Andean Geology 37 (2): 329-344. July, 2010

Andean Geology
formerly Revista Geológica de Chile
www.scielo.cl/andgeol.htm

Estuary deposits in the Río Baguales Formation (Chattian-Aquitanean), Magallanes Province, Chile

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ABSTRACT. Very little work has been done on the stratigraphy and sedimentology of the upper Oligocene-Lower Miocene Río Baguales Formation in the Magallanes Province of southern Chile since its original definition in 1957. A detailed stratigraphic section of the upper part of the formation exposed west of the Baguales River is presented, with an interpretation of depositional environments. This indicates a prograding shoreline in which estuary mouth, middle estuary (lagoon) and bay head delta facies are represented. Large-scale delta slope foresets indicate progradation towards the north and northwest, whereas southeast-directed cross-beds on the delta front probably suggest wave action. The general sequence reflects a gradual sea-level fall largely counteracted by tectonic subsidence, which provided the necessary accommodation space for thick tidal flat and subtidal deposits to accumulate. A longer period of transgression towards the top of the succession may be related to a rise in sea-level or accelerated tectonic subsidence, whereas a major regression commencing at around 23.3 Ma probably coincides with the opening of the Drake Passage and the growth of the East Antarctic Ice Sheet.

Keywords: Estuary, Gilbert-type delta, Oligocene-Miocene sea-level changes, Polykladichnus.

RESUMEN. Depósitos estuarinos en la Formación Río Baguales (Chattiano-Aquitaniano), Provincia de Magallanes, Chile. Hay muy pocos trabajos sobre la estratigrafía y sedimentología de la Formación Río Baguales del Oligoceno superior-Mioceno inferior en la Provincia de Magallanes del sur de Chile, luego de su primera definición en 1957. Se presenta un perfil estratigráfico detallado de la parte superior de la formación al oeste del río Baguales, con una interpretación de los ambientes de depositación. Se identificó una costa progradante con facies de boca de estuario, medio de estuario (laguna) y delta de cabecera. Las grandes capas frontales del talud deltaico indican progradación hacia el norte y noroeste, mientras que la presencia de laminación cruzada inclinada hacia el sureste sugiere la acción de oleaje. La sucesión en general refleja una caída gradual del nivel del mar, acompañada por subsidencia tectónica con la creación del espacio de acomodación necesario para la acumulación de potentes facies mareales y submareales. Un período de transgresión hacia la parte superior de la sucesión indica una subida del nivel del mar o una aceleración en la tasa de subsidencia tectónica, seguida por una regresión mayor que comenzó alrededor de 23,3 Ma, probablemente coincidente con la apertura del Pasaje de Drake y el crecimiento de la calota de hielo de la Antártica del este.

Palabras clave: Estuario, Delta tipo Gilbert, Cambios de nivel del mar del Oligoceno-Mioceneo, Polykladichnus.

1. Introduction

A little-known succession of marine deposits occurs in the Sierra Baguales about 120 km north of Puerto Natales, southern Chile (Fig. 1). Of uncertain stratigraphic position, age and correlation, it was defined by Hoffstetter *et al.* (1957) as the Río Baguales Formation, although earlier references had already been made to these deposits by Hauthal (1898) and Wilckens (1905). Hoffstetter *et al.* (1957) briefly described the formation as a 750 m thick sequence of shale, sandstone and conglomerate with numerous mollusk fossils, concordantly underlain by conglomerates of the Oligocene Cancha Carrera Formation and overlain by continental shale and sandstone rich in plant fossils belonging to the Las Flores Formation. They tentatively correlated the latter formation with the Oligocene (possibly lower Miocene) El Salto Formation north of the Gulf of Skyring.

On the 1:1,000,000 Geological Map of Chile (SERNAGEOMIN, 1982), the deposits are simply indicated as sub-littoral siltstones and shales correlated with the Eocene-Miocene Bahía Inútil Group, although the succession as a whole seems to correlate better with Oligocene-Miocene marine sandstones and coquinas east of Puerto Natales. The latter are correlated on the map with the Guadal Formation, described by Frassinetti and Covacevich (1999) in the Lake General Carrera district about 440 km to the north. According to this nomenclature, the Guadal Formation is overlain by the Santa Cruz Formation (De la Cruz and Suárez, 2006), a fluvial succession with mammal fossils that seems to correspond to the Las Flores Formation of Hoffstetter *et al.* (1957).

A different nomenclature is used for the formations correlated with these units in Argentina (Table 1). The Guadal Formation is there known as the Centinela Formation, which in turn was correlated by Griffin (1991) with the Río Turbio Formation of the Santa Cruz Province. A late Oligocene-early Miocene age (28-16 Ma) was assigned to both these formations based on their invertebrate fossils. On the other hand, the Santa Cruz Formation contains land mammals such as *Nesodon* belonging to the so-called Santacrucian fauna. According to radio-isotopic dates, the latter fauna range from 21.5-17.5 Ma (Bond and García, 2002; Charrier *et al.*, 2002; Flynn *et al.*, 2002; Croft *et al.*, 2003). If these correlations are correct, the Río Baguales Formation should therefore have a Chattian (latest Oligocene; 28.4-23.3 Ma) to Aquitanean (earliest Miocene; 23.03-20.43 Ma) age.

Considering the large distance between the type area of the Guadal Formation and Sierra Baguales, as well as the fact that different names are in use on different sides of the border, we consider the original definition of the succession in this area as the Río Baguales Formation to be a better alternative, at least until correlation can be proved by direct mapping or dating.

We measured a 240 m thick stratigraphic profile in the upper part of the formation west of the Baguales River (Fig. 1). The base of the section is situated in a deep ravine locally known as the 3R River (50°45'10.7"S/72°26'15.2"W), and its top is located at the base of a thick sill 2.58 km NW of the ravine (50°44'09.2"S/72°27'44.3"W). At the top of this sill about 750 m to the WNW (50°44'00.5"/72°27'09.1"), the succession continues as plant-bearing, interbedded shale, siltstone and very fine sandstone with medium- to coarse-grained sandstone lenses, but there is some uncertainty regarding its correlation. Part of the sequence may have been assimilated by the sill (as evidenced by outcrops along its southern border) and there is a strong possibility that these beds belong to the Las Flores Formation, which was originally described on the southern flank of Cerro Ciudadela northeast of the Baguales River (Fig. 1) by Hoffstetter *et al.* (1957).

