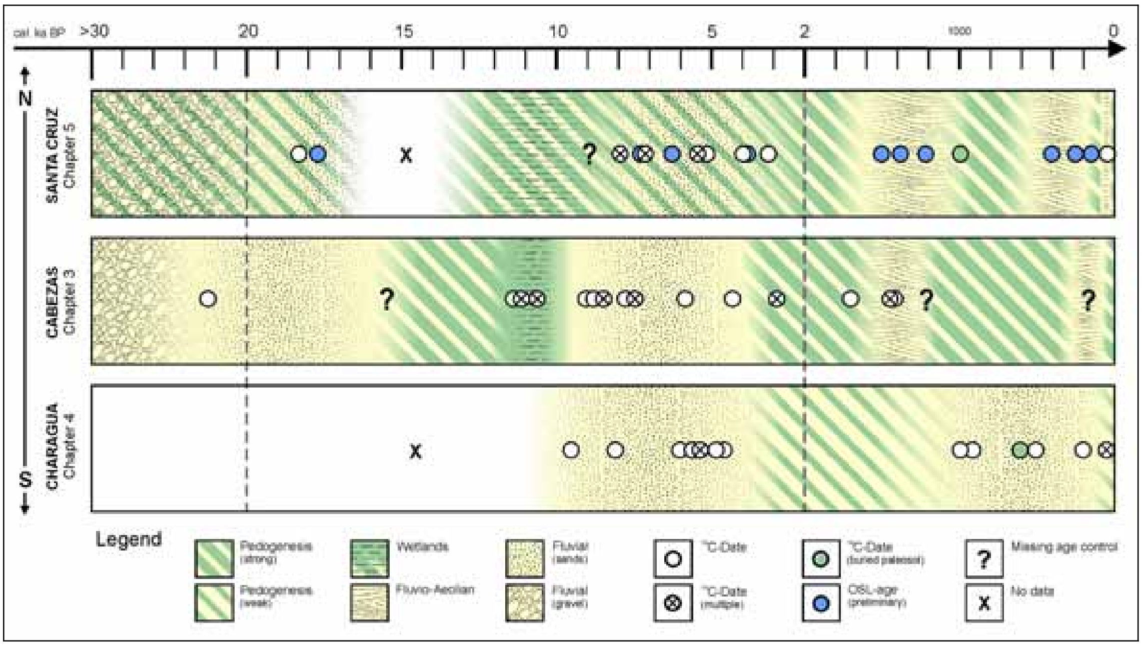

Fig. 6-1: *Summary of the paleoenvironmental interpretation and correlation of the three paleosol-sediment-sequences along the Andean piedmont. Note the change of temporal scale at 20 cal ka BP and 2 cal ka BP.*

The incised streams have relatively small catchments in the Subandean Ranges or the Subandean foothills. Therefore, each *paleosol-sediment-sequence* provides an archive for the local sedimentary, geomorphological and paleoenvironmental evolution of the individual piedmont catchment. The paleoenvironmental interpretation and correlation of the three investigated sequences are shown in Fig. 6-1.

The analysis of the paleosol-sediment-sequences has emphasized two important findings: (i) The climatic N-S gradient is expressed by a corresponding decrease in the number and intensity of the paleosols contained in the sequences, and (ii) similarities between all investigated locations and the overall consistent interpretation of the sequences, respectively, demonstrate the high potential of the piedmont to serve as valuable archive for the regional paleoenvironmental evolution of the Eastern Bolivian lowlands (Fig. 6-1). As discussed in detail in the chapters 3 to 5, various aspects of the interplay between geomorphology, sedimentology, pedogenesis and paleoclimate are synthesized for the three investigated localities.

6.1.3 PALEOSOL-SEDIMENT-SEQUENCES AT CABEZAS

At Cabezas (chapter 3), the investigated paleosol-sediment-sequences offer unique outcrop conditions with a horizontal extent of several kilometers. This enables a highly reliable correlation between the individual profiles, and the interpretation of the spatial variability of the sedimentary processes and pedogenesis. The mineral and total element composition in sediments and paleosols correlates with grain size and thereby essentially depends on temporal changes in transport mechanism and provenance. In that case, geochemical analysis cannot provide detailed information on type and intensity of pedogenesis. Therefore the interpretation of the sequences is mainly based on the succession of various sedimentary lithofacies including paleosols and soils. This ultimately leads to the distinction of sedimentary units as the base for paleoenvironmental interpretation.

