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# THE PETACA (LATE OLIGOCENE-MIDDLE MIOCENE) AND YECUA (LATE MIOCENE) FORMATIONS OF THE SUBANDEAN-CHACO BASIN, BOLIVIA, AND THEIR TECTONIC SIGNIFICANCE

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## Résumé

**Les formations Petaca (Oligocène terminal-Miocène moyen) et Yecua (Miocène terminal) du bassin subandin Chaco, Bolivie, et leur signification tectonique.**

Les formations Petaca et Yecua sont les deux premières unités du remplissage cénozoïque d'avant-pays dans la zone subandine centrale et méridionale de Bolivie. Leur datation biostratigraphique met en évidence une accélération notable de la subsidence tectonique vers ≈10 Ma, laquelle coïncide avec une incursion d'eaux marines restreintes peu profondes depuis la région du Río de la Plata, le long de la bordure orientale des Andes de Bolivie et du Nord-Ouest argentin. Le dépôt de la Formation Yecua est intervenu au cours de l'intervalle 10-8 Ma.

MOTS-CLÉS : Bolivie, Formations Petaca et Yecua, Oligo-Miocène, Tectonique, Paléontologie.

## Resumen

**Las formaciones Petaca (Oligoceno terminal-Mioceno medio) y Yecua (Mioceno terminal) de la cuenca subandina-chaqueña, Bolivia, y su significado tectónico.**

Las formaciones Petaca y Yecua son las dos primeras unidades del relleno de antepaís de la faja subandina centro y sur de Bolivia. Su datación bioestratigráfica evidencia una aceleración notable de la subsidencia tectónica alrededor de ≈10 Ma, la cual coincide con la ingresión de aguas marinas restringidas someras desde la región del Río de la Plata, a lo largo del borde oriental de los Andes bolivianos y del Norte argentino. La Formación Yecua se depositó en el curso del intervalo 10-8 Ma.

PALABRAS CLAVE : Bolivia, Formaciones Petaca y Yecua, Oligo-Mioceno, Tectónica, Paleontología.

## Abstract

**The Petaca (late Oligocene-middle Miocene) and Yecua (late Miocene) formations of the Subandean-Chaco basin, Bolivia, and their tectonic significance.**

The Petaca and Yecua formations are the first two units of the Cenozoic foreland fill in the central and southern Subandean belt of Bolivia. Their biostratigraphic dating permits to recognize a notable acceleration of tectonic subsidence at ≈10 Ma, which coincides with the ingression of shallow restricted-marine waters from the Río de la Plata area along the eastern edge of the Bolivian and northwestern Argentine Andes. The Yecua Formation was deposited some time between 10 and 8 Ma.

KEYWORDS : Bolivia, Petaca and Yecua formations, Oligo-Miocene, Tectonics, Palaeontology.


# INTRODUCTION

The strata from the Subandean fold-thrust belt and Llanura (lowlands) of southern and central Bolivia (fig. 1) include rocks of late Oligocene through Quaternary age (Sempere 1990 ; Marshall & Sempere 1991). This 4 000 to 6 500 m-thick clastic sequence was deposited in the last external Andean foreland basin, which initiated in the late Oligocene, at about 27 Ma (Sempere *et al.* 1990). Because this late Oligocene-Quaternary sequence records the tectonic evolution of the nearby central Andes during this time span, the respective biostratigraphic data may cast some light on the chronology of this evolution.

All fossiliferous localities mentioned hereafter occur in the Subandean belt of central and southern Bolivia. The abbreviations used hereafter are : **km**, kilometers ; **m**, meters ; **Ma**, megaannum or millions of years, a point in time ; **Myr**, millions of years, a duration of time.

# PETACA FORMATION

The basal rock unit of the central and southern Subandean foreland fill is the Petaca Formation. In the Santa Cruz area, it overlies the dinosaur-bearing Cajones Formation (late Cretaceous) with a sharp, slightly erosive unconformity, and consists of sandstones, and subordinate mudstones and conglomerates, of continental origin. It reaches a thickness of about 400 m (Sanjinés & Jiménez 1976 ; Sanjinés 1978).

Fossil vertebrates are known from four localities :

1. **Quebrada de Cuevo,** where this stream crosses the Serranía de Mandeyapecua (southern Subandean belt), about 110 km NNE of Villamontes. Ahlfeld & Branisa (1960, p. 143) report «*restos de fósiles de vertebrados indeterminables (...), uno de los cuales es un pequeño trozo de mandíbula de un mamífero*».

