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Depositional setting of the Middle to Late Miocene Yecua Formation of the Chaco Foreland Basin, southern Bolivia

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Abstract

Middle–Late Miocene marine incursions are known from several foreland basin systems adjacent to the Andes, likely a result of combined foreland basin loading and sea-level rising. The equivalent formation in the southern Bolivian Chaco foreland Basin is the Middle–Late Miocene (14–7 Ma) Yecua Formation. New lithological and paleontological data permit a reconstruction of the facies and depositional environment. These data suggest a coastal setting with humid to semiarid floodplains, shorelines, and tidal and restricted shallow marine environments. The marine facies diminishes to the south and west, suggesting a connection to the Amazon Basin. However, a connection to the Paranense Sea via the Paraguayan Chaco Basin is also possible.

Keywords: Chaco foreland Basin; Marine incursion of Middle–Late Miocene age; Yecua Formation

1. Introduction

A string of extensive Tertiary foreland basins east of the Andes is interpreted to record Andean shortening, uplift, and lithospheric loading (Flemings and Jordan, 1989). Among these foreland basins, the Chaco Basin in southern Bolivia formed in front of the widest extension of the sub-Andean belt (Dunn et al., 1995; Husson and Moretti, 2002) and is therefore particularly well suited to record central Andean tectonics and South American paleogeography (Fig. 1).

In the central Andes, upper crustal shortening in the Eastern Cordillera and the development of the sub-Andean fold-and-thrust belt started during the Oligocene/Miocene (Isacks, 1988; Gubbels et al., 1993; Kley et al., 1997; Müller et al., 2002). At the same time, tectonic subsidence increased in the Chaco Basin (Gubbels et al., 1993). Combined with a eustatic sea-level highstand between the Oligocene and Late Miocene (Aceñolaza and Sprechmann, 2002), shallow restricted marine incursions transgressed into southeastern Bolivia and are represented there by the Middle–Late Miocene Yecua Formation (Marshall and Sempere, 1991; Marshall et al., 1993).

Marine incursions during the Miocene also are known from several intracontinental basins in South America (Hoorn, 1994a; Alonso, 2000). In the Amazon Basin, several short marine incursions appeared in the Miocene Solimões and Pebas formations in Brazil, Peru, Ecuador, Columbia, and Venezuela (Hoorn, 1994a,b; Räsänen et al., 1995). The southernmost extension has been described within the Madre de Dios Basin along the Peruvian–Bolivian border (Räsänen et al., 1995).

South of the Chaco foreland Basin, the Miocene Paranense Sea covered a wide area in northern Argentina and Uruguay (Aceñolaza and Sprechmann, 2002). The westernmost extension of the Paranense Sea is documented in the Middle Miocene Anta Formation (Galli et al., 1996; Reynolds et al., 2000). In northeastern Argentina, the Middle Miocene–Pliocene Paraná Formation built marine deposits that belong to the Paranense Sea (Garrasino and Vrba, 2000). Finally, the Middle–Late Miocene Camacho Formation represents the Paranense Sea in Uruguay (Sprechmann et al., 2000).

This article describes the depositional settings of the Yecua Formation in the northern part of the Chaco foreland Basin on the basis of new lithological and paleontological data. We also compare the Chaco Basin with the Neogene depositional systems of several adjacent basins.

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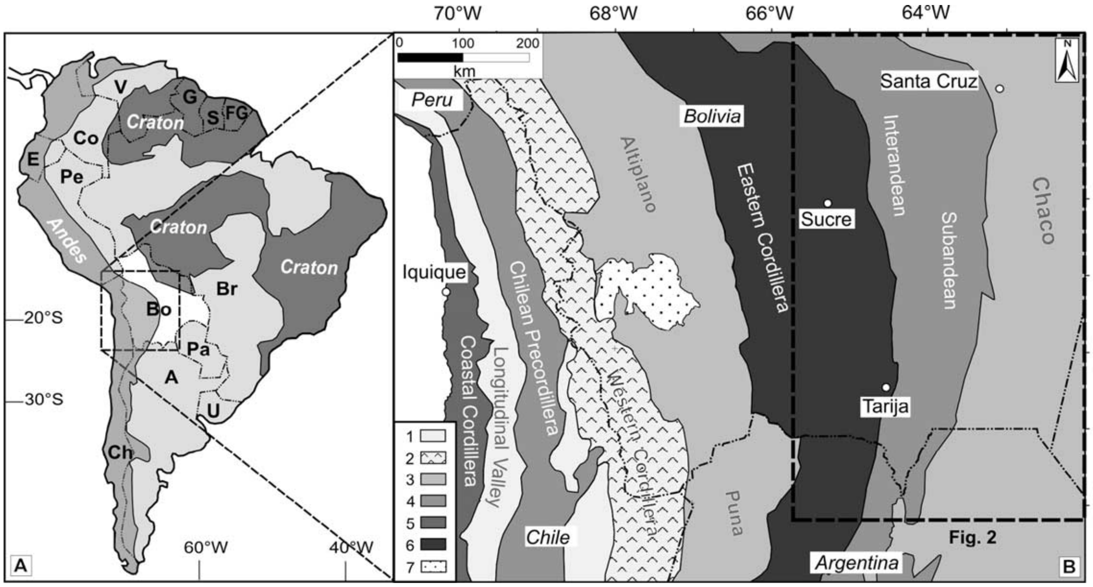

Fig. 1. (A) Map of South America, including the major geological provinces (Andes, sedimentary intracontinental basins, and cratons) and countries. (A = Argentina, Bo = Bolivia, Br = Brazil, Ch = Chile, Co = Columbia, E = Ecuador, FG = French Guiana, G = Guyana, P = Peru, S = Suriname, V = Venezuela). (B) Geologic map of the central Andes, modified after Scheuber and Reutter (1992), including international borders and major geological provinces. The Chaco Basin is located immediately east of the Andean orocline. Numbers refer to rock units: (1) Quaternary sediments, (2) Quaternary volcanism, (3) Tertiary sediments, (4) Cretaceous–Miocene sediments, (5) Silurian–Miocene rocks, (6) Precambrian–Ordovician rocks, and (7) Salar de Uyuni. Inset shows the location of the study area (Fig. 2).

2. Regional geology

The Chaco Basin is located east of the sub-Andean belt between 18° and 22°S (Dunn et al., 1995; Husson and Moretti, 2002). To the south, the basin grades into the thick-skinned Santa Barbara system; to the north, it transfers to the Beni Basin north of the Bolivian orocline near Santa Cruz (Figs. 1 and 2). The basin reaches an overall east-west extension of 150 km and approximately 400 km north–south (Fig. 2).

The study area is limited to the westernmost part of the Chaco Basin along the foothills of the sub-Andean belt, where the Yecua Formation is exposed in streambeds and several road cuts. To the east, the Cenozoic strata are covered by Holocene sediments. Ten measured stratigraphic sections between Santa Cruz and Boyuibe are used to describe and interpret the depositional environment of the Yecua Formation along the flanks of Serrania Borebigua, Serrania Charagua, and Serrania Mandeyapecua (Fig. 2).

3. Tectonics background

The evolution of the Andes is associated with the subduction of the Nazca plate along the convergent, western margin of the South American continent. The central Andes between 15° and 27°S (Isacks, 1988) resulted from complex horizontal shortening and crustal thickening processes during the Cenozoic (Isacks, 1988; Gubbels et al., 1993). The resulting loading of the central Andes onto the South American continent caused the development of retroarc foreland basins (Horton and DeCelles, 1997).

Different models exist for the development of the backarc region in the central Andes. Various authors have suggested a two-stage evolution (e.g. Isacks, 1988; Gubbels et al., 1993). In the first, Late Oligocene–Miocene stage, crustal shortening and plateau uplift were restricted to the Altiplano and the Eastern Cordillera. At that time, the region of the future sub-Andean belt and the Chaco Basin formed a broad foreland basin with very low sedimentation rates. In the second stage, beginning approximately 10 Ma ago, shortening propagated eastward into the foreland of the plateau. A broad, thin-skinned fold-and-thrust belt developed on the Brazilian lithosphere (Gubbels et al., 1993; Kley et al., 1997; Müller et al., 2002).

Other authors (DeCelles and Horton, 2003) postulate a continuous eastward propagation of a deformation front, which they deduce from the sedimentary record within the Andean mountain belt. In particular, a synorogenic foreland basin system with distinct depozones is inferred to have migrated from the Western Cordillera to its recent position in the Chaco foreland Basin since the Paleocene (Horton et al., 2001).

4. Stratigraphy of Cenozoic sediments within the Chaco Basin

Sedimentation related to the Chaco foreland Basin started in the Late Oligocene (27 Ma) and is ongoing (Sempere et al., 1990; Marshall et al., 1993). During this time, up to 6500 m thick clastic sediments were deposited, representing mainly alluvial and fluvial facies (Dunn et al., 1995). The sedimentary succession conventionally is subdivided into five formations (Fig. 3). The stratigraphy of the Chaco Basin still is based mainly on lithostratigraphy because of the paucity of radiometrically datable rocks.