In all sequences the lowermost unit is characterized by deposition of very coarse sediments (gravel, sands) in braided river environments. They are dated to > ~22.2 cal ka BP. These observations indicate overall dry and seasonal conditions and a significant reduction of vegetation cover. During the LGM, the coarse gravel grade into sands, possibly pointing to a minor environmental change of slightly increased moisture availability. An extensive paleosol developed on top of these sediments and implies the change to overall landscape stability and a dense vegetation cover under wetter conditions during the Lateglacial. Frequent inundation and a densely vegetated landscape during the Pleistocene-Holocene transition are interpreted from the deposition of fine-grained, palustrine sediments. Erosion, channel incision and subsequent accumulation of fluvial and/or fluvio aeolian sand provide evidence for a geomorphic instability under semi-arid to arid conditions during the Early- to Mid-Holocene. Between ~4 and 2.9 cal ka BP pedogenesis indicates the return to wetter conditions similar to today. However, a pulse of renewed fluvial and aeolian sedimentation seems to have occurred around 1.5 cal ka BP.

These results are generally corroborated by a variety of geomorphological findings (Räsänen et al., 1990; Iriondo and Garcia, 1993; Kruck, 1996; Kröhling and Iriondo, 1999; Barboza et al., 2000; Latrubesse, 2003) and paleobotanical records (Pessenda et al., 1998; Mayle et al., 2000; de Freitas et al., 2001; Behling, 2002; Burbridge et al., 2004) from tropical and subtropical South America. In agreement with recently published records (Baker et al., 2001; Haug et al., 2001; Cruz et al., 2005; Placzek et al., 2006; Wang et al., In Press), the results from Cabezas suggest that latitudinal shifts and intensity changes of the South American Summer Monsoon played a dominant role in controlling the Late Quaternary hydrological and environmental conditions along the Andean piedmont in Eastern Bolivia. Particularly the observation of a remarkably wet Pleistocene-Holocene transition, however, adds further evidence for significant modification of the regional environmental conditions by extratropical influences such as cold air incursion (Latrubesse and Ramonell, 1994; Behling, 2002; Servant and Servant-Vildary, 2003; Bush and Silman, 2004).

6.1.4 PALEOSOL-SEDIMENT-SEQUENCES AT CHARAGUA

The investigation of paleosol-sediment-sequences at Charagua (chapter 4) has combined a sedimentary/stratigraphical approach with large-scale geomorphological analysis, which enabled a more detailed documentation of the spatial and temporal variations of the geomorphological processes within the study area. The sequences are located in five different watersheds, and are exposed along incised stream channels. Most of the investigated profiles show the same vertical succession: two different units of fluvial sediments are divided by an intercalated paleosol of regional significance, which forms the base for correlation (marker horizon).

Based on the available age dates, none of the sequences extends into the Pleistocene. The lower part of the sequences covers the Mid-Holocene (~9-4 cal ka BP). It is predominantly composed of fluvial sands and to a lesser degree of silts, which were deposited by an overall aggrading and avulsive fluvial system. Probably comparatively dry and seasonal conditions prevailed. At ~4 cal ka BP, substantially wetter climate conditions caused gradual densification of the vegetation cover, extensive pedogenesis and overall landscape stability in the study area. The onset of renewed sedimentation before ~1 cal ka BP indicates a change within the fluvial system towards increased sediment supplies, probably during an interval of drier and/or more seasonal conditions. Throughout the last millennium and particularly during the last centuries the fluvial system of the study area has undergone the most profound changes of the entire Holocene with intense sedimentation of very coarse sediments and rapid incision.

The recent destabilization of the landscape is interpreted to reflect major changes in discharge and/or sediment supply, which has not been detected elsewhere along the Andean piedmont with comparable intensity. Especially on these short time scales, human impact may have triggered and/or amplified the observed changes and has been reported previously from several locations (Chepstow-Lusty et al., 1996; Balée, 2000; Abbott and Wolfe, 2003; Kulemeyer, 2005; Erickson, 2006; Lupo et al., 2006). Alternatively, shorter-term climate changes such as fluctuations in ENSO frequencies or the LIA have been considered as possible causes (Thompson et al., 1986; Villalba et al., 1998; Maas et al., 1999; Aalto et al., 2003; Liu et al., 2005; Rabatel et al., 2005; Polissar et al., 2006).