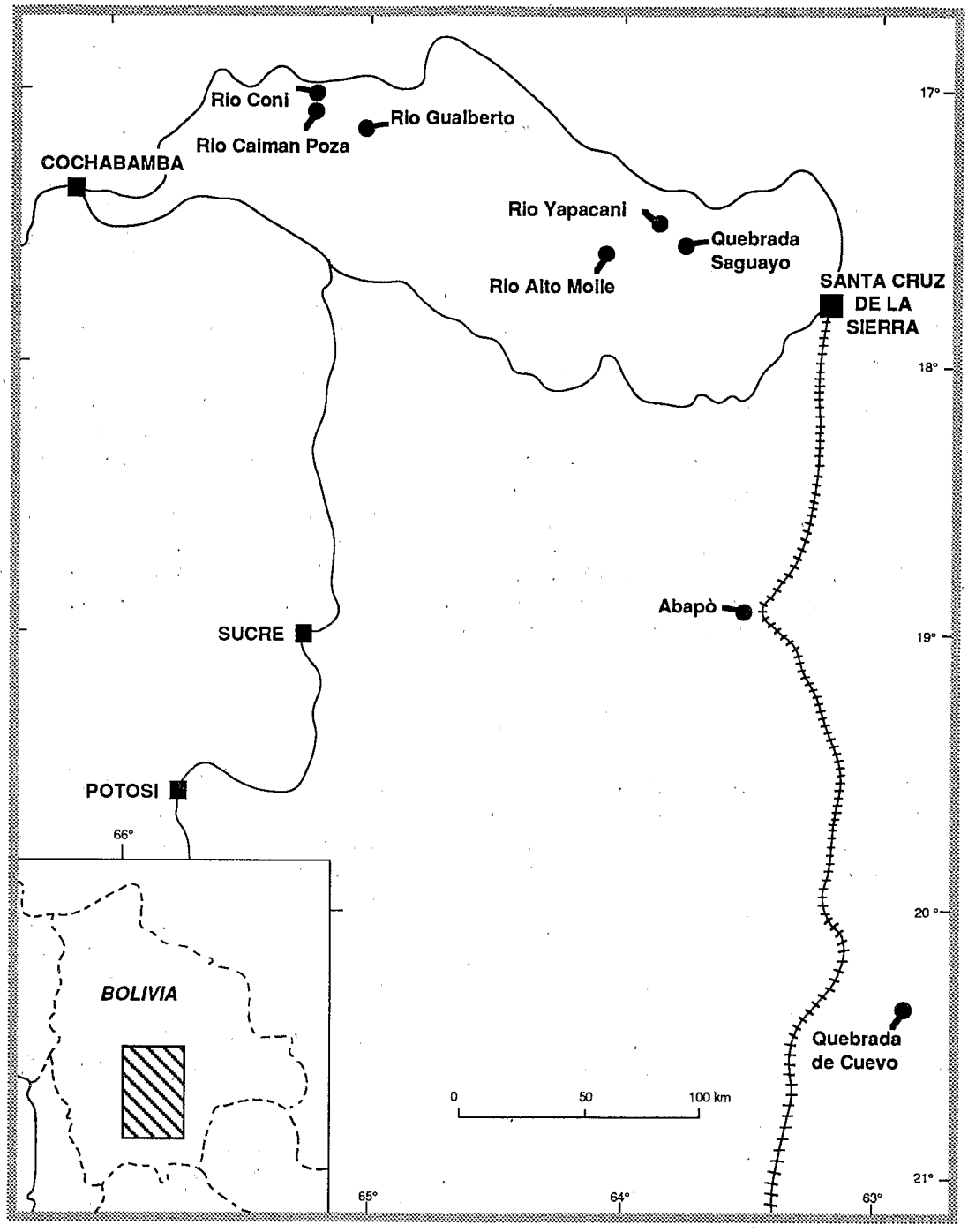


Fig. 1 - **Map of southcentral Bolivia showing fossil vertebrate localities of the Petaca and Yecua formations discussed in the text.**

2. **Serranía de Aguaragüe**, southern Subandean belt (lat 20°20' S-22°S). Ahlfeld & Branisa (1960, p. 144) report mention of discovery of bones of reptiles and mammals, which were determined by C. W. Gilmore, in the Conglomerado de Galarza (= Petaca).