2. Fossils in the Río Baguales Formation

Rodríguez and Oyarzún (2008) collected a large number of invertebrate fossils in the Río Baguales Formation between 1990 and 2007, including bryozoans, corals, crustaceans, brachiopods, bivalves, gastropods and nautiloids. Among these are species also found in the Guadal Formation of the Aysén Region (Frassinetti and Covacevich, 1999), including the brachiopod *Te-rebratella* aff. *patagonica* Sowerby, the bivalve *Pinna magellanica* Ihering, and gastropods such as *Gibulla dalli* Ihering, *Adelomelon burmeisteri* Ihering, and *Trochus laevis* Sowerby. Species also found in the Río Turbio Formation of Argentina (Griffin, 1991) include the bivalves *Panopea undatoides* Ortmann, *Lucina* cf. *neglecta* Ortmann, and *Nucula* cf. *suboblonga* Wilckens.

Vertebrates in the Río Baguales Formation are mostly represented by shark teeth, of which 10 different species were recorded from loose surface material of unclear stratigraphic origin. Several unidentified bone fragments of marine mammals were also recorded (Rodríguez and Oyarzún, 2008).

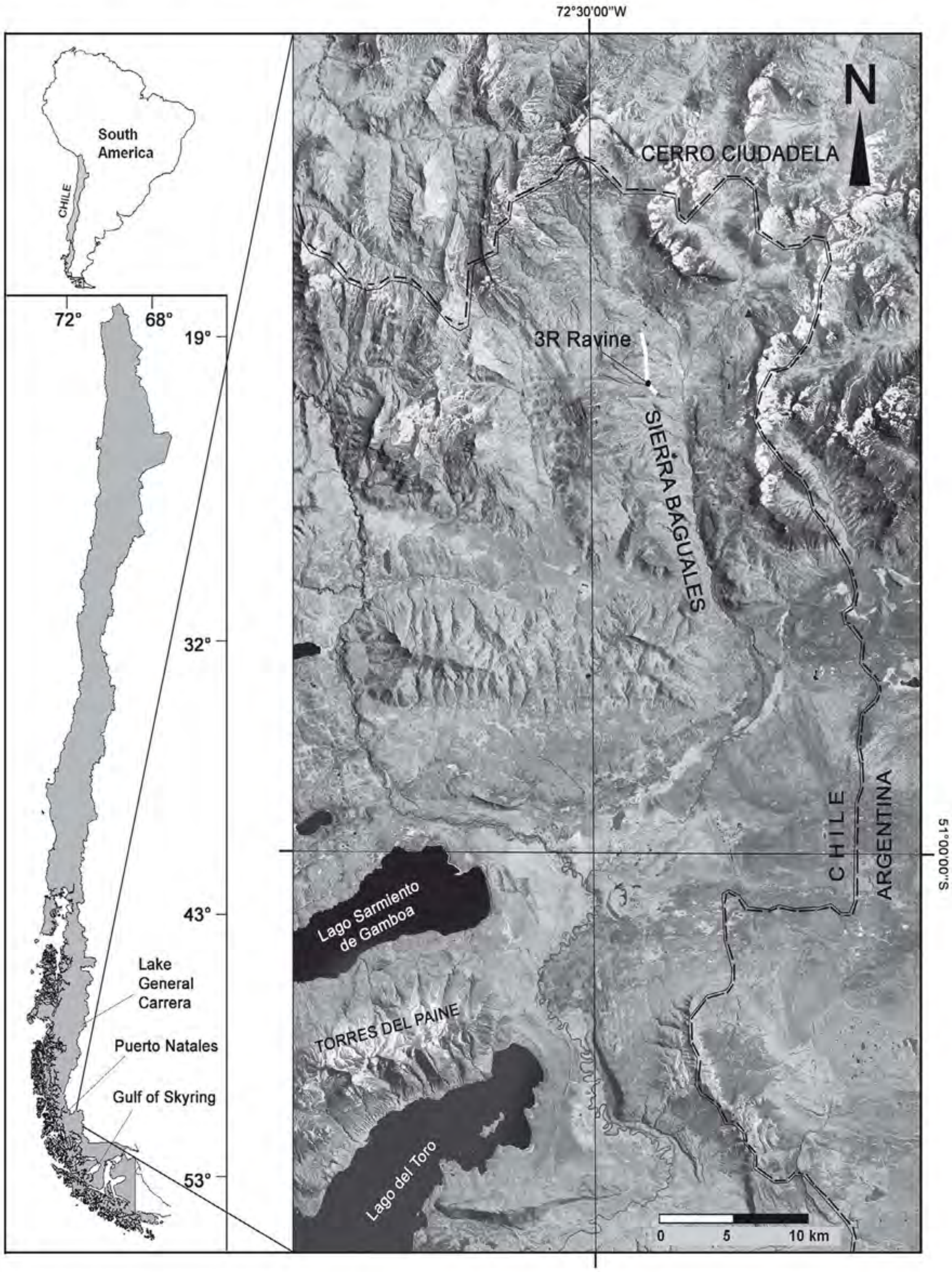

FIG. 1. Locality map and satellite image of Sierra Baguales area. White line north of 3R ravine indicates location of measured stratigraphic column (Fig. 2).

TABLE 1. CORRELATION OF RÍO BAGUALES AND LAS FLORES FORMATIONS WITH STRATIGRAPHIC UNITS AT THE GULF OF SKYRING AND LAKE GENERAL CARRERA (CHILE) AND IN ARGENTINA.