The Late Oligocene–Middle Miocene (27–10 Ma) Petaca Formation (Sempere et al., 1990; Marshall and Sempere, 1991) overlies Mesozoic strata with a distinct angular unconformity and is characterized by well-developed, commonly reworked calcrete

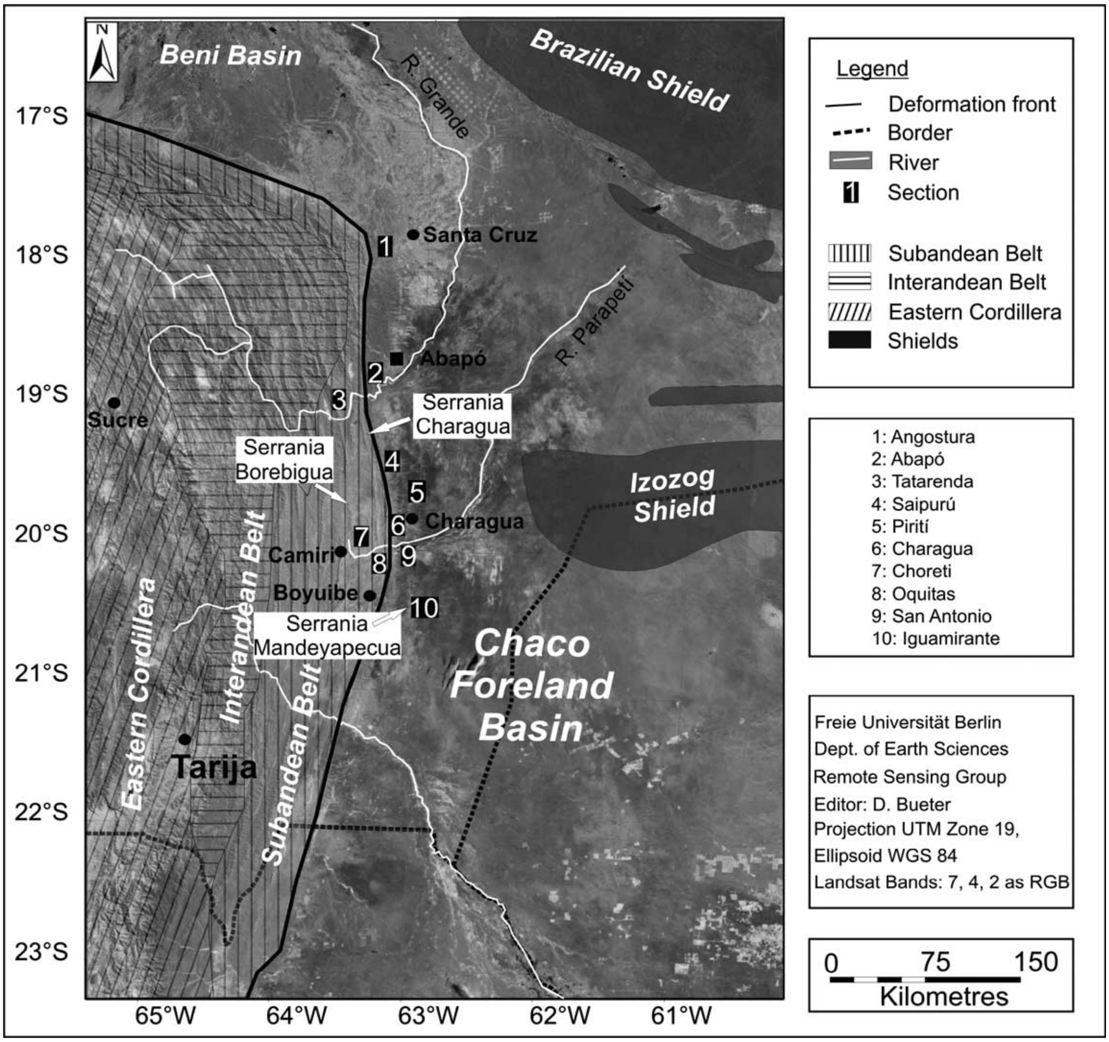

Fig. 2. Morphotectonic units of Bolivia (after Pareja et al., 1978), showing the study area along the sub-Andean foothills.

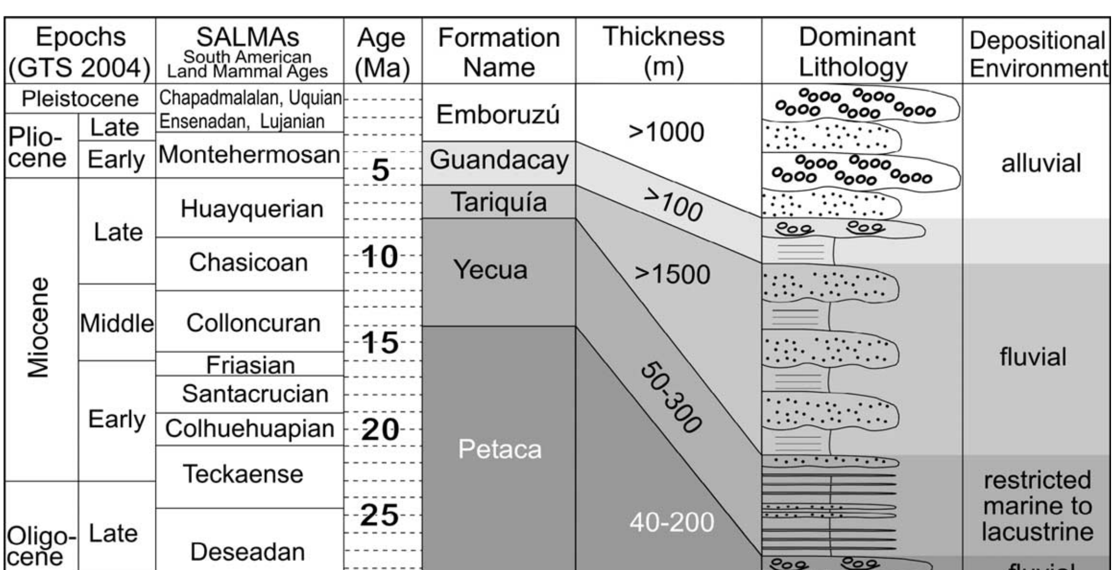

Fig. 3. Simplified stratigraphy of the Tertiary Chaco foreland Basin incorporating age estimates of Marshall and Sempere (1991), Gubbels et al. (1993), Marshall et al. (1993), Moretti et al. (1996), and data presented herein.

paleosols and subordinate fluvial channel systems. Numerous calcrete horizons are interbedded with thin sandstone beds or appear reworked as clasts in shallow channels of ephemeral streams. The sedimentary features indicate that the Petaca Formation was deposited in either the forebulge depozone of the foreland basin system, an area of nondeposition or very low sedimentation rates, or within the back-bulge depozone, an area of very low sedimentation rates (Horton and DeCelles, 1997; DeCelles and Horton, 2003). The age of the Petaca Formation is constrained by the biostratigraphic record. The notohippid cf. *Rhynchippus* found at the base of the Petaca Formation limits the start of sedimentation to the Deseadean (Late Oligocene/earliest Miocene) (Sempere et al., 1990; Marshall and Sempere, 1991). Marshall et al. (1993) describe the armadillo *Vassallia minuta*, of Chasicoan–Montehermosan age (Middle/Late Miocene–early Pliocene), at the top of the Petaca Formation.

Marshall et al. (1993) estimate the age of the overlying Yecua Formation to be 10–8 Ma because of the occurrence of the litoptern cf. *Theosodon* sp. of Colhuehiapian and Chasicoan (early–Late Miocene) age. Therefore, Yecua sedimentation must have begun in the Late Miocene. However, new biostratigraphic results suggest a Middle–Late Miocene age of 14–7 Ma. Results of absolute age-dating techniques, such as magnetostratigraphy or isotope analysis, have not been published yet for the Chaco Basin. The lithological change from the Petaca to the Yecua is clear, with the occurrence of green, grey, red, brown, and black mudstone, white marls, shell coquinas, plant hash, ooids, and secondary gypsum. The data suggest a restricted marine and/or lacustrine environment for the Yecua Formation. Deposition probably took place in the distal foredeep depozone of an underfilled foreland basin system with a higher subsidence rate than sedimentation rate (Horton and DeCelles, 1997; DeCelles and Horton, 2003).

The contact between the Yecua and overlying Tariquia formations is transitional. The Tariquia consists of channelized red sandstones, interbedded with red to brown mudstones, several km thick. It represents a fluvial environment dominated by mixed-load transport in the foredeep zone. Fish fossils at the base of the Tariquia Formation indicate a Late Miocene age (Chasicoan–Huaquerian) (Marshall and Sempere, 1991). Moretti et al. (1996) postulate an age of 8–6 Ma for the Tariquia Formation.

Conglomeratic material occurs in the upper Miocene–Lower Pliocene (6–3.3 Ma) Guandacay Formation. Finally, conglomeratic material dominates the upper Pliocene–Holocene (<3.3 Ma) Emborozú Formation (Gubbels et al., 1993; Moretti et al., 1996), which indicates the increasing proximity of the prograding deformation front.

5. Stratigraphy of the Yecua Formation

Ten sections, which we describe in the following paragraphs, were selected for detailed study in the Yecua Formation (Fig. 2).

5.1. Angostura section

The Angostura section along the Rio Piray, southwest of Santa Cruz, exposes the Yecua Formation in two outcrops, each of 30–35 m stratigraphic thickness. Calcrete nodules in the sandy-shaly sediments of the Petaca Formation gradually diminish toward the brown, red, and yellow mudstone package that marks the base of the Yecua Formation. The mudstones show abundant horizontal laminations and mudcracks. They are interbedded with very thin, oscillation-rippled, coarse-grained, poorly sorted, white calcareous sandstone. Several planar shell hash coquinas, up to 30 cm thick, include fragments of bivalves, ostracodes, and planktonic foraminifera in a calcareous matrix (Fig. 4). The stratigraphic higher outcrop is dominated by red mudstone, interbedded with numerous bivalves and ostracode hash coquinas. The coquinas are less than 5 cm thick but show excellent lateral extent (Fig. 4). Networks of secondary gypsum occur throughout the section but are more common near its top. The transition to the overlying Tariquia Formation is not exposed (Fig. 5).