3. **Quebrada Saguayo**, 60 km WNW of Santa Cruz de la Sierra. From a pink sandstone 2 m above the base of the unit, YPFB geologists collected a right maxilla with P2-M2 of *?Rhynchippus* sp. (Notoungulata, Notohippidae, Rhynchippinae), an indeterminate scute of an armadillo (Edentata, Dasypodidae), and the earliest remains of a tortoise (Chelonia, Testudinidae, cf. *Chelonoidis* sp.) in South America (Villarroel 1974 ; Sanjinés & Jiménez 1976 ; Hoffstetter 1977 ; Sanjinés 1978 ; Broin 1991 ; Marshall & Sempere 1991). Bone fragments of numerous small vertebrates, apparently mammals, were recovered on November 14, 1990, by LGM, yet the only identifiable specimen was a scute of another armadillo.

*Rhynchippus* is known only from Deseadan (late Oligocene-earliest Miocene) Land Mammal Age faunas elsewhere in South America, and the subfamily Rhynchippinae is unknown after Deseadan time, at least in Argentina (Marshall *et al.* 1986 ; Marshall & Sempere 1991).

4. **Río Yapacani,** 90 km WNW of Santa Cruz de la Sierra. A right dentary with five teeth of an armadillo (Edentata, Dasypodidae, Pampatheriinae, cf. *Vassallia minuta*) was collected from the top of the unit (Pascual *et al.* 1973 ; Villarroel 1974 ; Sanjinés & Jiménez 1976, pl. 5). An attempt was made by LGM to relocate this site on November 14, 1990, and it was discovered that the Petaca Formation occurs in fact about 20 km more to the southwest than originally illustrated.

Alone, the presence of cf. *Vassallia minuta* indicates a Chasicoan (early late Miocene) to Montehermosan (early and middle Pliocene) age for this level of the Petaca Formation. But the presence of cf. *Theosodon* (Litopterna, Macraucheniidae), which indicates a Colhuehuapian (middle early Miocene) to Chasicoan age, in the overlying Yecua Formation (see below) shows that the Río Yapacani level and at least the lower part of the Yecua are most likely Chasicoan, i.e. early late Miocene, in age.

## YECUA FORMATION

Transitionally overlying the Petaca Formation is the restricted-marine to lacustrine and distal alluvial Yecua Formation, which consists principally of 0 to 300 m (or more) of green to black marls and subordinate calcareous sandstones (López-Murillo 1975 ; Sanjinés & Jiménez 1976). It is transitionally overlain by the Tariquía Formation, which consists of reddish mudstones and subordinate sandstones.

The Yecua Formation has yielded many fossils indicating continental, brackish, and shallow-marine environments. Fossils indicating a marine influence are apparently known only from localities south of lat 18°S. However, it appears likely that the Yecua Formation consists of an alternation of continental and restricted-marine beds, depending on slight variations in tectonic subsidence and global sea-level, and that continental facies become predominant toward the north, i.e. in the direction opposite to the geographic origin of the marine ingression (see below and fig. 2). Evolution of the restricted-marine areas with time probably led to development of lakes and/or distal alluvial plains, according to position in the basin and subsidence history.

Fossil invertebrates from the Yecua Formation include :

- foraminifera : *Ammonia beccarii*, which indicate very shallow, generally marine waters with a salinity lower than normal (Branisa 1970 ; pers. com. from J. E. Hazel to L. Branisa, 1970) ;

- pelecypods : *Tellina* sp. (E. O. Ulrich, *in* Mather 1922) ; forms referable to cf. *Cyrena* sp. (of the mostly brackish to freshwater family Corbiculidae), cf. *Astarte* sp. (of the marine family Astartidae), or cf. *Lucina* sp. (of the marine to estuarine family Lucinidae), and suggesting a shallow and brackish environment (Palmer, cited by Branisa, 1970) ; *Senis* cf. *elongatus*, of the marine to estuarine family Cultellidae, and cf. «*Corbula*» (Corbulidae) or *Cymbophora* (Mactridae) sp. (R. Suárez-Soruco, pers. com.) ; cf. *Nucula* sp., of the marine family Nuculidae (López-Pugliessi & Pareja 1971) ;

- gastropods : large cf. *Gyrodes* or *Natica* sp. (Naticidae, a mostly marine family), and smaller turriculate forms (Branisa 1970) ; cf. *Turritella* sp., of the mostly marine family Turritellidae (López-Pugliessi & Pareja 1971) ;