Sierra Baguales	Skyring/General Carrera	Argentina	Age
Las Flores Fm.	El Salto/Santa Cruz Fm.	Santa Cruz Fm.	21.5-17.5 Ma
Río Baguales Fm.	Guadal Fm.	Centinela/Río Turbio Fm.	28-21.5 Ma

The present field campaign has yielded abundant teeth that allow at least two different ecological and chronostratigraphic assemblages to be recognized. The first is represented by several taxa previously known exclusively from the Maastrichtian of central Chile, including one cosmopolitan family (Schlerorhynchidae) that remains unreported after the Cretaceous/Paleogene boundary. The studied assemblage includes the species *Ischyrhiza chilensis* Philippi (Rajiformes, Schlerorhynchidae), a very frequent taxon in Maastrichtian beds of the Quiriquina Formation (Biró-Bagóczky, 1982) and equivalent units of central Chile (Suárez and Cappetta, 2004), and the genus *Centrophoroides* (Squaliformes, Squalidae), known in Chile only from these units. A third characteristic taxon is constituted by a still unnamed dasyatid ray (Myliobatiformes; Dasyatidae), previously known exclusively from the Quiriquina Formation (Suárez *et al*., 2003; Muñoz-Ramírez *et al.*, 2007). The beds hosting this material are located in the western part of Sierra Baguales and stratigraphically underlie the measured section of this study by at least several tens of meters.

The second assemblage is characterized by a rich diversity of sharks, rays and chimeroid fishes, that includes the following identified taxa: *Striatolamia macrota* Agassiz (Lamniformes, Mitsukurinidae); *Carcharocles* aff. *angustidens* (Lamniformes, Otodontidae); *Myliobatis* sp. (Myliobatiformes, Myliobatidae) and *Callorhinchus* aff. *regulbensis* Gurr (Chimaeriformes, Callorhynchidae). Most of the host beds have been lost as a result of erosion higher up on the mountain, but hard material such as elasmobranch teeth, spines and other phosphatic bony elements have nevertheless been preserved in the soil. The scarce *in situ* material indicates that the host beds are located below conglomerates with bivalve casts possibly correlating with our unit 4 (see below). This assemblage shows affinities with typical Late Eocene faunas of the Tethyan coastal basins.

Plant remains are fairly rare in the Río Baguales Formation, being mostly of the genus *Nothofagus* (Rodríguez and Oyarzún, 2008). In the overlying Las Flores Formation, we collected 389 samples of which 70% are *Nothofagus*, including the species *N. paleoalessandri*, *N. subferruginea, N. simplicidens, N. serrulata, N. densinervosa,* and *N. variabilis.* Associated are 19 species of angiosperms.

In general, invertebrate fossils recovered from the Río Baguales Formation confirm its tentative correlation with the Chattian (28.4-23.0 Ma) Guadal and Río Turbio/Centinela Formations, whereas the second assemblage of sharks, rays and chimeroid fishes suggest a maximum Late Eocene age (33.9 Ma) for the basal part of our measured section.

3. Lithostratigraphy

We subdivide the measured portion of the Río Baguales Formation into nine informal lithostratigraphic units (Fig. 2).

3.1. Unit 1: Trough and planar cross-laminated sandstones containing *Skolithos* ichnofacies

The lower part of unit 1 (sub-unit 1a) is formed by a 15 m thick, coarsening-upward succession of fine- to coarse-grained, cross-laminated sandstones with some plant remains (fragments of tree trunks and leaves), trace fossils and rare shark teeth. The sandstones are light grey where fresh and weather from buff to light and reddish brown.

The basal, fine- to medium-grained sandstones (sub-unit 1a) show wide, shallow troughs as well as high-angle planar cross-lamination with occasional tree trunk fragments and shark teeth (Odontaspididae cf. *Carcharias*). Scattered clay pellets and thin lenses of clay pellet conglomerate are present. These sandstones are interrupted by thin, grey, bioturbated horizons of silty sandstone with lower flow regime horizontal-planar lamination,