Bivalves and ostracodes of the Angostura section are poorly preserved, leaving little room for detailed identification. However, some ostracodes have been identified as *Cyprideis aff. torosa*, *Cyprideis aff. amazonica*, and *Cyprideis aff. truncata* in the lower part of the section. The genus *Heterocypris* is common in the upper part. Foraminifera of this section belong to benthic families. The samples reveal

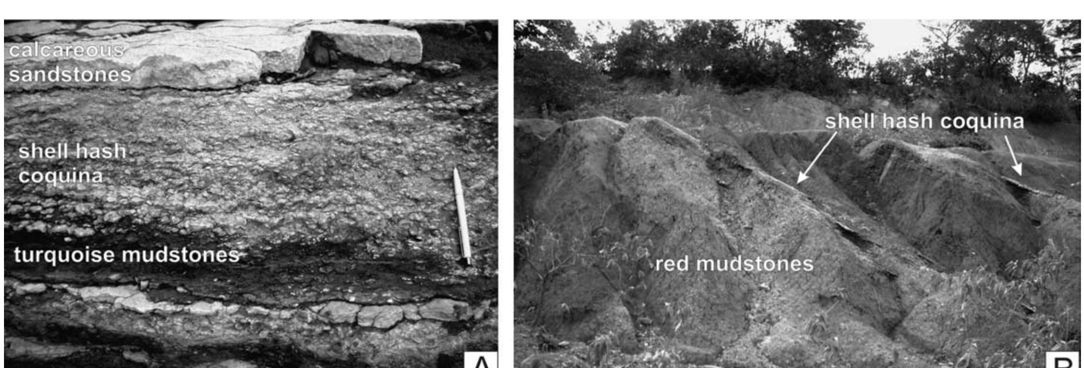

Fig. 4. Outcrop photographs of the Yecua Formation at the Angostura section. (A) Shell hash coquina of the lower part, pencil is 15 cm long. (B) Dominantly red mudstone interbedded with thin planar shell hash coquinas of the upper part, outcrop height approximately 7 m.

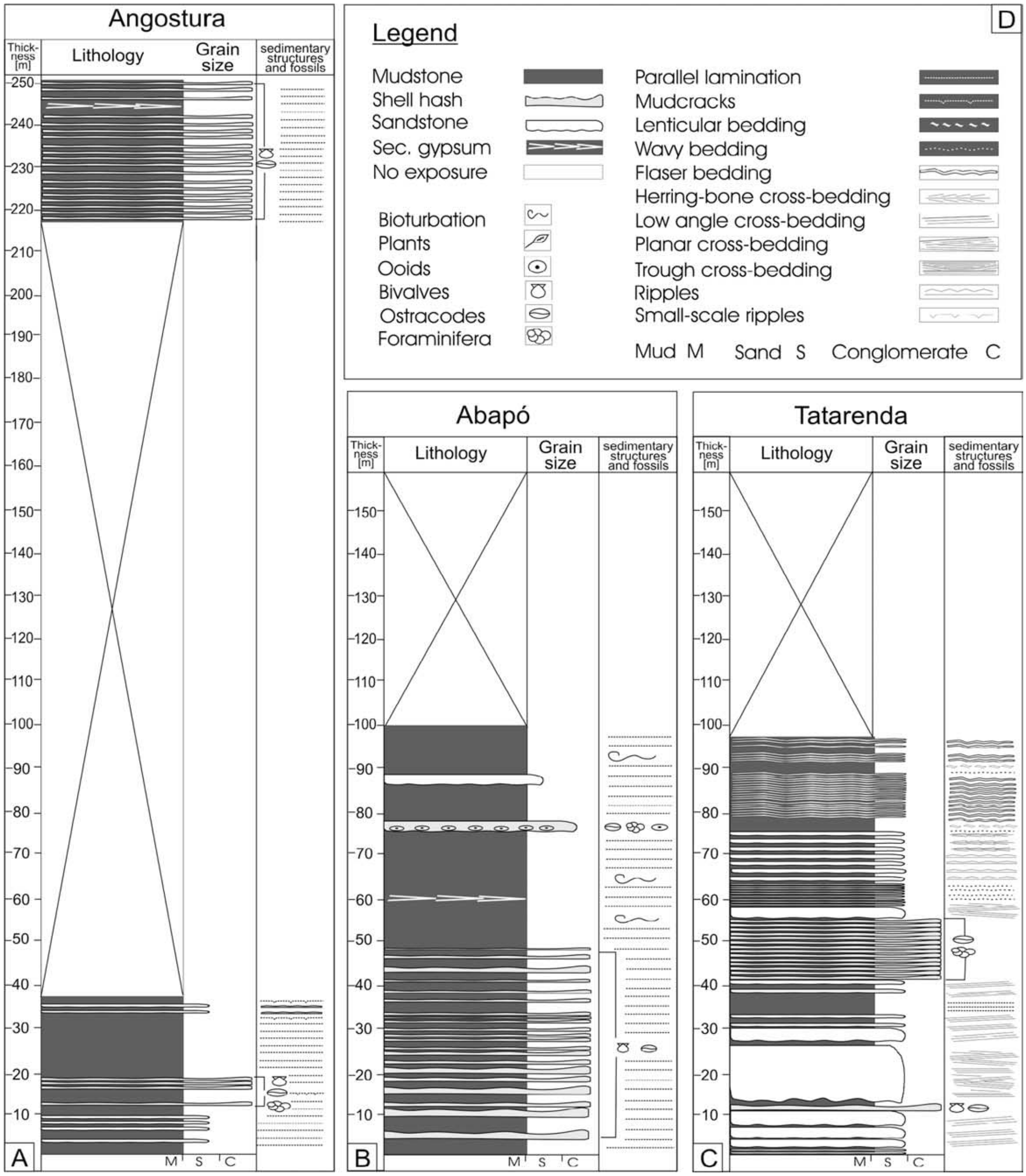

Fig. 5. Lithostratigraphic column of the sections (A) Angostura, (B) Abapó, and (C) Tatarenda. (D) Column legend is the same for Figs. 8 and 9.

Anomalinoides cf. *salinasensis*, *Cibicidoides* cf. *cushmani*, *Cibicidoides aff. mckannai*, and *Gyroidina rosaformis*.

5.2. Abapó section

The Abapó section is situated along the banks of the Rio Grande, approximately 5 km west of Abapó village, and exposes gently dipping strata of the Yecua Formation for approximately 100 m. Contacts with the underlying Petaca and overlying Tariquia formations are not exposed. The lower half of the outcrop is dominated by numerous cycles of 20–40 cm thickness, each composed of (from base to top) laminated reddish to greenish mudstones; fine-grained, horizontally laminated and rippled sandstone; and a thin bivalve and ostracode coquina. The upper half of the section exposes bioturbated, red, laminated mudstone, which is rarely interbedded with secondary gypsum or calcarenitic, coarse-grained ooid sandstones. These sandstones contain ostracodes and foraminifera (Figs. 5 and 6).

Bivalves of the Abapó section are too poorly preserved to allow identification at the genus or species level. Ostracodes show a low biodiversity and are identified as *Cyprideis aff. torosa, Cyprideis aff. truncata*, and *Cyprideis aff*. amazonica. Foraminifera include *Holmanella valmonteensis*, *Nonionella miocenica*, *Pseudoparella californica*, *Hansenisca multicamerata*, and *Holmanella baggi*.

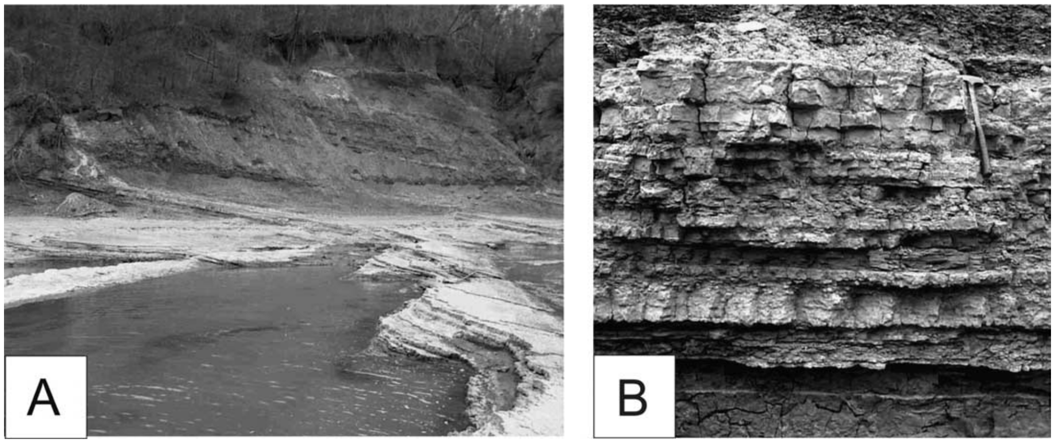

Fig. 6. Outcrop photographs of the Yecua Formation at Abapó. (A) Numerous cycles of reddish to greenish mudstones, fine-grained sandstone, and a thin coquina. (B) Ooid-bearing sandstone and green to red mudstone.

5.3. Tatarenda section

The Yecua Formation in Tatarenda, 40 km west of Abapó, is exposed along the Rio Grande for approximately 100 m. The contact between the Petaca and Yecua formations is marked by greyish-white, coarse-grained, low-angle, cross-stratified, calcareous sandstones interbedded with brown, red, and yellow mudstone and rare bivalve fragment coquinas. Approximately 40 m above the base, numerous sandy coquinas of bivalves, ostracodes, and foraminifera occur, interbedded with greenish-grey to black mudstones. Coquina components show hydrodynamic, stable, convex-up orientation, which suggests a tempestitic origin. The uppermost 50 m of the section show thinly bedded mudstone and sandstone in flaser, wavy, and lenticular bedding with abundant small-scale erosional channels 5–15 cm deep, herringbone cross-stratification, convolute bedding, channel-margin slumping, and abundant small-scale symmetrical ripples (Figs. 5 and 7).