- ostracods : *Bythocypris* sp. (E. O. Ulrich, *in* Mather 1922), of the marine family Bairdiidae ; and *Cyprideis* sp., which indicate brackish (particularly mesohaline) or hypersaline waters, and is not seen in normal marine or purely fresh waters (pers. com. from J. E. Hazel to L. Branisa, 1970) ;

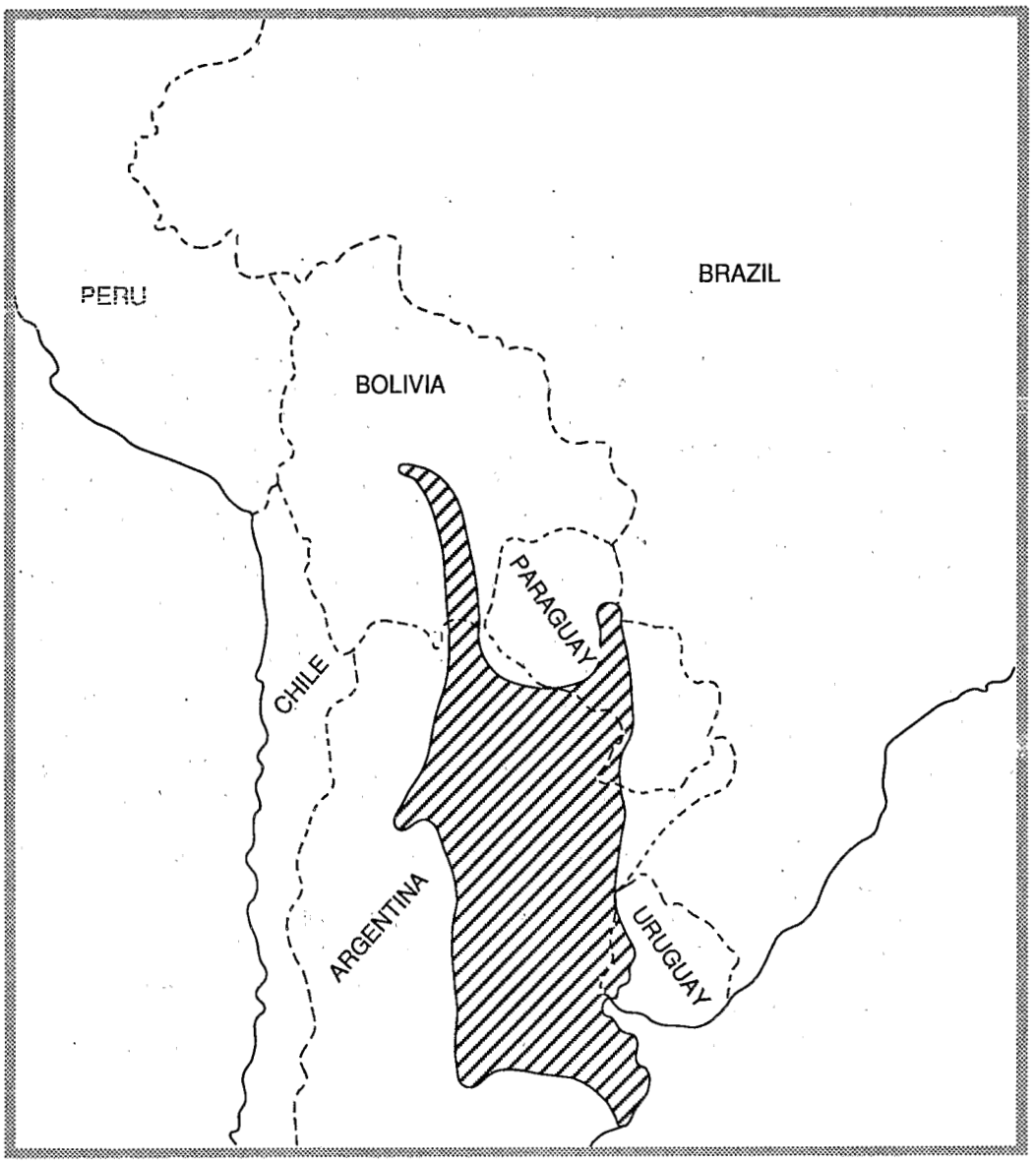


**Fig. 2 - Map of central part of South America showing known extent (cross-hatching) of the Paranense epicontinental seaway about 10 Ma.**

- cirripeds : cf. *Balanus* sp. (Branisa 1970), which marks a marine influence ;
- decapods : indeterminate crabs (Branisa 1970).