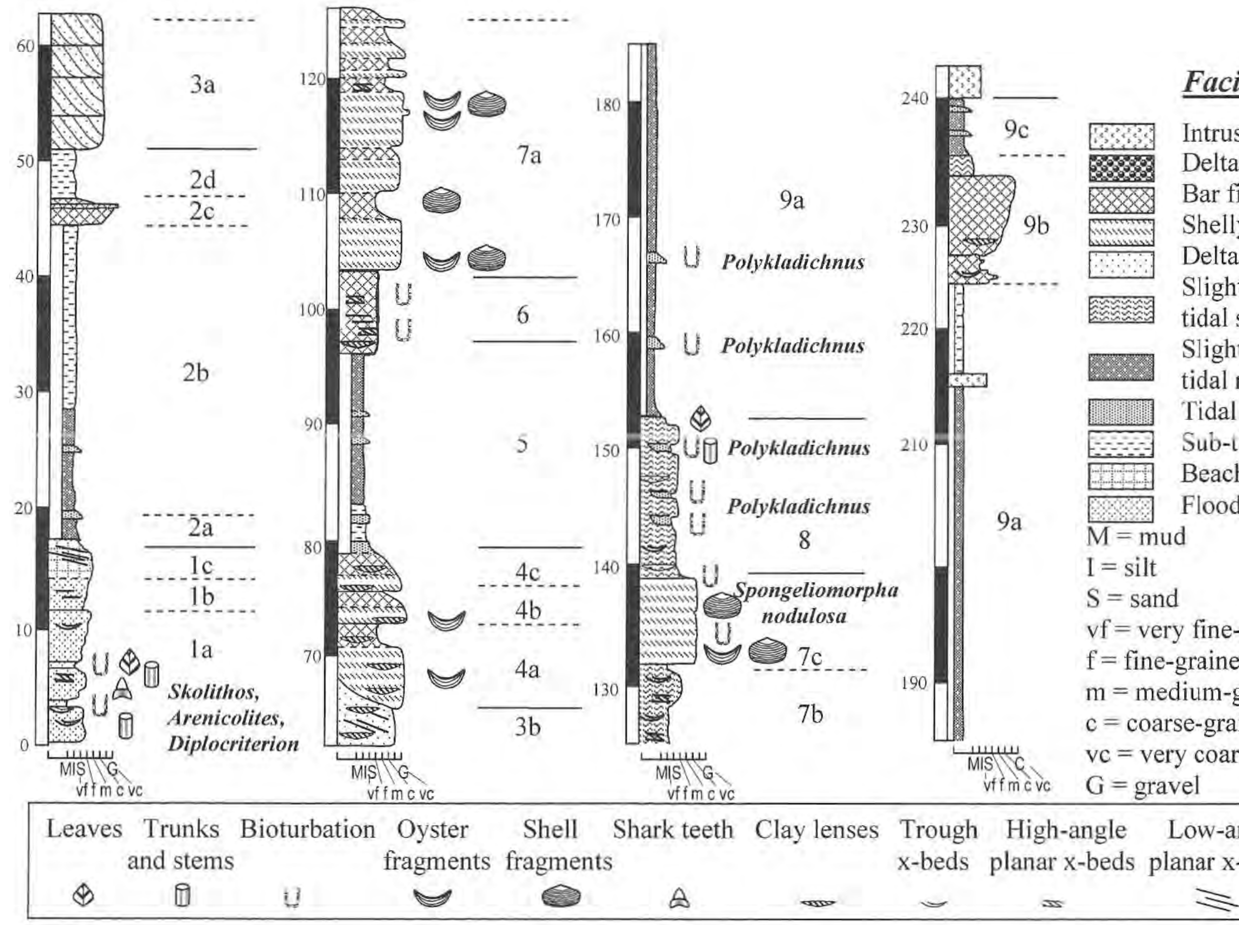

FIG. 2. Measured stratigraphic column in upper part of Río Baguales Formation. For location, see figure 1.

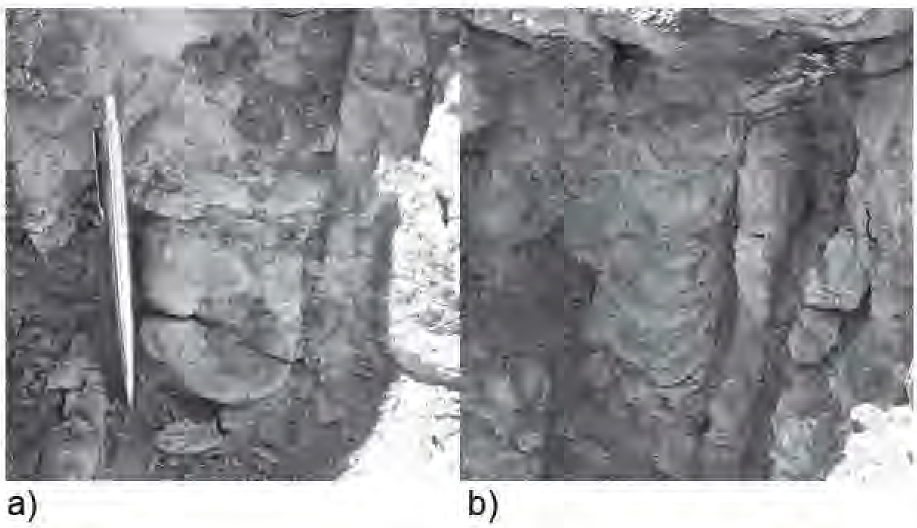

FIG. 3. Trace fossils in unit 1. **a.** *Arenicolites*; **b.** *Diplocriterion*. Same scale used on both photographs.

which contain plant fragments and trace fossils including *Arenicolites*, *Skolithos*, and *Diplocriterion* (Fig. 3). Unidentified, oblique to horizontal tubes about 1 cm in diameter, without spreiten, were also observed.

Towards the top of unit 1 are fine- to coarse-grained sandstones with scattered pebbles and small to medium-sized troughs (sub-unit 1b), overlain sharply by medium- to coarse-grained sandstone showing low-angle tangential cross-lamination and upper flow-regime horizontal-planar lamination (sub-unit 1c).

3.2. Unit 2: Interbedded siltstone and shale with minor sandstone and coarsening-up conglomerate lenses

Sub-unit 2a at the base of this unit has a thickness of about 4.5 m, consisting of light brown, medium- to very fine-grained sandstones with vague cross-lamination. These grade into a partially covered, soft-weathering interval of dark grey shale and siltstone with a total thickness of about 22.6 m (sub-unit 2b), individual beds ranging between 5 and 10 cm in thickness. The siltstone-shale interval is interrupted near its top by sub-unit 2c, a 2 m thick, massive, very coarse-grained sandstone grading to fine-grained conglomerate with well-rounded chert clasts in its uppermost 20-30 cm. It has a gradual contact with the overlying shale and siltstone of sub-unit 2d, which is 4.6 m thick.

3.3. Unit 3: Sandstones and conglomerates with large-scale planar cross-bedding

Unit 3 is represented by two large-scale cross-bedded sub-units of coarse- to very coarse-grained sandstones and conglomerates apparently devoid of fossils. The basal sub-unit (3a) is an almost 12 m thick, coarse- to very coarse-grained sandstone interbedded with fine-grained conglomerate arranged into high-angle planar cross-bedded sets each about 3 m thick. Each cross-bed is composed of 5-10 cm of conglomerate grading into 10-20 cm of coarse-grained sandstone, with recorded dips of 27° towards the north (Fig. 4). This sub-unit is sharply overlain by sub-unit 3b, a 3.5 m thick conglomeratic sandstone with chert and lava pebbles up to 5 mm in diameter, as well as large mudstone clasts reaching 70 cm in length that were probably derived from *in situ* lenses of mudrock located close by. The conglomeratic sandstone shows large-scale cross-bedding dipping at 20-24° towards the northwest.

FIG. 4. Large-scale high-angle planar cross-beds in unit 3a. Thickness of cross-bed set between stippled lines is 3 m.