Among the shell hashes, low taxonomic diversity is evident. The lower part of the section contains poorly preserved bivalves and ostracodes. *Tellina* sp. may be presented in the bivalves' shell hash. Ostracodes resemble *Cyprideis* sp. Near the top of the section, some bivalves were tentatively identified as *Neocorbicula* sp. and other genera of the family Corbiculidae.

5.4. Saipurú section

The Saipurú section at the eastern flank of the Serrania Charagua, approximately 40 km north of Charagua, exposes the Yecua Formation in the Rio Saipurú for approximately 75 m in two outcrops. Basal and upper contacts are not exposed. Greenish-grey mudstones and shell hash coquinas up to 1 m thick, containing ostracodes and bivalve fragments, dominate the lower part of the section. Upward, very coarse-grained, moderately sorted, calcareous, and quartzose sandstones are amalgamated to a unit of approximately 10 m and contain low-angle cross-beds with shell hash. The top of the section shows wavy and lenticular bedding in greenish mudstones (Fig. 8).

Because of their poor preservation, fossil specimens could not be identified at the species level. Some bivalves resemble *Tellina* sp.; ostracodes resemble *Cyprideis* sp.

5.5. Pirití section

The Pirití section, 15 km northeast of Charagua, exposes approximately 85 m of the Yecua Formation. The transition from the fine-grained, reddish, pedogenic sandstone of the Petaca Formation is marked by thick-bedded, fine-grained, well-sorted sandstone showing large-scale cross-beds at the base of the Yecua. In the next 20 m, the dominant lithology changes to brown, red, and yellow mudstones, interbedded with very thin calcareous sandstones and bivalve-bearing shell hash coquinas. In the upper part of the section, secondary gypsum occurs in red laminated mudstone. The Yecua–Tariquia contact is not exposed (Fig. 8).

Some bivalves resemble the family Corbiculidae.

5.6. Charagua section

Approximately 75 m of the Yecua Formation crop out along the ephemeral Rio Charagua, just south of Charagua.

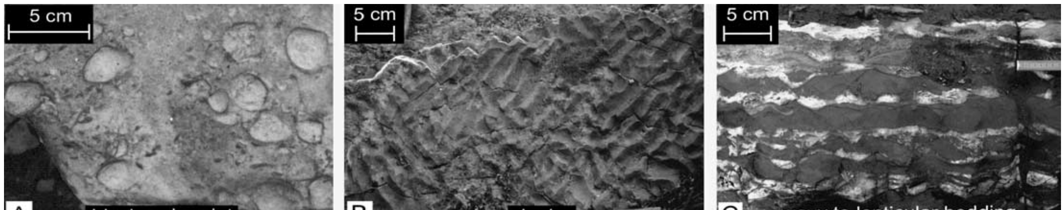

Fig. 7. Outcrop photographs of the Yecua Formation at Tatarenda. (A) Imprints of bivalves near the top of the section. (B) Crossing ripples near the base of the section. (C) Wavy to lenticular bedding near the base of the section.

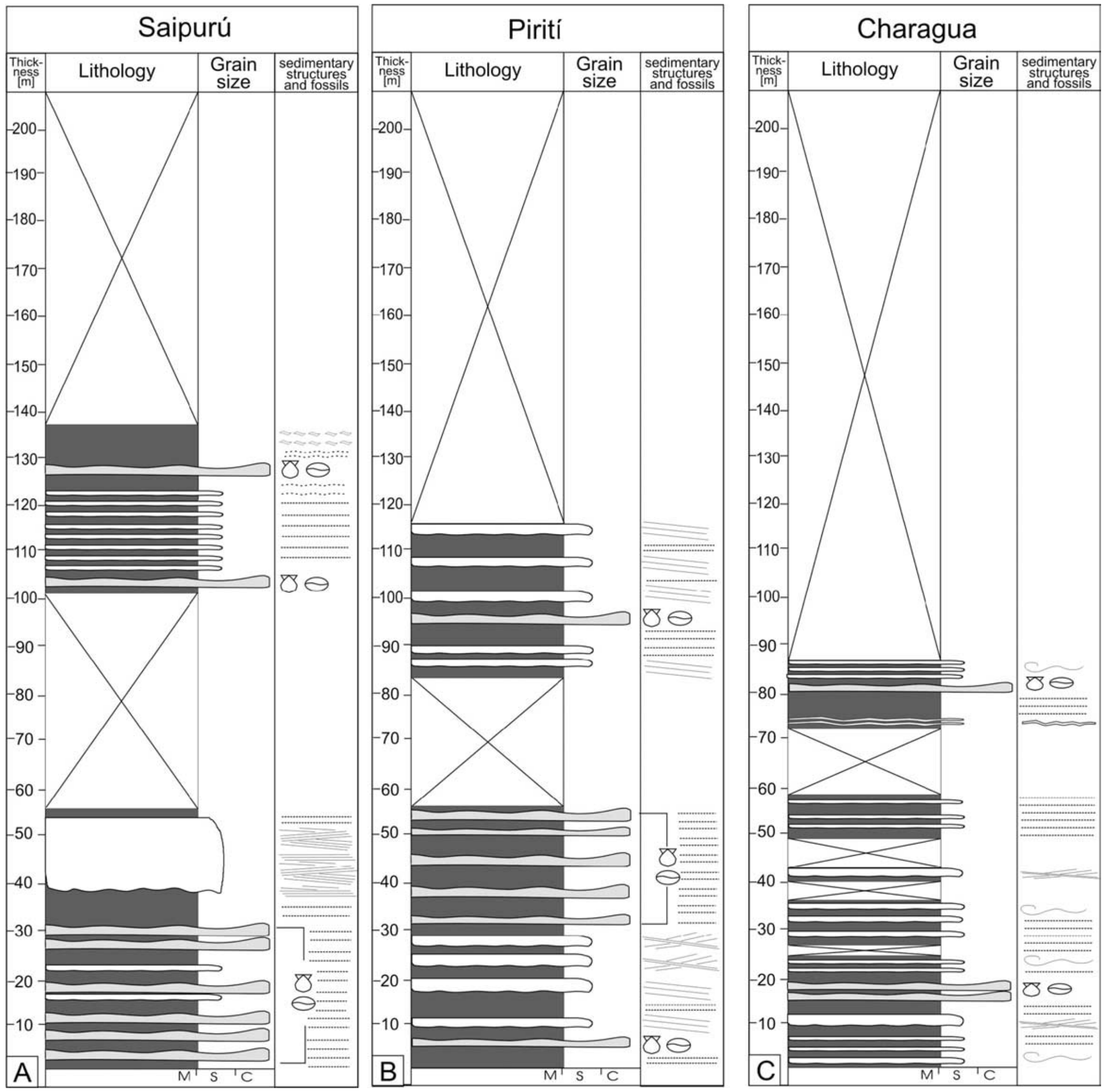

Fig. 8. Lithostratigraphy of sections (A) Saipurú, (B) Pirití, and (C) Charagua. For legend, see Fig. 5.

The Petaca–Yecua contact is not exposed. The base of the outcrop is characterized by laminated greenish-grey mudstones, interbedded with coarse-grained, poorly sorted calcareous sandstones and a few thin coquinas with poorly preserved bivalve fragments and ostracodes. Parallel cross-bedding, oscillation and climbing ripples, and burrows are common. Upsection, the brown, red, and yellow mudstone shows sedimentary structures including flaser, low-angle, and trough cross-bedding with a high degree of bioturbation. The Yecua–Tariquia contact is not exposed (Fig. 8).

Some bivalves resemble *Tellina* sp.; ostracodes resemble *Cyprideis* sp.

5.7. Choretí section

The westernmost section along the Rio Parapetí, a few km north of Camiri, shows approximately 200 m of poorly exposed Yecua Formation with transitional Petaca–Yecua and Yecua–Tariquia contacts. The Yecua Formation mostly consists of red to brown mudstones, interbedded with thin beds of medium-grained, well-sorted, yellow quartzose sandstone and secondary gypsum that forms thin veins. Ripples and trough and parallel cross-bedding are the principal sedimentary structures in this apparently fossil-free section (Fig. 9).

5.8. Oquitas section

The Oquitas section is situated approximately 30 km east of Camiri along the Rio Parapetí. The section exposes approximately 200 m of the Yecua Formation, with transitional contacts at the base and top. Red, apparently massive, mudcracked, and bioturbated mudstones of the Yecua Formation are interbedded with thin, laterally extensive, coarse-grained, poorly sorted, granule-bearing quartzose sandstones with erosional bases, ripples, and small-scale cross-beds. Thin-shell hash coquinas and secondary gypsum, developed as veins, occur near the top (Fig. 9).