Fossil vertebrates are known from four localities of the Yecua Formation :

1. **Río Alto Moile**, 95 km WNW of Santa Cruz de la Sierra. López-Murillo (1975) recovered fossils from his level RL-1596 in the upper part of the Yecua Formation. He noted : «*de este horizonte se han extraido numerosas piezas dentarias y óseas de vertebrados grandes; escamas, aletas y peces más o menos bien conservados; variadas formas de invertebrados, especialmente pelecípodos, gastrópodos y artrópodos como también microfósiles y multiples formas de hojas y tallos incluyendo restos carbonitizados*». Many of these fossils have been apparently lost, as the only remains now in the YPFB (Centro de Tecnología Petrolera) collection in Santa Cruz are (Gayet 1991 ; Marshall & Sempere 1991) :

- a distal limb bone of a litoptern (Macraucheniidae, cf. *Theosodon* sp.) ;
- an indeterminate rodent tooth ;

- the first fossil remains of electric eels : Gymnotiformes, family *incertae sedis*, *Ellisella kirschbaumi* Gayet & Meunier 1991, one of which presents, for the first time in the paleontological record, a repaired morphogenesis of the caudal endoskeleton as occurs in living members of this group (Meunier & Gayet 1991) (pl. 1, figs. 1-3) ;

- indeterminate catfishes (Siluriformes) (pl. 1, figs. 4-5), a bone of which might be assigned to the family Ariidae ;

- one scale possibly of Characiformes or Clupeiformes (pl. 1, fig. 6).

Remains of at least two kinds of indeterminate terrestrial plants were also found (pl. 1, figs. 7-8).

The fishes, as the associated mammals and plants, indicate a continental environment. An attempt by LGM to relocate this site on November 12, 1990, was unsuccessful.

If the identification of cf. *Theosodon* is correct, then the age of this level of the Yecua Formation is somewhere between Colhuehuapian (middle early Miocene) and Chasicoan (early late Miocene), which is the known chronologic range of this genus elsewhere in South America (Marshall & Sempere 1991). Because of the biostratigraphic data from the underlying Petaca (see above), at least the part of the Yecua Formation located between its base and this level is Chasicoan in age.

In the same area, López-Murillo (1975) reported discovery of fish, invertebrates and plants in a green claystone level near the base of the Tariquía Formation. Given the overall brownish red color of the Tariquía mudstones, we suggest that this green level should be considered as belonging to the uppermost Yecua Formation. On November 12, 1990, LGM collected numerous fish specimens (teleost vertebrae and indeterminate remains), part of a possible crab, several pelecypods, fragments of wood and leaf impressions from this site. René Osinaga (pers. com.) reports that he and other members of YPFB made a large collection of fossils from this site, all of which are now in the CTP in Santa Cruz.

2. **Río Gualberto**, near San Pablo, 210 km WNW of Santa Cruz de la Sierra and 210 km ENE of Cochabamba. A new fossil locality in the lower part of the Yecua Formation was discovered by YPFB geologists under the direction of Ing. Javier Blanco (René Osinaga, pers. com.). From this red mudstone level on the east side of the Río Gualberto, LGM collected the proximal part of a left tibia of a large crocodile (F. de Broin, pers. com.) (pl. 1, fig. 9), fragments of turtle shells, numerous remains of fish (vertebrae), an ornamented bivalve, and possible leaf impressions. This appears to be currently the most richly fossiliferous site known in the Yecua Formation.

From a green siltstone level higher in the formation, LGM collected fragments of indeterminate fish.

3. **Río Coni and Río Caimán Poza**, about 230 km WNW from Santa Cruz de la Sierra and 110 km ENE from Cochabamba. Fish spines, turtle plates and crocodile teeth were found by Brigada 9 of YPFB in 1991 (YPFB-Pal 7361 and 7362).

4. **Abapó**, on the Río Grande, 130 km SSW of Santa Cruz. Branisa (1970) mentions bone fragments up to 2-3 cm in length.