3.4. Unit 4: Lenticular interbeds of pebbly sandstone, sandy, locally fossiliferous conglomerates and mudrock lenses

Overlying unit 3 with a sharp contact, this 13.8 m thick unit is characterized by sandy conglomerates, pebbly sandstones, sandstones with conglomerate and mudrock lenses and locally fossiliferous conglomerates with sandstone and mudrock lenses.

The basal sub-unit (4a) is a lenticular, massive, clast-supported conglomerate with pebbles generally less than 5 mm in diameter, but reaching up to 2 cm. It has a medium-grained sandstone matrix. Lenses of intercalated clay and very fine-grained sandstone are present in its lower portion, and towards the top it grades into massive, medium-grained sandstone with conglomerate lenses up to 20 cm thick. Sub-unit 4a has a maximum thickness of 7.6 m and is overlain with a sharp contact by sub-unit 4b, a horizontally-stratified conglomerate containing oyster fragments (possibly *Ostrea torresi*, considered to be synonymous to *Ostrea orbignyi* by Brandmayr, 1946) and other shell debris, as well as thin shale lenses, grading upward into coarse-grained sandstone intercalated with clay lenses. A total thickness of 2.4 m was recorded. Sub-unit 4c, 3.8 m thick, also has a sharp basal contact and consists of well-stratified clast- to matrix-supported conglomerates intercalated with lenticular shale up to a few cm thick, which in turn fine upward into medium-grained sandstone with clay lenses.

3.5. Unit 5: Interbedded siltstone and shale with minor sandstone

Similar to unit 2, this unit is largely covered, but shows occasional outcrops of fine- to medium-grained sandstone. It has a total thickness of about 17 m.

3.6. Unit 6: Horizontal-planar laminated and cross-laminated, bioturbated sandstone

This unit, about 7 m thick, is formed by upper flow regime horizontal-planar laminated, medium-grained sandstone with conglomerate lenses, sharply overlain by fine- to medium-grained, trough and planar cross-laminated sandstone with clay and shale lenses. The latter are oxidized and partially bioturbated.

3.7. Unit 7: Lenticular interbeds of pebbly sandstone, sandy, locally fossiliferous conglomerates and mudrock lenses

Unit 7 is lithologically similar to unit 4, but reaches a total thickness of about 32 m. At the base are about 20 m of massive, fossiliferous, clast-supported conglomerates interspersed with less fossiliferous, matrix-supported conglomerates and subordinate fine- to coarse-grained sandstone with rare shell fragments and conglomerate lenses (sub-unit 7a). Contacts between these different lithologies are dominantly gradual. Although the sandstones are generally massive, vague cross-lamination can be discerned locally. The conglomeratic interval is overlain by a dominantly arenaceous zone about 6 m thick (sub-unit 7b), consisting of fine- to very coarse-grained sandstone showing massive bedding, horizontal-planar lamination, as well as trough and planar cross-lamination. This sub-unit is followed by another fining-upward succession of fossiliferous conglomerates grading upward into very coarse- to medium-grained sandstones (sub-unit 7c). It commences with a matrix-supported conglomerate containing poorly to moderately sorted chert and volcanic pebbles as well as scattered clay pellets, showing medium-scale (~50 cm), planar cross-bedding dipping 28° towards the southeast. Fossil fragments include bivalves, oysters and gastropods. The conglomerate is overlain with a sharp contact by a medium-grained, clast-supported conglomerate containing chert and volcanic clasts at the base, but showing an increase in clay pellets towards the top. This unit is massive to low-angle planar cross-bedded.

In addition to scarce bivalve fragments, slightly sinuous, branching traces about 1 cm in diameter and more than 20 cm long are present, showing an incomplete lining of clay pellets (Fig. 5). In shape the traces resemble *Spongeliomorpha nodosa*, although the clay pellets are more typical of *Ophiomorpha irregulaire*

FIG. 5. Trace of *Spongeliomorpha nodulosa* in conglomerates of unit 7c.

Frey *et al.*, 1978. Schlirf (2000) recommended synonymization of *Ophiomorpha* Lundgren, 1891 with *Spongeliomorpha* Saporta, 1887, but Bromley and Pedersen (2008) suggested that *Ophiomorpha* should rather be considered as an ichnosubgenus of *Spongeliomorpha*. However, because *Ophiomorpha irregulaire* has thus far been reported only from the Jurassic and Cretaceous and seems to have wider tunnels (Bromley and Pedersen, 2008), we consider the ichnogenus to be *Spongeliomorpha*.

3.8. Unit 8: Cross-laminated, very coarse to medium-grained sandstone with clay pellets and fine-grained, bioturbated, dark red sandstone lenses

Unit 8 has a gradational contact with the conglomerates of sub-unit 7c and reaches a total thickness of about 13 m. The basal part fines upward into light grey to buff, very coarse, trough cross-laminated sandstone with small clay pellets and fine-grained, dark red sandstone lenses. The latter contains small (2 mm thick, 2 cm long) y-shaped *Polykladichnus* traces, as well as calcareous concretions on average 20-30 cm in diameter. This is followed by medium-grained sandstone with numerous small clay pellets, also containing dark red, fine-grained sandstone lenses with *Polykladichnus* traces. At the top is a reddish brown, fine sandstone with scattered chert pebbles, clay pellets and plant fragments.

3.9. Unit 9: Interbedded siltstone and shale with minor sandstone and coarsening-up conglomerate lenses

The basal sub-unit 9a, which has a total thickness of 69.5 m, is composed of largely covered, buff-colored shale with occasional beds or lenses of yellowish to dark brown, fine-grained, massive sandstones containing *Polykladichnus* traces. This predominantly fine-grained succession is interrupted by sub-unit 9b, a 9 m thick, coarse-grained interval with a sharp basal contact and gradual top. The basal part consists of trough cross-laminated, fine- to very coarse-grained sandstone intercalated with thin (up to 10 cm) conglomerate lenses. The latter contain small, well-rounded pebbles of sandstone and chert. The sandstones grade into coarsening-up conglomerates varying from matrix-supported at the base to clast-supported at the top, where pebbles reach up to 5 cm in diameter. Lenses of medium- to coarse-grained sandstone are present within the conglomerate. The top of the conglomerate grades through very fine-grained sandstone to 6.8 m of interbedded siltstone and shale (sub-unit 9c) up to the base of a thick sill (50°44'09.2"S/72°27'44.3").