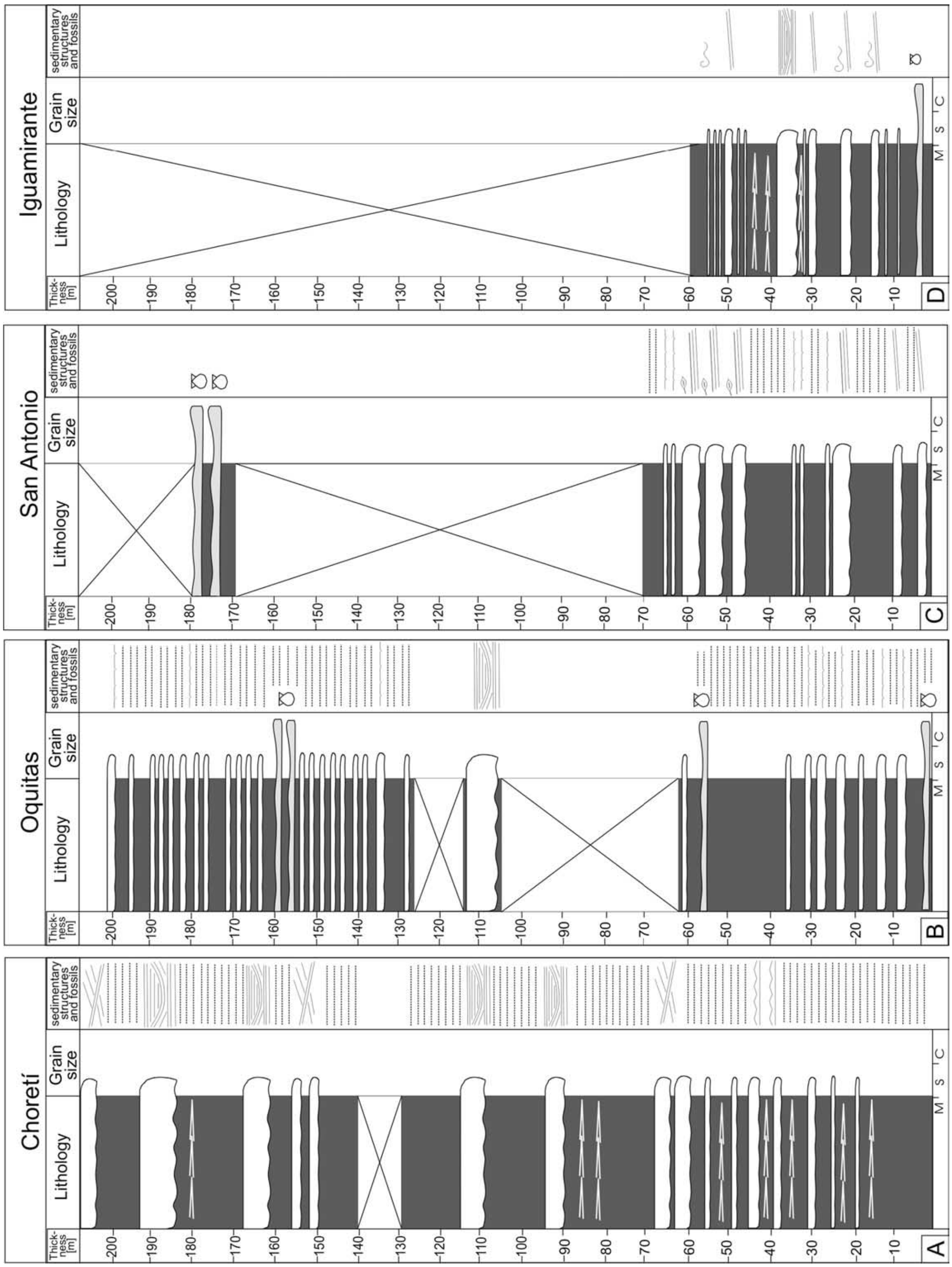

Fig. 9. Lithostratigraphy of sections (A) Choretí, (B) Oquitas, (C) San Antonio, and (D) Iguamirante. For legend, see Fig. 5.

The bivalves resemble *Neocorbicula* sp. and other genera of the family Corbiculidae. Ostracodes have been designated as *Cyprideis* sp. and *Heterocypris* sp.

5.9. San Antonio section

The San Antonio section constitutes the easternmost outcrop along the Rio Parapetí in the foothills of the Serrania Charagua. The base of the Yecua Formation, transitionally overlying the pedogenic redbed Petaca Formation, is dominated by red mudstones interbedded with thin beds of medium-grained, moderately sorted, plant hash-bearing, channelized sandstone. The top of the Yecua Formation consists of greenish mudstone in which bivalve fragments occur. The shell hash coquinas reach up to 1 m thickness. The bivalves show a low taxonomic diversity. However, poor preservation does not allow for a more detailed identification. The Yecua–Tariquia contact is not exposed (Fig. 9).

5.10. Iguamirante section

The Iguamirante section is situated in an ephemeral stream bed, 25 km east of Boyuibe, and exposes approximately 55 m of the Yecua Formation. The basal contact with the Petaca Formation is sharp. Green mudstones are interbedded with thin, very coarse-grained, poorly sorted, white calcareous sandstones with parallel, small-scale trough and low-angle cross-bedding. Higher up, bioturbated, fossil-free red mudstones with rare secondary gypsum along mostly bedding-parallel veins increase in abundance and dominate the section after 15 m. The base of the Tariquia Formation is defined by the first appearance of redbed fluvial channels (Fig. 9).

The fossiliferous beds contain bivalves (*Tellina* sp.) and ostracodes (*Cyprideis* sp.).

6. Lithofacies interpretation

The sedimentary structures and textures of the Yecua Formation suggest two dominant depositional systems: a semiarid, mostly low-energy floodplain and a coastal facies represented by tidal, high-energy shoreline, and shallow marine deposits. We present detailed descriptions and interpretations of these lithofacies in the following sections.

6.1. Semiarid coastal floodplain

Reddish to pale turquoise and green-grey, thinly laminated to occasionally massive mudstones are commonly interbedded with very thin ($\leq$1–4 cm) 'stringer' beds of fine-grained quartzose sandstone. This facies is well exposed in the Angostura section. Centimeter-sized iron oxide concretions appear randomly distributed throughout the mudstones, and secondary gypsum seems restricted to the brown, red, and yellow mudstone package, which suggests that migration of $CaSO_4$-bearing fluids was limited to the dissolution of gypsum nodules in a semiarid, subaerial floodplain environment. The processes that resulted in the deposition of these sediments must have been dominantly low energy. Interbeds of rare cm-thick shell hash coquinas indicate punctuated, rare high-energy events.

The coquinas contain bivalve fragments and rare ostracodes, with very low taxonomic diversity. Some bivalves resemble the widespread family Corbiculidae, which occurs in many freshwater systems in South America, though certain species tolerate a wide range of salinities (Meister, 1997). However, the appearance of the genus *Neocorbicula* sp., indicative of freshwater systems, suggests the presence of lacustrine facies in the backshore environment. The ostracode genera *Heterocypris* and *Cyprideis* have been documented in floodplain facies. Meisch (2000) describes species of the genus *Heterocypris* with variable salinity tolerances that mostly live in freshwater and brackish environments. *Cyprideis* is a typical brackish water genus, preferring a meso- to polyhaline environment, but it may tolerate marine or even hypersaline environments. Thus, the genus can occur in places that experience mixohaline influence (Meisch, 2000) such as lagoons, marshes, and estuaries (Fig. 10).

6.2. Tidal facies

This lithofacies mostly consists of grey mudstones interbedded with small-scale erosional channels. The channels are filled with fine-grained sandstones that show herringbone cross-stratification, convolute bedding, channel-margin slumping, and abundant small-scale symmetrical ripples. The sedimentary structures suggest a cut-and-fill environment with plane bed, flaser, wavy, and lenticular bedding. The Tatarenda section represents these lithologies and structures best. Sediments were deposited under periodically reversing currents of slow to intermediate flow velocity. Deposition took place in a mostly aggradational but locally erosional regime through broad, flat channels that collectively suggest a low-energy tidal environment.

6.3. Shoreline facies

Coarse-grained calcareous to quartzose sandstones dominate this facies and commonly contain approximately 20–40% shell hash. The beds show well-developed low-angle cross-bedding that represents high-energy conditions indicating an

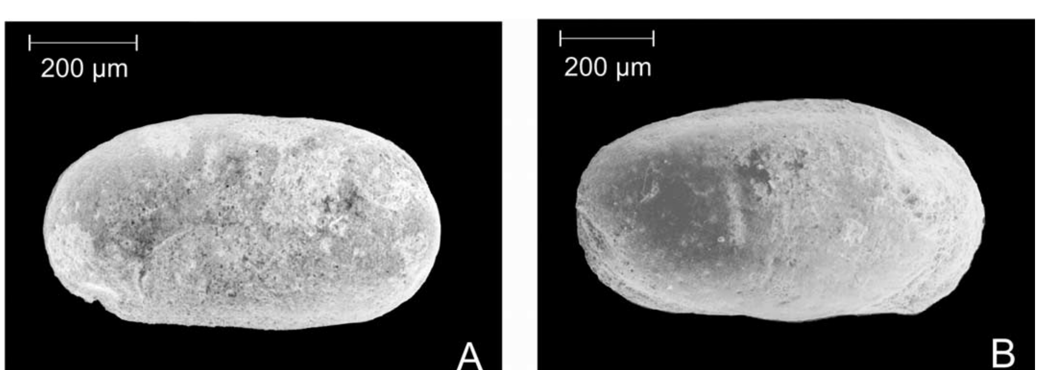

Fig. 10. SEM photographs of *Heterocypris* sp. (Ostracoda), Angostura section. (A) Left valve, (B) complete carapace, lateral view of right valve.

upper foreshore beach depositional environment. Possibly reworked sands were delivered from a nearby delta complex. The facies is best preserved in the Saipurú, Charagua, and Oquitas sections.

The shell hash of the high-energy shoreline contains bivalves with an affinity to the marine genus *Tellina* and the ostracode genus *Cyprideis*. The typical environment of *Tellina* is intertidal or offshore, as well as sheltered lagoons in shallow water (0.5–1 m depth) (Oliver, 1992). The ostracode species *Cyprideis aff. torosa* is characteristic for meso- to polyhaline environments with salinity levels up to 80%. However, other identified species (*Cyprideis aff. amazonica* and *Cyprideis aff. truncata*) can occur in freshwater to fully marine environments and thus collectively suggest a mixohaline environment (Fig. 11).

