6. Summary

6.1 Results

Oligocene-to-Recent, dominantly clastic foreland basin sediments reach up to 7500 m thick in the Chaco Basin. Lithostratigraphic and petrologic characteristics indicate five formations, which include (from base to top) the Petaca, Yecua, Tariquia, Guandacay and Emborozú Formations. Their lithologies, facies, and depositional environments are described by Uba (in revision).

This dissertation focused on addressing several well-defined aspects of the foreland basin development, including Chaco basin sandstone petrography, Yecua Formation depositional environment, Yecua water provenance, and depositional ages.

6.1.1 Sandstone composition, paleocurrents, and provenance

Petaca sandstones are composed of quartzarenites and quartz-rich subarkoses derived from a cratonic provenance. A significant amount of samples has an enriched content of polycrystalline quartz and may reflect a minor influence of quartzose-recycled provenance or sedimentary recycling. The very high ratio of monocrystalline quartz with respect to feldspar argues for intensive abrasive processes within eolian environments or in high-bedload fluvial environments. Paleocurrents indicate a westward-directed transport, which suggests that the underlying Mesozoic source rocks provided much of the detritus (chapter 2).

Yecua sandstones are composed of quartzarenites, subordinate quartz-rich subarkoses, and quartz-rich sublitharenites, indicating a cratonic provenance. The very high monocrystalline quartz content suggests a high degree of sedimentary reworking and only minor recycled fold-thrust belt input. The principal transport direction of the Yecua sandstones is north-to-south, suggesting a Brazilian Shield provenance (chapter 2).

Sandstones of the Tariquia Formation are composed of sublitharenites and quartz-rich subarkoses, reflecting a mixed cratonic-interior and recycled-orogen provenance. Their polycrystalline quartz content is significantly higher compared to that of the underlying formations, suggesting a shift to quartzose recycled fold-thrust-belt provenance. The high quartz-to-feldspar ratio may indicate not only a high degree of sedimentary recycling from erosion and reworking of quartzose sandstones but also a high degree of chemical weathering and long-transport distance. Tariquia paleocurrents indicate a western provenance, which attests a quartzose recycled fold-thrust-belt provenance from the Central Andes (chapter 2).

Sandstones of the Guandacay Formation consist of sublitharenites with reduced monocrystalline and polycrystalline quartz content, indicating a recycled orogen provenance. Their high content of lithic fragments denotes a quartzose fold-thrust provenance. The west-to-east directed paleocurrents also imply a Central Andean fold-thrust belts provenance (chapter 2).

Sandstones of the Emborozú Formation are made up of litharenites to lithic arkoses, indicating a quartzose– to transitional recycled orogen provenance. The trend of decreasing monocrystalline and polycrystalline quartz content, which has been observed from the

Tariquia toward the Guandacay Formations, continues. A dissected magmatic arc provenance is noticeable aside from the fold-thrust belt provenance. The petrological and lithofacies interpretation of the Emborozú Formation suggests short transport from the west, implying the adjacent fold-thrust belt as source (chapter 2).

Foreland basin depozone

Lithostratigraphy and sandstone provenance of the five Cenozoic formations identify the characteristic foreland basin depozones (Horton and DeCelles, 1997).

The base of the Petaca Formation shows evidence of a forebulge depozone with low to zero sedimentation. The upper part of the Petaca Formation exhibits an east-to-west directed transport of underlying Mesozoic material, which indicates deposition along the western flank of the forebulge high toward the foredeep.

The foredeep represents a zone of high sediment accumulation rate and includes the deposits of the Yecua, Tariquia, and the Guandacay Formations. The Yecua Formation shows evidence for a very distal foredeep deposition because of its moderate sedimentation rate, north-to-south longitudinal transport, and Brazilian Shield provenance. The Tariquia Formation occupies a more distal (lower Tariquia) to more proximal (upper Tariquia) foredeep depozone setting, represented by the high sedimentation rate, eastward-directed transport, and Andean fold-thrust provenance with high to moderate quartz content. The Guandacay Formation was deposited proximal to the deformation front because of its increasing coarse-grained clasts and decreasing quartz content within the sandstones.

The Emborozú Formation presents a typical wedge-top depozone with very coarse-grained material and quartzose to transitional recycled orogen source rock.

6.1.2 Depositional environment of the Yecua wetland

Lithology

The up to 250 m thick Yecua Formation is composed of a mudstone-sandstone facies south of 20.5° S, as well as a thinly interbedded mudstone-sandstone facies, a shell hash facies, a coarse-grained sandstone facies, and a vary-colored mudstone facies north of 20.5° S. The mudstone-sandstone facies shows laminated sand sheets and sandy bedform elements, indication an overbank and floodplain depositional environments. The vary-colored mudstone facies shows colors changes from brown and red to grey, green, and yellow. Additionally, thin-bedded sandstone beds occur with sheet-like extent and a thickness of up to 20 cm, as well as very thin beds (up to 5 cm) of bivalves and ostracodes within a marly or sandy matrix. In few outcrops, secondary gypsum occurs. The lithofacies and architectural elements suggest an overbank and floodplain depositional environment with occasional flash flood deposits as well as ponds or even hypersaline lakes. The coarse-grained sandstone facies consists of calcareous and quartzose sandy material. The beds show low-angle cross-stratification, representing high-energy conditions that are indicative for upper foreshore beach depositional environment. The shell-hash facies includes a microfossil-dominated, up to 30 cm thick bed that bears bivalves, ostracodes, and foraminifera within a calcareous matrix. The ecology of the microfossils displays a shallow marine environment. The thinly interbedded mudstone-sandstone facies is exposed in few outcrops and is composed of thinly interbedded sandstone and mudstone beds with planar, flaser, wavy, and lenticular stratification, indicating a low-energy tidal depositional. The facies north of 20.5° S document a coastal environment with shallow marine, tidal and shoreline environment, as well as overbank and floodplain deposits.