Although we consider this to represent the top of our section, the succession possibly continues about 750 m towards the WNW. Here an almost 17 m thick sequence of interbedded shale and siltstone with occasional very fine-grained sandstones containing plant fossils and thin carbon seams and lenses overlies the sill. Showing some typical characteristics of fluvial deposits (*e.g.*, sandstones filling channels), there is a possibility that this already belongs to the base of the Las Flores Formation.

4. Facies description and paleoenvironmental interpretation

The presence of marine fossils in the Río Baguales Formation, together with oyster and plant fragments, suggest a salt- to brackish water environment with input from a nearby river. However, a delta can probably be ruled out, as the succession lacks the typical coarsening-upward profile of a prograding delta, as well as other characteristic features such as levee or marsh deposits. On the other hand, many of the features typical of an aggradational estuary are represented, which include thick mud- and siltstone deposits requiring a fairly protected environment.

Estuaries are generally subdivided into three main depositional environments, but the terminology varies from author to author (*e.g.*, Roy *et al.*, 1980; Nichols *et al.*, 1991; Dalrymple *et al.*, 1992; Allen and Posamentier, 1993). Here we define an estuary mouth, middle estuary (lagoon) and bay head delta facies within the Río Baguales Formation, each with its own characteristic subfacies.

4.1. Estuary mouth facies

The estuary mouth environment includes barrier spits with sandy beaches, together with tidal inlet channels, tidal deltas and sand bars (Dalrymple *et al.*, 1992; Buatois *et al.*, 1997). In the Río Baguales Formation this facies is represented by unit 1, which consists of a generally coarsening-upward succession of trough to planar cross-laminated sandstone with bioturbated intervals. Two subfacies are recognized.

4.1.1. Flood tidal deltas

Within sub-unit 1a, a trace fossil suite of *Skolithos*, *Arenicolites* and *Diplocriterion* belonging to the *Skolithos* ichnofacies, indicates the presence of organisms filtering organic material kept in suspension by wave or current action or deposited within the sediments during slack periods. Energy conditions of the *Skolithos* ichnofacies are generally moderate to high, with alternating periods of erosion and deposition (Buatois *et al.*, 2002). Although this ichnofacies is typically associated with shoreface facies, such an environment is contradicted by the presence of tree trunks, other plant fragments, and clay pellets, which will rarely be found in the surf zone along open coastlines. These materials typically collect on the upper beach or backshore, from where they may be transported by storm waves onto washover fans and flood tidal deltas within the estuary mouth.

Washover fans can probably be eliminated as a possible environment, because they are generally characterized by upper flow regime parallel stratification and low-angle, landward-dipping planar cross-stratification (Schwarz, 1975), as well as antidunes and chute- and-pool structures, which were not observed. The presence of planar and trough cross-lamination, on the other hand, is compatible with straight-crested and lunate dunes on flood tidal deltas (Boothroyd, 1985; Elliot, 1986; Reinson, 1992). A shark tooth crown found in sub-unit 1a (not *in situ*) belongs to the Odontaspididae cf. *Carcharias* or sand tiger sharks. These are extant littoral sharks today found in warm-temperate and tropical coastal waters, where they inhabit offshore banks and reefs as well as troughs in sandy coastal sediments. However, they also venture into shallow bays and estuaries (http://www.marineboidiversity.ca/shark/english/stiger.htm), and although they have been recorded from the intertidal zone down to about 200 m, most are found at a depth between 15 and 25 m (Compagno, 2001).

The clay pellets commonly found in this facies probably derive from surrounding higher, dessicated supratidal flats with semi-consolidated muds, which would explain their conservation.

4.1.2. Barrier spits

Barrier spits are probably represented by sub-unit 1c, which is formed by a medium- to coarse-grained sandstone with low-angle planar cross-lamination and upper flow regime horizontal-planar lamination. These are typical foreshore features (Nichols, 1999).

A single, about 2 m thick planar cross-bedded sandstone (Fig. 6) observed at some distance from the measured section but evidently within unit 1, might represent the tip of a migrating barrier spit from which

FIG. 6. Large-scale planar cross-bedded set in unit 1, possibly representing a migrating barrier spit.

sand avalanched into the tidal inlet channel (Johannessen and Nielsen, 1986). However, this unit was not investigated in any detail.

4.2. Middle estuary (lagoon) facies

The middle estuary can be described as that part of the system largely protected from wave action and only occasionally affected by river input. It includes the lagoon and surrounding tidal flats landward of the barrier spits. In the Río Baguales Formation, this facies also includes bar-finger gravels that prograded into the lagoon during periods of high sediment input.

In the description of tidal flat facies below, the classification scheme of Flemming (2000) is used, where mudflats have more than 95% mud, slightly sandy mudflats between 75 and 95% mud, sandy mudflats between 50 and 75% mud, muddy sandflats between 25 and 50% mud, slightly muddy sandflats between 5 and 25% mud, and sandflats less than 5% mud.

4.2.1. Subtidal zone and slightly sandy tidal mudflats

This facies occurs in sub-units 2b, 2d, 9a and 9c. It is composed of intercalated dark grey, buff-weathering siltstone and shale forming successions between 30 m and 70 m thick, with individual beds varying between 5 and 10 cm. These deposits are interpreted as muddy subtidal (lagoon) facies and distal (with respect to the river mouth) slightly sandy tidal mudflat facies, although their generally poor exposure precludes the proper distinction of these two sub-environments. Slightly sandy mudflats generally occur landward of slightly muddy sandflats, for example where wave action winnows fines along the seaward edge, which are then carried by flood tides towards the supratidal zone (Reinson, 1992). However, within estuary lagoons such facies can also occur in distal areas partially protected from wave action (such as behind barrier spits) and away from the influence of strong inflowing river currents. Under such conditions they may grade into sub-tidal muds deposited in the deeper water of the lagoon.