6.4. Shallow marine facies

The cyclically thickening- and coarsening-upward mud-sandstone bundles, best exposed at Abapó, are likely related to periodic minor fluctuations in the sea level or (less likely) climate. The consistent color change (from red to green) in the mudstone indicates a systematic change from oxidizing to reducing conditions. Thin-bedded, plane-laminated, or small, low-inclination rippled white sandstones build the top of each cycle. The sandstones formed in marine, low- to medium-energy, periodically changing conditions near or below the wave base, which indicates transgressive-regressive events on a shallow, mud-dominated shelf. Thin beds (up to 30 cm thick) of shell hash coquinas occur within this facies, bearing bivalves, ostracodes, and foraminifera.

In this facies, the ostracodes resemble *Cyprideis aff. torosa*. The following foraminifera species occur: *Anomalinoides* cf. *salinasensis*, *Cibicidoides* cf. *cushmani*, *Cibicidoides* aff. *mckannai*, *Gyroidina rosaformis*, *Holmanella valmonteensis*, *Nonionella miocenica*, *Pseudoparella californica*, *Hansenisca multicamerat*a, and *Holmanella baggi* (Fig. 12). These collectively suggest sedimentation on a Middle–Late Miocene (14–7 Ma) shallow marine shelf (Finger, 1990, 1992).

7. Stratigraphic correlation

In the absence of alternative methods, any stratigraphic correlation of the Yecua Formation must be based on lithological differences. A characteristic, approximately 30 cm thick shell coquina in the Yecua Formation has been interpreted as the result of a single major event. Across a distance of approximately 300 km, this bed was used for preliminary correlations (Fig. 13) of the Angostura, Abapó, Saipurú, and Charagua sections (Fig. 2).

The N–S-striking stratigraphic correlation of sections located along the eastern flank of the Serrania Charagua (Fig. 13) may indicate a transgression from the north because the thickest and best developed marine facies exist in the northernmost sections. Southward, indicators of unambiguous marine facies disappear rapidly, limiting the maximum extent

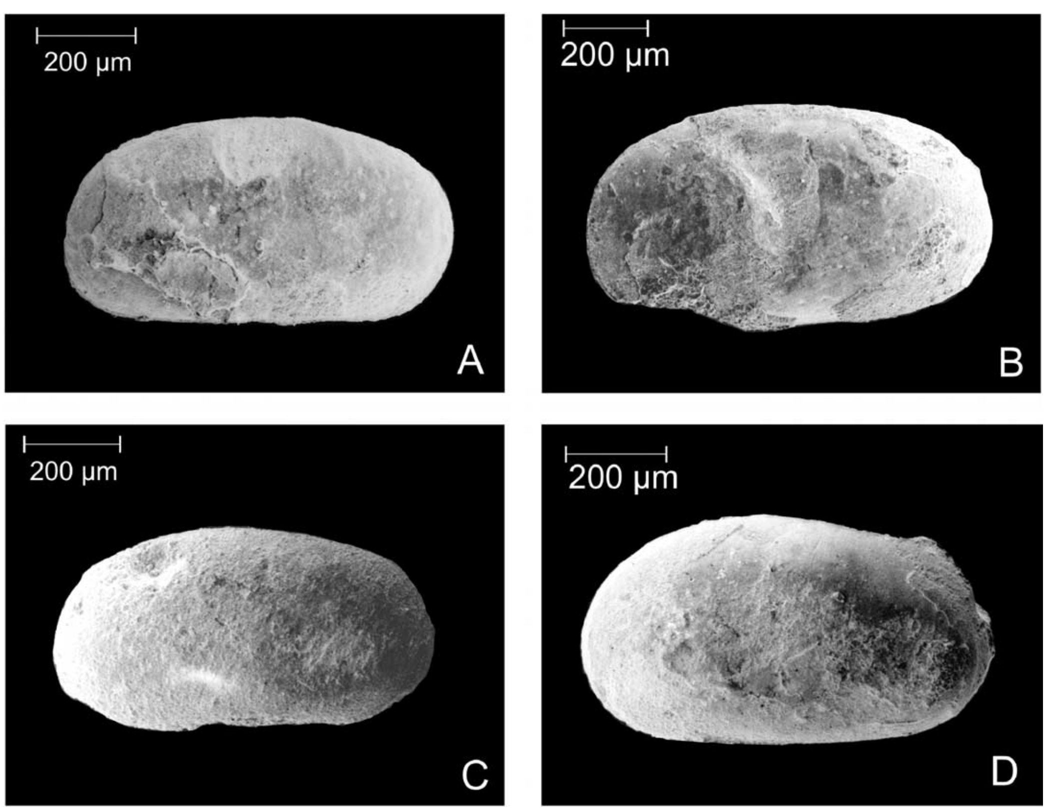

Fig. 11. SEM photographs of ostracodes from the Abapó section. (A) *Cyprideis* aff. *torosa*, left valve; (B) *Cyprideis* aff. *torosa*, right valve; (C) *Cyprideis* aff. *amazonica*, right valve; and (D) *Cyprideis* aff. *truncata*, right valve.

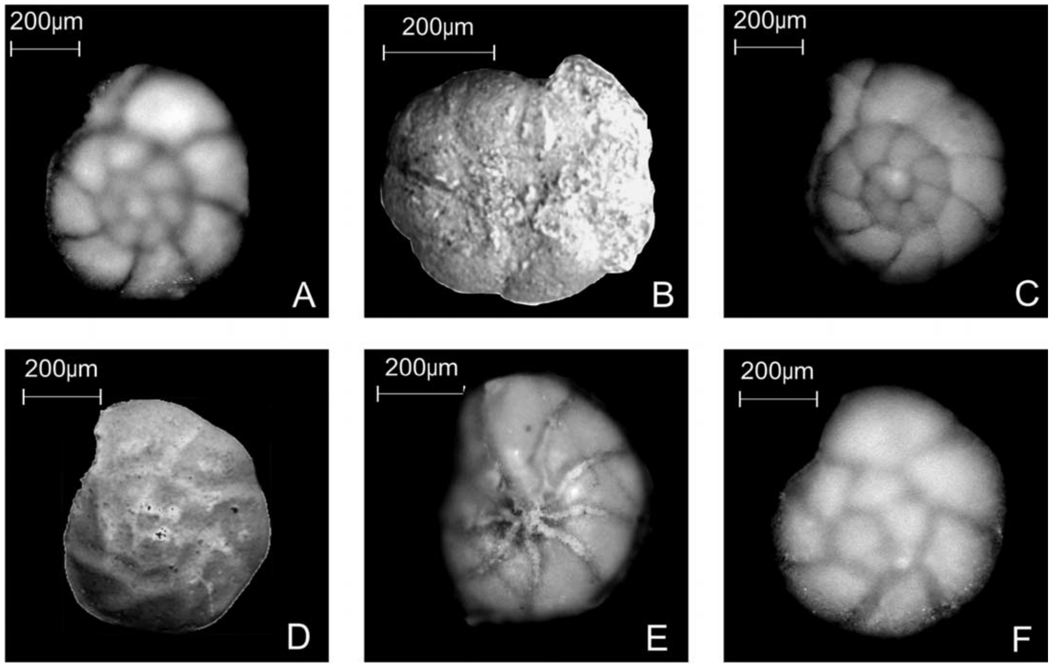

Fig. 12. SEM photographs and optical microscope photographs of foraminifera from the Angostura section. (A) *Cibicidoides cushmani*, (B) *Gyroidina rosaformis*, (C) *Cibicidoides mckannai*, (D) *Pseudoparelle california*, (E) *Pseudoparelle california*, and (F) *Pseudoparelle california*.

of a marine-brackish tongue to near the Argentine–Bolivian border. Along the Rio Parapetí and in Iguamirante (Fig. 2), marginal marine deposits are only a few meters thick. Farther south, the presence of the Yecua Formation is ambiguous because only terrestrial deposits have been studied. No lithological indicators of Yecua deposits have been found from outcrop sections near either Villamontes or farther south, and it is therefore doubtful if the Yecua Formation ever formed there. According to well descriptions of the Yacimientos Petrolíferos Fiscales Bolivianos (YPFB), the Yecua Formation is widespread throughout the Chaco Basin, including to the south. However, in our surface studies, we find no evidence of marine facies in the southern Chaco Basin.

Another limit appears to exist to the west. The Choretí and other sections west of the Serrania de Borebigua (Fig. 2) indicate dominant backswamp and possibly deltaic environments but lack any convincing marine indicators. Therefore, the marine sediments of the Yecua Formation either eroded during progradation of the orogenic wedge or never were deposited at all.

8. Discussion

The presented lithological and paleontological data support subaerial, brackish, and marine environments for the Yecua Formation between the Middle and Late Miocene (14–7 Ma). Therefore, we envision an overall coastal depositional setting for the Yecua Formation, including marshes, lakes, and streams embedded in a semiarid floodplain, as well as tidal zone, shoreline, and shallow marine environments.

Deposits of the five depozones widespread in the foreland basin system extend through the backarc of the central Andes from west to east (Horton and DeCelles, 1997). The Yecua Formation may represent the distal fill of the Andean foredeep between 14 and 7 Ma. The lacustrine to marine facies indicate an underfilled system in which the subsidence rate exceeded the sedimentation rate.

The transgression of the Middle–Late Miocene sea into the Chaco Basin may be related to the global sea-level highstand during the Miocene, which was interrupted by a major sea-level regression in the early Late Miocene between 10.5 and 10 Ma (Haq et al., 1988). Therefore, the deposition of the marine Yecua facies may be older (14–10.5 Ma, Middle Miocene) or younger (10–7 Ma, Late Miocene) than the major sea-level regression in the early Late Miocene. Marshall et al. (1993) suggest a Late Miocene age for the Yecua Formation according to their biostratigraphic results for the underlying Petaca Formation (early Late Miocene). The new biostratigraphic records presented here give no distinct evidence for a Middle or Late Miocene transgression.