## BIOSTRATIGRAPHIC SUMMARY

There are no volcanic rocks (i.e. basalts, tuffs, etc.) in either the Petaca or Yecua formations, which deters dating by radioisotopic methods. Furthermore, although both units are ideal for magnetostratigraphic analysis, this has not yet been attempted. Thus, the dating of these rocks currently relies on fossil content and on age constraints provided by dated underlying and overlying rock units.

As already noted, the occurrence of the Chasicoan to Montehermosan cf. *Vassallia minuta* below a level with the Colhuehuapian to Chasicoan cf. *Theosodon* sp. implies that the top of the Petaca Formation and at least a large part of the Yecua Formation are Chasicoan in age (i.e. 11 to 9 Ma ; Marshall & Sempere 1991). This age assignment is supported by the fact that the Yecua Formation represents the northern extent of the Paranense epicontinental seaway (Sempere 1990), which is, at least in part, temporally equivalent to Chasicoan (see below).

As a whole, the available biostratigraphic data demonstrate that the Petaca Formation, which is about 400 m thick, spans the Deseadan-Chasicoan, i.e. late Oligocene-early late Miocene, interval. This time interval being at least 13 Myr-long, the corresponding mean sedimentation rate (undecompacted) is not over 30 m/Myr. In contrast, more than 3 500 m of alternating and coarsening-upward mudstones, sandstones and

conglomerates were deposited during the last 10-11 Myr, which corresponds to a minimum (undecompacted) sedimentation rate of about 320 m/Myr, i.e. more than ten times the maximum value for the late Oligocene-early late Miocene interval. This marked contrast points to a noteworthy acceleration of subsidence at about 11-10 Ma, and hence to an acceleration of tectonic loading in the west, which represents the onset of a major tectonic development, accompanied by the resumption of felsic explosive magmatism, in the Bolivian Andes (Sempere et al. 1989 ; Sempere 1991). The Yecua Formation, where a marine influence is clearly perceptible, was thus the first unit to be deposited in relation with this late Miocene major tectonic crisis in Bolivia (Sempere 1990).

## PARANENSE EPICONTINENTAL SEAWAY

The Paraná Formation was named by Doering (1882 ; i.e. his «Piso Paranense»), who applied this term to what is now recognized as a late Miocene marine transgression along the western part of the Chaco-Paraná basin (fig. 2). A historical overview of the debated age of this rock unit and of its fossil content in Argentina is provided by Aceñolaza (1976) and Muizon & Bond (1982).

The Paraná Formation is a stratigraphic and temporal equivalent of the Camacho Formation of southwest Uruguay (Mones 1979 ; Fernández 1989) ; the San José Formation in Catamarca and Tucumán provinces of NW Argentina (Bossi & Palma 1982; Strecker *et al.* 1989) ; the Anta Formation in Salta and Jujuy provinces, NW Argentina (Torres 1985 ; Strecker *et al.* 1989) ; and is lithologically similar to the Yecua Formation of Bolivia (Sempere 1990).

In the Yecua Formation, south of 18°S, are recorded foraminifera of the species *Ammonia beccarii* d'Orbigny (see above), and this same species is reported from the Paraná Formation (Zabert & Herbst 1977 ; Bertels 1979) and from the Camacho Formation of Uruguay (Bertels 1979 ; Mones 1979), where it is listed as *Rotalia beccarii* var. *parkinsoniana*. This species and the other foraminifera reported from the Paraná, Camacho and San José formations are benthonic forms and indicate very shallow marine to littoral environments, and a late Miocene age (see Bertels & Zabert 1980).

Based on K-Ar dates on tuffs from underlying and overlying rock units, the Paraná Formation and its equivalents are younger than 11 Ma (Strecker *et al.* 1989) and older than 8 Ma (see dates in Butler *et al.* 1984), which is consistent with the age inferred above for the Yecua Formation on the basis of fossil evidence. Furthermore, this marine unit is temporally equivalent to the «Rionegrense» at Punta Cracker, south of Peninsula Valdés, which has a K-Ar date of 9.41 Ma on a glass concentrate from a tuff in the top of this unit (Zinsmeister *et al.* 1981).

A major global drop in sea level is reported between ≈10.5 and 10 Ma (Haq *et al.* 1987). If this is true, then it is likely that the Paranense transgression did not develop during this interval, but, given the age constraints, after this major regression, i.e. some time between 10 and 8 Ma.