4.2.2. Slightly muddy tidal sandflats

This mainly arenaceous facies occurs in units 6 and 8, where it forms a transitional zone between slightly sandy mud flats and delta front facies. The sandstones are light grey to light brown and buff-weathering, varying from very coarse- to very fine-grained. They are locally massive, but generally show upper flow regime horizontal-planar lamination, as well as trough and planar cross-lamination. The sandstones commonly contain clay pellets and clasts, as well as lenses of conglomerate and clay, the latter often showing bioturbation. Shell fragments are occasionally present.

The association of this facies with both delta front and slightly sandy tidal mudflat facies suggests that it occurred in a more proximal environment than the latter, closer to the delta slope and river mouth (Fig. 7). The presence of trough and planar cross-lamination indicates fairly strong currents, possibly enhanced during ebb-flow when bedforms such as lunate and straight-crested dunes migrated seaward. Horizontal-planar lamination, on the other hand, could be attributed to wave action on local beaches developing along the edge of the tidal flats. Waves passing through the estuary inlet would have broken directly on the opposite delta slope and adjacent tidal flats, whereas they would have been mitigated in the areas close to the inlet by deeper water within the estuary itself, as well as the orientation of the coastline with respect to the direction of wave propagation.

4.2.3. Tidal creeks

The third middle estuary subfacies is formed by dark to reddish brown and dark red (yellowish-weathering), fine-grained, massive sandstones occurring as lenses or beds within the slightly sandy tidal mudflats of unit 9a and the slightly muddy tidal sandflats of unit 8. Distinguishing characteristics of these sandstones include the presence of minute, y-shaped *Polykladichnus* traces, abundant clay pellets, occasional plant fragments, and calcareous concretions.

Polykladichnus is presently formed by polychaetes, *e.g., Nepthys* and *Nereis*, on modern tidal flats

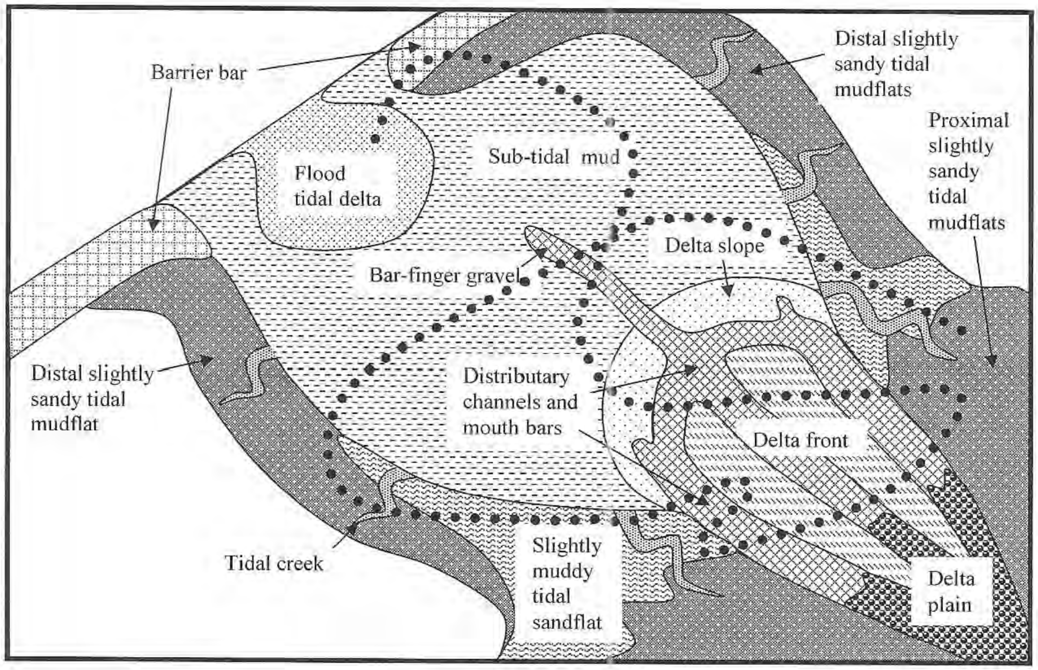

FIG. 7. Schematic paleogeographic reconstruction during the deposition of the Río Baguales Formation. Thick, stippled black line indicates inferred time-sequence of facies deposition, starting with flood tidal delta sands and ending with proximal slightly sandy tidal mudflats, which eventually grade into the continental Las Flores Formation. Legend as in figure 2.

(http://graduate.eas.ualberta.ca/lzabcic/web-content/Ichnology.html) and in the muddy point bar deposits of tidal creeks (Pearson and Gingras, 2006). Such an environment is supported by the fining-upward nature of these sandstones, which is typical of point bars in meandering river systems. The scarcity of chert and volcanic clasts indicates that these creeks did not extend far into the hinterland, whereas the abundance of clay pellets can be attributed to bank collapse of partially dried tidal flat muds during meander undercutting.

The fact this subfacies is finer-grained than the slightly muddy sandflat facies in unit 8 may be because these creeks drained slightly sandy mudflats landward of the latter, or because winnowing of fines by waves would have been abated by the deeper water and seaward current flow within the channels.

4.2.4. Bar-fingers

Fine- to very coarse-grained, massive to trough cross-laminated, lenticular sandstones with sharp basal contacts, grading upward into matrix- and then clast-supported conglomerate with well-rounded chert and volcanic clasts are attributed to this facies, which occurs in units 2c and 9b. The sandstones contain thin conglomerate lenses with similar pebbles, whereas the conglomerates enclose thin, medium- to coarse-grained sandstone lenses and fine upward into the siltstone-shale sub-facies. The erosive basal contacts, together with the presence of lithologically different lenses and cross-lamination, indicate shifting turbulent currents, so that these lenses are interpreted as bar-finger gravels formed by distributary mouth bars prograding over the delta slope and into the sub-tidal environment. Such bar-finger deposits typically show inverse to normal grading (Fisk *et al.*, 1954; Leeder, 1999). However, that debris flow events may also have contributed to these deposits cannot be excluded. Kleinspehn *et al.* (1984) and Surlyk (1984) interpreted inverse to normally graded gravels associated with fan-delta sequences as having formed from high-density turbidity currents transitional to liquefied flows. In the Río Baguales Formation, such hyperconcentrated flows would probably have exploited existing channels formed by distributary mouth progradation, or may have originated as slump scars on the steep, Gilbert-type delta slope (Postma *et al.*, 1983; Massari, 1984).