The stratigraphic correlation supports the decreasing influence of the marine facies to the south and west, as has been reported by Erikson and Kelley (1995). This distribution of the marine Yecua facies indicates three possible scenarios for the connection of the marine Yecua facies through adjacent foreland basins to the ocean:

1. The marine Yecua facies formed the northernmost branch of the Paranense Sea while the interconnection proceeded along Paraguay to the northernmost Chaco Basin during the Middle–Late Miocene.
2. The marine Yecua facies was part of the Middle – Late Miocene marine incursions in the Amazon Basin.
3. The marine Yecua facies may provide a connection between the Paranense Sea and the Amazon Basin via the Paraguayan and northern Bolivian Chaco Basin during

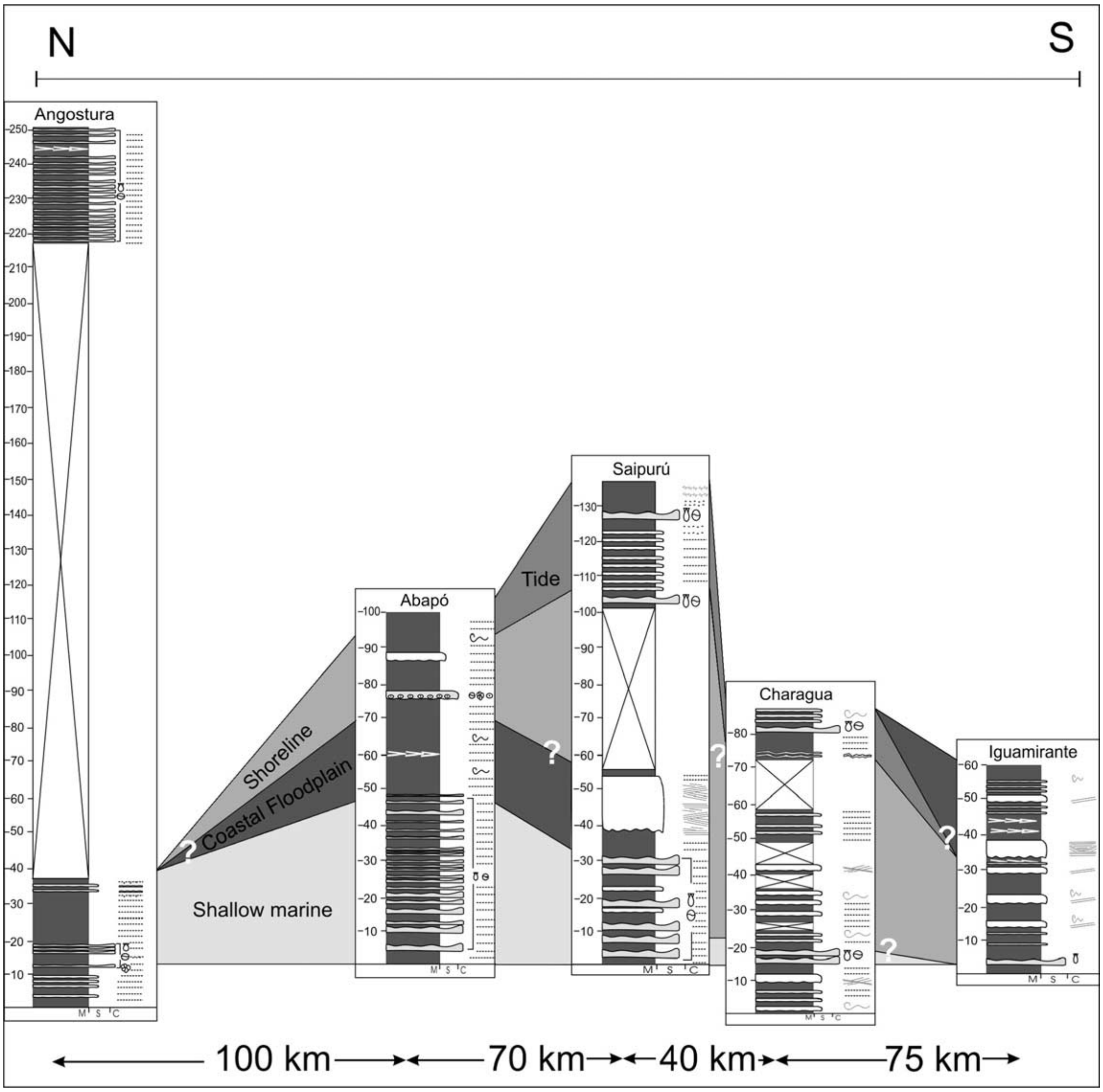

Fig. 13. Tentative lithostratigraphic correlation of the Middle–Late Miocene Yecua Formation along the eastern flank of the Serrania Charagua.

the Middle – Late Miocene. According to this scenario, the Yecua Formation of the northern Chaco foreland Basin represents an important connection for an enormous intracontinental seaway.

8.1. Comparison: Yecua Formation and Paranense Sea

The Paranense Sea, a large paleoestuary of the South Atlantic of Middle Miocene–lower Pliocene age, is developed south of the Chaco Basin (Aceñolaza and Sprechmann, 2002). Marengo (2000) and Alonso (2000) suggest that the marine transgressions of the Paranense Sea reached from Uruguay through northern Argentina to Paraguay and probably into the southern Bolivian Chaco Basin. The marine deposits are locally separated into three formations: the Anta in NW Argentina (Reynolds et al., 2000), the Paraná in NE Argentina (Garrasino and Vrba, 2000), and the Camacho in Uruguay (Sprechmann et al., 2000). For the Camacho Formation, Sprechmann et al. (2000) conclude that several marine transgressions occurred between the Middle Miocene (15–11 Ma) and the Late Miocene (11–6 Ma). In agreement with this timing, the Paraná Formation has a Middle Miocene (Aceñolaza, 2000) or Middle Miocene-lower Pliocene (Garrasino and Vrba, 2000) age. For the NW Argentinean Anta Formation, Reynolds et al. (2000) postulate a Middle Miocene (14.8–13.2 Ma) age. Hernández et al. (1999) define the age of the Anta Formation significantly more widely as 16–8 Ma (Fig. 14).

These data show that the Yecua Formation may be a northern expression of the Paranense Sea. Even so, a transgression from the NW Argentinean branch of the Paranense Sea toward the Chaco Basin in southern Bolivia is unlikely, because the marine Yecua facies is absent in the southernmost part of the Bolivian Chaco Basin. Therefore, we propose a connection between the Paranense Sea and the northern part of the Chaco Basin via the Paraguayan Chaco (Fig. 15).

The transgression–regression record of the Paranense Sea points to dominant marginal marine and shallow marine

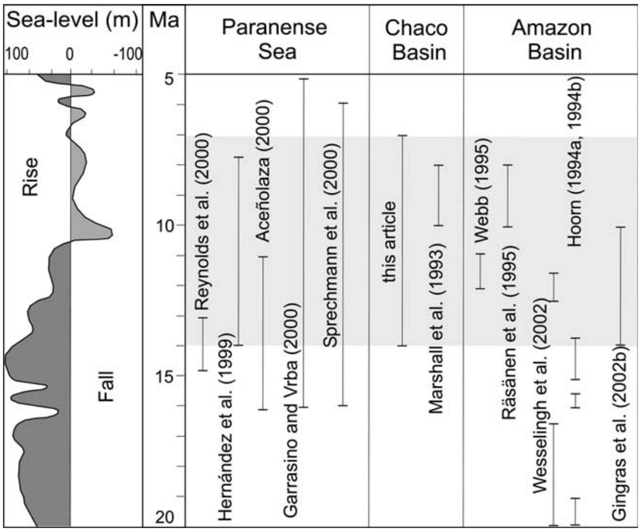

Fig. 14. Compared Miocene marine incursions of the Amazon Basin, Chaco Basin, and the Paranense Sea (after several authors).

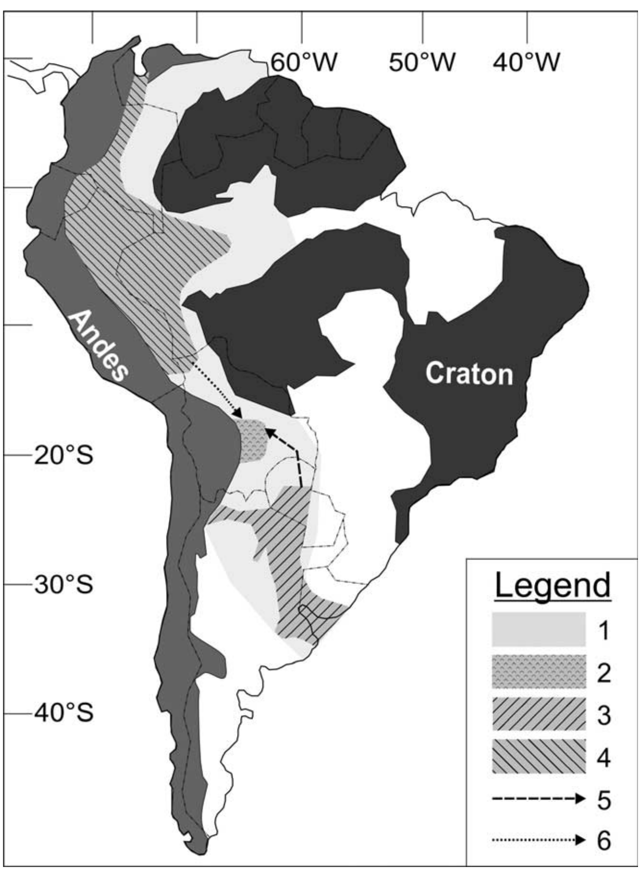

Fig. 15. Paleogeographic map, showing the distribution of the Miocene marine incursions in the South American continent, including international borders and major geological provinces. Numbers refer to marine facies: (1) Intracontinental seaway (Webb, 1995); (2) marine Yecua facies of the Bolivia Chaco Basin; (3) marine facies of the Paranense Sea (Aceñolaza and Sprechmann, 2002); (4) marine facies in the Amazon Basin (Wesselingh et al., 2002); (5) possible marine seaway between the Paranense Sea and the Bolivian Chaco Basin; (6) possible marine seaway between the Amazon Basin and the Chaco Basin.

sedimentation, which was interrupted by coastal and probably deltaic systems (Marengo, 2000). The outcrops contain limestones and sandy to muddy facies with abundant fossils (Aceñolaza, 2000).