## CONCLUSIONS

Initiation of the present Andean foreland basin in Bolivia occurred in the late Oligocene (Sempere *et al.* 1990). From the late Oligocene through the middle Miocene, what is now the Andean foothills was located in the outer (distal) part of this foreland basin, where subsidence is generally low (see Flemings & Jordan 1989). It is likely that the basin axis slowly migrated toward the east during this time span. Subsidence notably increased in late Miocene time, indicating resumption of tectonic loading in the Andes to the west, produced by reactivation of shortening and uplift. Because there was a lagtime before erosion could provide enough material to compensate subsidence in the foreland basin, its axial groove subsided without being completely filled by alluvial deposits, and this permitted shallow restricted-marine waters to ingress into the basin from the south. The transgression documented by the Yecua Formation thus appears to be tectonically related and not associated with the global eustatic history, which on the contrary reputedly shows a major drop between 10.5 and 10 Ma, and comparatively «low» highstands afterwards (Haq *et al.* 1987).

Several lines of evidence suggest that a high rate of tectonic loading established in the central Andes at 11-10 Ma, accompanied by a noteworthy coeval resumption of explosive felsic magmatism in the Altiplano

and western Cordillera Oriental (Sempere *et al.* 1989 ; Sempere 1991), and monitored the position of the foreland basin axis, which was probably located rather close to the Andean thrust front as predicted by current models (Flemings & Jordan 1989, 1990).

The late Miocene «marine» ingression entered Bolivia by following the axial groove of the Andean foreland basin, which at that time was underfilled because of probably abrupt resumption of tectonic loading in the Andes and hence tectonic subsidence in the foreland. Along this groove, and north of a domain permanently in connection with the sea, must have stretched a stringer of lagoons and lakes, generally isolated from one another, and with waters less and less saline toward the north.

The Petaca and Yecua formations thus document two significant events in the tectonic history of Bolivia in particular and in southern-central South America in general. Initiation of a major compressional episode and foreland basin development at about 27 Ma resulted in deposition of the Petaca Formation, and another episode beginning 11-10 Ma resulted in the onset of deposition of the Yecua Formation, which is the northernmost extent of a restricted-marine environment of an epicontinental sea from the south via Argentina. The western part of the Petaca and Yecua formations depositional area was deformed through subsequent (and ongoing) propagation of thrust deformation from the west.

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# PLATE 1

Fig. 1 - *Ellisella kischbaumi* Gayet & Meunier, 1991 (Gymnotiformes) from Río Alto Moile (Yecua Formation). N° RL-1596-1 (Centro de Tecnología Petrolera, Santa Cruz de la Sierra, on loan to the CST, Lyon I, France). General view of the posterior part of the body showing repair morphogenesis of the caudal skeleton (arrow) (x 2). Photograph by D. Serrette, CNRS URA 12, Paris.

Fig. 2 - Natural cast of an opercular of *Ellisella kischbaumi* Gayet & Meunier, 1991, from Río Alto Moile (Yecua Formation). N° RL-1596-5 (Centro de Tecnología Petrolera, Santa Cruz de la Sierra, on loan to the CST, Lyon I, France) (x 6). Photograph by N. Podevigne, CNRS URA 11, Lyon.

Fig. 3 - Fragment of the ventral part of the body with anal fin of *Ellisella kischbaumi* Gayet & Meunier, 1991, from Río Alto Moile (Yecua Formation). N° RL-1596-5 (Centro de Tecnología Petrolera, Santa Cruz de la Sierra, on loan to the CST, Lyon I, France) (x 3). Photograph by N. Podevigne, CNRS URA 11, Lyon.

Fig. 4 - Anterior view of the anteriormost proximal axonoste of an indeterminate catfish from Río Alto Moile (Yecua Formation). N° RL-1596-8 (Centro de Tecnología Petrolera, Santa Cruz de la Sierra, on loan to the CST, Lyon I, France) (x 1.5). Photograph by N. Podevigne, CNRS URA 11, Lyon.

Fig. 5 - Upper view of a fragment of a posterior cranial bone of an indeterminate catfish (cf. Ariidae) from Río Alto Moile (Yecua Formation). N° YPFB-Pal-815 (Centro de Tecnología Petrolera, Santa Cruz de la Sierra, on loan to the CST, Lyon I, France) (x 1). Photograph by N. Podevigne, CNRS URA 11, Lyon.