6.1.5 PALEOSOL-SEDIMENT-SEQUENCES AT SANTA CRUZ

The investigated paleosol-sediment-sequences at Santa Cruz (chapter 5) are characterized by a high sedimentological, geomorphological and paleopedological complexity. Aside from the sedimentological interpretation of the sequences, thorough field description and micromorphological interpretation enabled the distinction of three genetically different types of paleosols. Based on detailed geochemical and clay mineralogical analysis, different pedogenetic processes could be associated with the individual horizons, allowing interpretation of the paleoenvironmental conditions under which pedogenesis occurred. Particularly soil water flow seems to be the dominant control on type and intensity of pedogenesis.
Based on the chronological data from radiocarbon and OSL dating, the sequences extend back into the Pleistocene. Coarse fluvial sediments and largely restricted soil formation characterize the time > 20 cal ka BP, suggesting generally dry environmental conditions during the last glacial cycle. A subsequent change to wetter conditions is indicated by the formation of well-developed B_t horizons (characterized by clay illuviation) and/or deposition of fine grained overbank deposits. Whether these observations correlate to Lateglacial or Early Holocene records elsewhere can not be decided without improved age control. Renewed deposition of sands by an overall aggrading fluvial system points to higher sediment loads and widespread landscape activity during the Mid-Holocene. Despite active sedimentation processes the frequent incorporation of charcoal from forest fires implies the persistence of a fragmented or somewhat reduced forest cover around Santa Cruz (savannah landscape). The generally dry conditions caused a substantial modification of the pedogenetic processes during the Mid-Holocene towards predominance of ascendant soil water flow and possibly evaporation. Nevertheless, the overall moisture availability in the study area was still high enough to maintain a certain degree of pedogenesis throughout the Mid-Holocene, reflecting the relative proximity of the study area to the Amazon basin as the principal tropical moisture source. In the Late Holocene, the formation of well-developed paleosols and subsequent incision mark the onset of wetter conditions after ~5.5 cal ka BP. Since ~3.8 ka (OSL age) the successive incision was interrupted by several intervals of increased sedimentation and dune formation. These intervals reflect significant changes in runoff and sediment supply, which are probably related to larger-scale

environmental phenomena such as precipitation changes resulting from ENSO variability.
Despite several chronological constraints (Kadereit et al., in preparation), the paleoenvironmental interpretation of the paleosol-sediment-sequences at Santa Cruz is largely corroborated by other regional geomorphological and palynological records (Servant et al., 1981; Barboza et al., 2000; Mayle et al., 2000; Burbridge et al., 2004). Particularly the integration of geomorphological observations provided evidence for significant paleoenvironmental changes in the Eastern Bolivian lowlands during the last two millennia, which had previously been reported only from the Andean highlands (Thompson et al., 1985; Thompson et al., 1986; Maas et al., 1999; Liu et al., 2005; Rabatel et al., 2005).

6.2 OUTLOOK

This thesis shows that detailed geomorphological, sedimentological and paleopedological analysis of paleosol-sediment-sequences, particularly in combination with remote sensing data and the documentation of large-scale geomorphology, offers a variety of insights into the Late Quaternary paleoenvironmental evolution of the Eastern Bolivian lowlands and geomorphological processes involved.

6.2.1 PALEOSOL-SEDIMENT-SEQUENCES

In order to corroborate and refine the results obtained from the analysis of *paleosol-sediment-sequences*, and to fill remaining regional gaps, further sequences at different localities should be studied. Numerous, promising sites – predominantly within incised stream channels – have been discovered along the piedmont and await further field work. Future research should continue to integrate sedimentological and geomorphological methods for a better understanding of the processes involved in the construction of the sequences. This is particularly true for the observation of changes within the recent geological past (< 2 ka). Only the analysis of several sequences within an individual study area can provide reliable conclusions regarding the spatial and temporal variability of the geomorphological processes. Where a sufficient number of paleosols is present, paleopedological methods including determination of total element content and clay mineralogy could be expanded to successively build a data base for regional comparison.
Generally, the correlation and paleoenvironmental interpretation of the sequences largely depend on the establishment of a reliable *chronological framework*. Efforts should continue to integrate several independent methods such as radiocarbon dating and OSL dating. Nevertheless, the application of these methods has shown considerable difficulties as well, suggesting further methodological efforts and care with all interpretations.