The stratigraphy of the Yecua Formation and its vertical and lateral facies change indicates a wetland environment with decreasing lacustrine and marine influence to the south, and a decreasing marine influence to the west. The southern part of the Subandean-Chaco region was under the influence of floodplain to fluvial overbank deposition coastal environments with backshore, shoreline, tidal, lacustrine and shallow marine facies dominated in the north. The differentiation between lacustrine and shallow marine shelf environment is based on the ecology of several microfossil taxa (bivalves, ostracodes, and foraminifera; chapter 3).

Water fingerprinting

Stable isotopes (strontium, oxygen, and carbon) of the shallow marine foraminifera and ostracodes reflect a mixing water system between dominant cratonic water runoff, moderate Andean water, and subordinate marine contribution. Based on the ecology of the microfossils, we propose that the primary marine isotopic composition of the microfossil calcite shells had been modified after having been exposed to a terrestrial water system that consisted of Andean and cratonic water runoff. Possibly, a very short-lived marine incursion transgressed into a long-lived lacustrine or wetland environment, which was supported by Andean and cratonic water runoff. The microfossils died after regression and were incorporated in non-marine shales and marls where foraminifera and ostracode shells acquired the isotopic composition of the surrounding water system during early diagenesis (chapter 4).

The Yecua Formation compared to other Miocene foreland basin deposits

Similar to the short marine incursion of the middle to late Miocene Yecua Formation, Miocene marine transgressions are also known from other Andean retroarc foreland basins. North and southeast of the Chaco Basin, marine facies occurs within the northern Amazon foreland basin (including the Madre de Dios basin) and the southern Paranense Sea (known from northeastern Argentina and Uruguay), respectively. We suggest that a hydrological connection to the Amazon foreland basin via the Beni Basin and the Madre de Dios basin is likely. Several authors (e.g. Hoorn, 1994a; Vonhof et al., 2003) described a development of the marine facies within the Amazon Basin similar to the Yecua Formation: short, facies-restricted, and shallow marine. In contrast, deposits of the Paranense Sea represent a shallow but widespread and long-lived marine incursion (e.g. Aceñolaza and Sprechmann, 2002). The extension of the marine facies to southern Bolivia suggests a connection to the north. Alternatively, the marine facies of the Paranense Sea might have been established during a short-lived connection toward the northern Chaco Basin via the Paraguayan Chaco Plain.

6.1.3 Chronology of the Subandean-Chaco Basin

A compilation of new and existing radiometric and biostratigraphic age data from the five Cenozoic formations of the Subandean-Chaco Basin suggests diachronous deposition resulting from eastward progradation of the foreland basin system throughout the eastern backarc as postulated by Sempere et al. (1990), Husson and Moretti (2002), DeCelles and Horton (2003), Echavarria et al. (2003), McQuarrie et al. (2005). However, our results suggest that the eastward progradation also varies between north and south, consistent with the variable shortening events and rate in the central Andean backarc. The variable shortening events led to the development of north-to-south decreasing depositional age for each deformation (chapter 5).

Our results implicate some important consequences: the diachronous ages of the west-east as well as north-south over several million years. Therefore, correlations of stratigraphic and structural profiles must be treated with caution.

Seismic interpretation has to proceed with caution because seismic facies may not be equal to lithostratigraphic facies (which defines the formation). The seismic facies can be traced through the basin and may represent a single major sedimentation event, whereas the lithostratigraphic facies change with distance to the deformation front.

6.2 Open questions

1. How did the paleosols of the Petaca Formation develop? What is their mineral composition and what is the implication of the mineral composition? Do the composition, thickness, and age of the paleosols change throughout the Subandean-Chaco Basin?

2. How is the lithostratigraphy of the Cenozoic sediments developed in the central and eastern Chaco Basin? Can lithostratigraphic units of the Subandean-Chaco Basin be correlated to the east (Paraguay)? Present the seismic stratigraphic units of the Guandacay and the Emborozú Formations a forebulge facies in the very eastern part of our study area?

3. Could a detailed magnetic-polarity stratigraphy of the Cenozoic sediments within the southern Bolivian Subandean-Chaco Basin confirm the diachronous ages as documented in chapter 5?

4. How will the new ages modify the detailed subsidence pattern analysis?

5. How will the two tAo –models along 22° S and 20° S look like/differ? What does this different development indicate regarding foreland basin development?