Fig. 6 - Scale of an indeterminate teleost (Characiformes or Clupeiformes) from Río Alto Moile (Yecua Formation). N° RL-1596-10 (Centro de Tecnología Petrolera, Santa Cruz de la Sierra, on loan to the CST, Lyon I, France) (x 5). Photograph by N. Podevigne, CNRS URA 11, Lyon.

Fig. 7 - Indeterminate remains of leaves from Río Alto Moile (Yecua Formation). N° RL-1596-8 (Centro de Tecnología Petrolera, Santa Cruz de la Sierra, on loan to the CST, Lyon I, France) (x 3). Photograph by N. Podevigne, CNRS URA 11, Lyon.

Fig. 8 - Indeterminate remains of leaves from Río Alto Moile (Yecua Formation). N° RL-1596-11 (Centro de Tecnología Petrolera, Santa Cruz de la Sierra, on loan to the CST, Lyon I, France) (x 3). Photograph by N. Podevigne, CNRS URA 11, Lyon.

Fig. 9 - Lateral view of a proximal tip of a left tibia of a large crocodile from Río Gualberto (Yecua Formation). N° FSL 571000 (CST, Lyon I, France) (x 1). Photograph by N. Podevigne, CNRS URA 11, Lyon.


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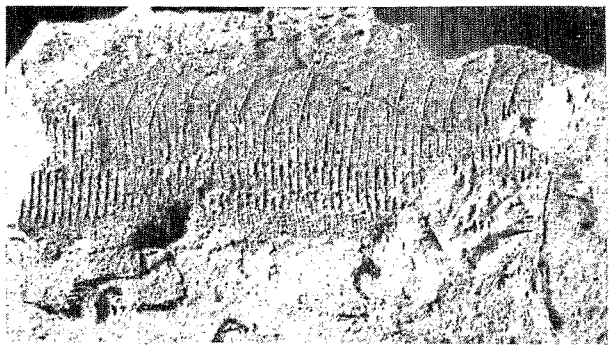
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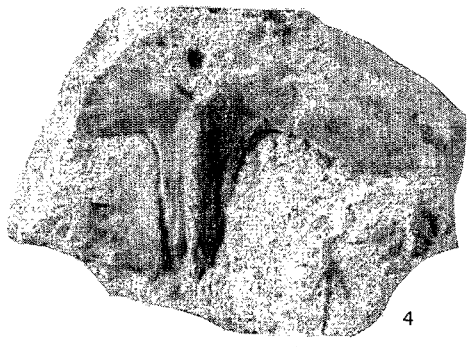
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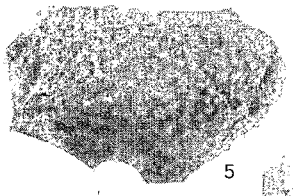
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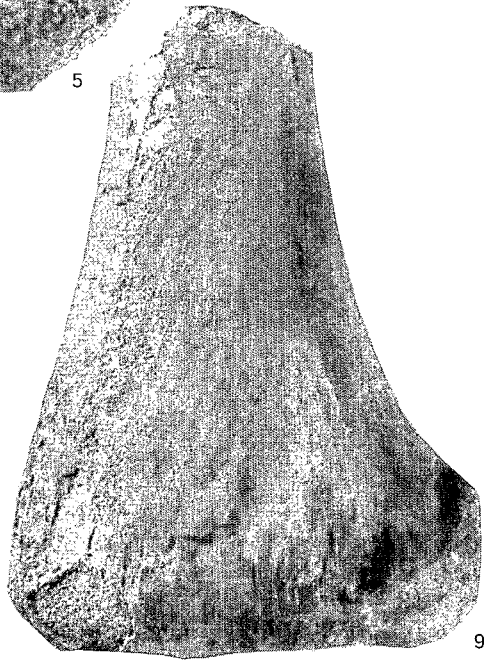
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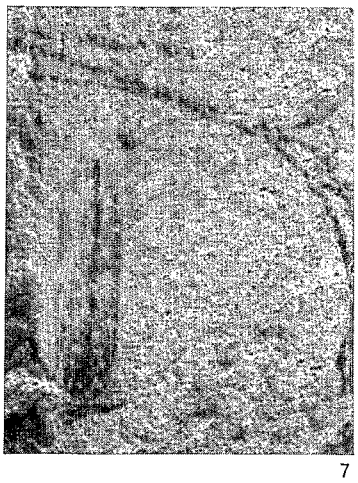
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