6.2.2 PALEOENVIRONMENTAL POTENTIALS IN EASTERN BOLIVIA

Based on the available results from large-scale geomorphological analysis and the extensive field work conducted over the last four years, several topics relevant for paleoenvironmental research are suggested for future studies. Even though these topics do not constitute integral elements of this dissertation, in some cases preliminary results are already available.

Megafan evolution

The detailed geomorphological description of the *fluvial megafans* of the Río Grande and the Río Parapetí (and to a lesser extent the Río Piraí) is regarded a starting point for studies concerned with the medium and long-term fluvial history of these large river systems (Werding, 1977; Horton and DeCelles, 2001; Leier et al., 2005). Two approaches are suggested in order to date and interpret the numerous paleochannels present across the megafans, and to deduce the timing and process rates of river migration and avulsion: inactive riverine dunes are coupled to paleofloodplains, and dating of these features should determine the abandonment of past river channels. Several samples from five localities have been taken for OSL dating and are currently processed. Further downstream, the study of abandoned alluvial ridges by means of coring transects has already shown to produce valuable results for the reconstruction of the more recent fluvial history of these systems. In order to extrapolate these results, which are summarized in a diploma thesis (Ines Röhringer, TU Dresden), focus should be set on the oldest recognizable alluvial ridges and/or paleochannels. Considering the enormous economic damage recently caused by extensive inundations in Eastern Bolivia, an improved understanding of the fluvial processes and their short-term variability should be of substantial importance for natural hazard mitigation (Wachholtz and Herold-Mergl, 2003; Charriere et al., 2004; Gautier et al., 2006)

Aeolian geomorphology

The manifold and widespread existence of inactive and – to a lesser extent – active *aeolian landforms* has long since been reported from several locations throughout the South American lowlands (Tricart, 1974b; Tricart, 1974a; Khobzi, 1981; Klammer, 1982; Santos et al., 1993). A variety of dunes and paleodunes has also been documented from remote sensing and field studies in the Eastern Bolivian lowlands. However, the large complexity of these landforms and the scarcity of chronological data require further research in order to achieve a better understanding of the fluvio-aeolian interactions and their paleoenvironmental significance. In this regard, OSL dating has shown to provide a potential means for the dating of aeolian landforms and the preliminary results suggest very young widespread aeolian activity (~1.5 ka; OSL age) in the Eastern Bolivian lowlands. Currently, further samples from the dune field Lomas de Arena are being processed for OSL dating.

Paleolakes and lakes

In Eastern Bolivia, the large paleoenvironmental potential contained in lake systems has been exploited only in a few cases (Mayle et al., 2000; Burbridge et al., 2004; Whitney and Mayle, 2006). A series of *paleolakes* and presently saline lake basins in the Chaco near the Paraguayan border have shown evidence for both dune formation and higher lake levels in the past. The existence and timing of these geomorphological phases should be identifiable in the lake record as well, provided the logistical problems of field work in these remote areas of the Chaco can be overcome. Similarly, a number of lake basins within the Subandean Ranges are characterized by large, seasonal and inter-annual lake level fluctuations. Preliminary investigations at the Laguna Tatarenda have shown enormous sedimentary variability within these lake systems, which likely reflects recent fluctuations in lake level and sedimentary input.

Neotectonics

Even though not containing direct information on the paleoenvironmental history, detailed analysis of *neotectonic activity* is highly valuable for the interpretation of any sedimentary and/or geomorphological record. Despite the large number of publications concerned with the structural geology of the Cenozoic Andean foreland, knowledge regarding rates and timing of Quaternary tectonic activity is very limited (Lavenu et al., 2000; Hinsch et al., 2003; Mugnier et al., 2005; Strub et al., 2005). The observation of several, apparently young tectonic features along the piedmont might offer the possibility to obtain sedimentary records regarding the timing and rates of local to regional activity.

Archaeology

Very little is still known about the pre-Colombian *archaeology* of the central South American lowlands. The sedimentological records of the paleosol-sediment-sequences, however, have shown to contain archaeological artifacts at several localities. A closer cooperation with archaeologists should therefore provide new insights regarding the timing and type of human presence, and the potential human impact on landscape evolution in the lowlands. Particularly in the context of new findings from the NE Bolivian lowlands, we consider theses issues an essential focus of future geo-archaeological research currently in preparation.