Throughout the sediments of the Paranense Sea, the foraminifera *Rotalia beccarii parkinsoniana* (also known as *Ammonia parkinsoniana*) and *Protelphidium tuberculatum* have been reported (Sprechmann, 1978; Herbst et al., 1987; Marengo; 2000). Marshall et al. (1993) found the species *Rotalia beccarii parkinsoniana* within the Yecua Formation of the northern part of the Bolivian Chaco Basin. The foraminifera species that we identified in the Yecua Formation—*Anomalinoides*, *Cibicidoides*, *Gyroidina*, *Holmanella*, *Nonionella*, *Pseudoparella*, and *Hansenisca*—are not mentioned in the sediments of the Paranense Sea (Fig. 16).

The ostracode genus *Cyprideis*, widespread in the South American continent, is common in the northern part of the Bolivian Chaco Basin (Marshall et al., 1993). In addition, it is mentioned in the Camacho and Paraná formations (Sprechmann, 1978; Herbst et al., 1987). The ostracode genus *Heterocypris*, which we found in the Yecua Formation of the Bolivian Chaco Basin, is not known for the Paranense Sea. Marshall et al. (1993) specify the brackish ostracode genus *Bythocypris*, but it is not described from either the adjacent Paranense Sea or in this article (Fig. 16).

The bivalve family Corbiculidae and its genus Neocorbicula (Sprechmann, 1978) are common in the Paranense Sea and the northern part of the Chaco Formation (Fig. 16).

8.2. Comparison: Yecua Formation and Amazon Basin

At the same time that the marine facies of the Yecua Formation was deposited in the northern part of the Bolivian Chaco Basin, an extensive freshwater wetland covered the Amazon Basin. The fluvial–deltaic to lacustrine environment of the basin was influenced by several marine incursions (Hoorn, 1993; Wesselingh et al., 2002; Vonhof et al., 2003). The marine incursions are represented by tidal and bay facies (Räsänen et al., 1995; Wesselingh et al., 2002; Gingras et al., 2002b). In Peru, Columbia, and northern Brazil, the wetland deposits are grouped as the Pebas Formation, whereas in southern Brazil and northern Bolivia, the deposits are recorded as the Solimões Formation (Gingras et al., 2002b). The marine incursions are documented as far south as the Madre de Dios Basin in northernmost Bolivia (Räsänen et al., 1995; Gingras et al., 2002b).

In the early Miocene existed a period with marine incursions (Hoorn, 1994b). Related to the Late Burdigalian (20–19 Ma), a global sea-level rise transgression passed from the Caribbean Sea into the Amazon Basin and generated marine facies within the Pebas and Solimões formations (Hoorn, 1993; Lovejoy et al., 1998). Considering the low topography of the Andes in Ecuador during that time, a connection to the western Pacific is possible (Hoorn, 1993). However, the Late Burdigalian sea-level high has not been established for the Chaco Basin in southern Bolivia.

Paranense Sea (Sprechmann, 1978; Herbst et al., 1987)	**Yecua Fm** (Marshall et al., 1993)	**Yecua Fm** (new data)	**Pebas/Solimoes Fm** (Hoorn, 1994a; Wesselingth et al., 2002)	
Ammonia parkinsoniana *Nonion demens* *Nonion tisburyensis* *Protelphidium tuberculatum*	*Ammonia parkinsoniana*	*Anomalinoides* cf. *salinasensis* *Cibicidoides* cf. *cushmani* *Cibicidoides* aff. *mckannai* *Gyroidina rosaformis* *Hansenisca multicamerata* *Holmanella baggi* *Holmanella valmonteensis* *Nonionella miocenica* *Pseudoparella californica*	*Ammodiscus* sp. *Halophragmoides* sp. *Protoelphidium* sp. *Trochammina* sp.	**Foraminifera**
Cyprideis sp. *Perissocytheridea* sp.	*Cyprideis* sp. *Bythocypris* sp.	*Cyprideis* aff. *amazonica* *Cyprideis* aff. *torosa* *Cyprideis* aff. *truncata* *Cyprideis* sp. *Heterocypris* sp.	*Cyprideis* sp.	**Ostracoda**
Neocorbicula sp.	*Astarte* sp. *Corbula* sp. *Cyrena* sp. *Lucina* sp. *Neocorbicula* sp. *Nucula* sp. *Senis* cf. *elongatus* *Tellina* sp.	*Neocorbicula* sp. *Tellina* sp.	*Anticorbula* sp. *Corbicula* sp. *Eupera* sp. *Macoma* sp. *Ostomya* sp. *Panamicorbula* sp. *Pachydon* sp. *Pebasia* sp. *Pisidium* sp.	**Bivalvia**

Fig. 16. Comparison of the reported fossils for the Middle–Late Miocene marine facies of the Amazon Basin, Chaco Basin, and Paranense Sea.

Between the Middle and Late Miocene, marine incursions were deposited within the Amazon Basin as a consequence of the Langhian and Serravallian sea-level high (Hoorn, 1994a). Studies show that the incursions passed from the north into the Amazon Basin (Hoorn, 1993; Lovejoy et al., 1998). However, a gap in the eastern Andes presents another possible entrance for the marine incursions during the Middle and Late Miocene. This passage closed around 9 Ma (Steinmann et al., 1999). Gingras et al. (2002a,b) describe evidence for tidal facies along the southern part of the Amazon Basin in the Middle to Late Miocene age (14–10 Ma), whereas Räsänen et al. (1995) describe tidal facies of Late Miocene age (10–8 Ma) for the southernmost marine influence in Peru and Brazil. However, if all age data are fitted together for the southern Amazon Basin, the marine transgressions have a similar time interval as the Bolivian Yecua Formation of the Chaco Basin (Fig. 14).

Foraminifera, ostracodes, molluscs, and several fragments of vertebrates are described by several authors as widespread in the Pebas Formation (Hoorn, 1994a; Wesselingh et al., 2002). The foraminifera genera *Ammodiscus*, *Halophragmoides*, *Protoelphidium*, and *Trochammina* are documented (Hoorn, 1994a). The results differ from the genera of the Chaco Basin (Fig. 16). The ostracode genus *Cyprideis*, widespread in the South American continent during the Miocene (Fig. 16), also is documented for the Amazon Basin (Hoorn, 1994a; Wesselingh et al., 2002).

Several bivalvia genera are reported for the Amazon Basin (Wesselingh et al., 2002). Of these, only the genus *Corbula* was reported within the Yecua Formation (Fig. 16) in the northern part of the Chaco (Marshall et al., 1993).

8.3. Hypothesis of an intracontinental seaway

Combining both previous scenarios, the northern Chaco Basin in southeastern Bolivia may represent the location where the Paranense Sea and Amazon Basin linked and built a hypothetical seaway (Fig. 15). Ihering (1927) documents molluscs and foraminifera species of Miocene age in locations affected by marine incursions from the Caribbean Sea and areas influenced by the Atlantic Ocean. Therefore, he suggests a large intracontinental seaway from the Caribbean Sea to the Atlantic Ocean, connecting the developing Andean foreland basins. Webb (1995) determines a Middle Miocene age for the intracontinental seaway (Fig. 14), whereas according to Räsänen et al. (1995), a connection between the Amazon Basin and the Paranense Sea was most probable during the Late Miocene (10–8 Ma).

9. Conclusions

New lithology data of the southern Bolivian Yecua Formation within the Chaco Basin indicate depositional environments of floodplain facies and restricted shallow marine facies. The study of foraminifera establishes the marine incursions of the Chaco Basin between 14 and 7 Ma. Our lithostratigraphic data support decreasing marine influence within the Bolivian Yecua Formation to the south.

Time-equivalent marine incursions have been determined in the Amazon Basin (north of the Chaco Basin) and the Paranense Sea (south of the Chaco Basin). Several marine incursions have been determined as widespread in the wetlands of the Amazon Basin and reached their southernmost extension in the Madre de Dios Basin along the Brazilian–Bolivian border (Räsänen et al., 1995; Wesselingh et al., 2002; Gingras et al., 2002a). A connection between the marine incursions of the Madre de Dios Basin and the northern part of the Chaco Basin is possible along the foothills of the Andean belts. However, a connection between the marine facies of the Chaco Basin and the Paranense Sea is also possible, if the seaway passed along the Paraguayan Chaco. As postulated by Alonso (2000), a straight connection between the Yecua of the Chaco Basin and the Anta in NW Argentina is unlikely. Because the marine Yecua facies may be linked to the Paranense Sea in the south and the Amazon Basin in the north, the hypothesis of an intracontinental connection between the two areas via the Chaco Basin is feasible.

Unfortunately, the fossil record of the Chaco Basin (new data, Marshall et al., 1993) shows little overlap with either the fossils of the Pebas/Solimões Formation or those of the Paranense Sea.

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