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CLOSING WORDS

"With these manifold and auspicious perspectives, it is my personal and academic concern to express my sincerest hope that this study will stimulate further investigations in the Eastern Bolivian lowlands."

ACKNOWLEDGEMENTS

This dissertation is the outcome of four very intense and fascinating years of scientific research. Thousands of air miles between Europe and South America were necessary to make this academic step, which for me has meant a large step ahead on the path of my life, in which South America has come to play a major role.

First of all, I would like to direct my sincerest thanks to my supervisor *Heinz Veit* for always having supported (and suffered?) my personal and academic enthusiasm for geomorphology. I will always have to consider his perfect timing in proposing a new project dealing with the lowlands in Bolivia a matter beyond coincidence. Throughout my time in Berne, his humor and tolerance as the leader of the paleogroup have motivated my research and sustainably encouraged the realization of my own ideas even beyond this dissertation.

My special thanks are dedicated to *Frank Schäbitz*, who agreed to co-supervise my dissertation. His kind invitation to Bamberg years ago contributed an essential part to my decision to direct my academic focus towards South America!

In South America, I would like to thank *Jaime Argollo* of the Universidad Mayor de San Andres, La Paz, for his hospitality. During many conversations I have enjoyed the shared passion for the Bolivian geomorphology and I am looking forward to continue and intensify our cooperation. I dedicate my sincerest thanks to *Judith Montero Angulo* for her unconditional emotional support, and for sharing the trouble of Bolivian exile. In Santa Cruz de la Sierra I would gratefully like to acknowledge the logistical support by the Museo de Historia Natural NKM, whose staff assisted and sometimes solved my numerous problems with the never-ending paperwork for certificates, conventions and permits wherever they could. In particular, *Maria Esther Montaño* is being thanked for always finding a minute to listen to my broken Spanish. My most profound thanks go to *Bernardo Vogt, Daniel Tristram, Gary Correa Figueroa, Ines Röhringer, Rolando Bustillos and Ueli Reinmann,* who were always reliable and cheerful company as soon as field work was in the air. Without the technical assistance of *Gary Correa Figueroa* and the unbreakable will of *Bernardo Vogt,* it is questionable if I ever would have found my way into and out of the vastness of the Bolivian Chaco.

In Berne, I gratefully appreciate the work of *Basri Qerimi*, who carried out the major part of my laboratory analyses. *Ivan Mercolli* and *Urs Eggenberger* are being thanked for the XRF-, and XRD-measurements and their advice regarding the interpretation of the results. Without the complaisant and patient help of *Basilio Ferrante* and *Hubert Gerhardinger* with software and computer issues the digital illustration and composition of the results would not have been possible.

For many fruitful and inspiring discussions I would like to thank *Christian Neumann-Redlin (Cochabamba, Bolivia), Heiko Prümers (Bonn, Germany), Ignacio "Pana" Sabino (Comodo Rivadavia, Argentina), Julio and Liliana Kulemeyer (Jujuy, Argentina), Lutz Werding (Santa Cruz, Bolivia), Roberto Langstroth (Mexico D.F., Mexico), Rolf Wachholz (Santa Cruz, Bolivia) and Umberto Lombardo (Spoleto, Italy)*.

Having spent a major part of the last four years in GIUB, it is probably needless to mention the importance of my academic family, the working group for "Paleoecology and landscape development" at the Institute of Geography, University of Berne. The *"Paleos"* and all associates between 2003 and 2007 are being thanked for uncountable discussions and conversations, shared laughs and troubles, and probably more than one shared beer. Many of the "Paleos", "Bokus" and "Klimets" have been – and hopefully continue to be – much more than colleagues for me: thank you *Andreas Schellenberger, Anina Schmidhauser, Bernhard Wehren, Christoph Kull, Ingrid Hincapié, Jana Ilgner, Lucien von Gunten, Matthias Retter, Nadja Riedwyl, Roland Zech and Sämi Imhof!*

Last but not least, my dearest thanks are directed to my parents *Friedhelm and Ingrid*, and my brother *Matthias*. I consider their unconditional support, friendship and interest among the most valuable things in my life.

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