4.3. Bayhead delta facies

4.3.1. Delta front (subaquatic platform)

This facies occurs in unit 7 and is characterized by lenticular units of fossiliferous conglomerates with sharp basal contacts grading upward into sandstones. The conglomerates are matrix- to clast-supported with numerous small, very fine-grained sandstone, siltstone and clay lenses showing bioturbation. They contain oyster, gastropod and bivalve fragments as well as occasional traces of *Spongeliomorpha nodosa*. The presence of oysters suggests a brackish water environment closer to the river outlet.

The conglomerates are generally massive to horizontally stratified, but also show low-angle planar cross-bedding as well as planar cross-beds dipping 28° towards the southeast. This dip is opposite to the northerly and northwesterly dip of large-scale cross-beds on the delta slope, which either suggests that flood tides strong enough to transport pebbles and form straight-crested megaripples affected this part of the delta front (which we consider unlikely in the present setting), or that wave action caused the landward migration of shore-parallel gravel bars. Wave action on local beaches formed by partially submerged gravel bars may also be responsible for the horizontal-planar stratification to low-angle planar cross-bedding (Nemec and Steel, 1984).

Spongeliomorpha nodosa has been reported from medium- to very coarse-grained sandstone containing shell debris, deposited in storm and wave-influenced upper shoreface to foreshore environments in Jurassic deposits in France (Schlirf, 2000), and would thus fit into a delta front environment. This trace is probably made by crustaceans (Schlirf, 2000) and commonly belongs to the *Glossifungites* ichnofacies, which reflects firmgrounds somewhat resistant to erosion, typically consisting of surfaces formed by estuarine incision, tidal channel migration, coastal erosion, or shoreface retreat (Pemberton *et al.*, 1992; MacEachern *et al.*, 1992).

The sandstones are generally pebbly, coarse to medium-grained and contain conglomerate and mudrock lenses. The presence of trough and planar cross-lamination indicates current action, so that they are interpreted as distributary channel and mouth bar deposits on the delta front. Rojas and Le Roux (2005), in their study of the underwater morphology and sedimentology of a Gilbert-type delta in Lake Llanquihue, southern Chile, reported distributary channels filled with matrix-supported gravel and gravelly sand traversing pebble and cobble bars on the inner delta front. The latter are affected by wave action that winnows much of the sand fraction, whereas the somewhat deeper distributary channels are more protected and contain finer-grained sediments. The distributary mouth bar and outer delta front are also formed by pebbly sand facies. The distribution of algae on the Lake Llanquihue delta coincides with the cobble bars of the inner delta front, which also attract gastropods. A similar situation might explain the relative abundance of oyster and other shell fragments within the delta front gravel bar facies of the present study area, in comparison with their relative scarcity within the distributary channel and mouth bar facies, as well as in the delta slope facies. Because it is inconceivable that marine organisms would be able to cope with strong river flow and gravel transport, their presence in this setting probably indicates strongly seasonal or episodic flow, with organisms being able to settle and grow during lower river stages.

Rigsby (1994) described a very similar delta front facies assemblage in the Santa Ynez Mountains of California as consisting of non-graded to normally graded, sandy, cobble to pebble conglomerates and conglomeratic sandstones forming both channelized and non-channelized units, with abundant oysters, pecten and shallow water gastropods, burrowed bed tops, and small-scale lenticular bedding.

4.3.2. Gilbert-type delta slope

Occurring in unit 3a, this facies is composed of apparently unfossiliferous, coarse to very coarse sandstones and conglomerates with chert and lava pebbles generally less than 5 mm in diameter, as well clay pellets and clasts. The facies is characterized by large-scale planar cross-bedding with tangential bases dipping between 20 and 27° towards the north and northwest. Cross-bed sets are 3-3.5 m thick, with individual cross-beds reaching 30 cm in thickness and showing distinctly bipartite, fining-upward trends from conglomerate to coarse-grained sandstone. However, contacts between the foresets are gradual. Similar foresets have been described on Gilbert-type delta slopes in Lake Llanquihue (Rojas and Le Roux, 2005) and on the shores of Lake General Carrera in southern Chile (Bell, 2009).

The superposition of cross-bed sets indicates periods of rapid marine transgression followed by delta progradation. Although the apparent absence of fossils could be attributed to a rapid sedimentation rate and unstable slope setting relatively hostile to organisms, Rojas and Le Roux (2005) did record the presence of bivalves on the Lake Llanquihue delta slope. On the other hand, Bell (2009) found no fossils on similar foresets at Lake General Carrera.

4.4. General paleoenvironmental interpretation

Estuaries are normally classified into salt-wedge, well-mixed, partially mixed and fjord types (Pritchard, 1955; Duxbury and Duxbury, 2001). The first type forms where there is strong river inflow and relatively weak tides, the second where intertidal volumes are strong and river inflow is weak, the third where both strong tidal flows and relatively high rates of freshwater discharge occur, and the fourth in fjords experiencing weak tidal currents, except at the entrance. The studied succession apparently reflects a hydrodynamically variable estuary, with evidence for tidal effects (presence of tidal flats with tidal creeks) offset by strong river discharge periods. It is conceivable that the latter episodes coincided with relative marine regression, during which seaward progradation of the Gilbert-delta took place. However, seasonal discharge allowed marine organisms to settling during low river stages. The tens of meters of slightly sandy tidal mudflat and subtidal facies, on the other hand, were probably deposited during marine highstand periods, when this part of the estuary changed from a river- and wave-dominated to tide-dominated environment.

A generalized paleoenvironmental interpretation of the Río Baguales Formation is presented in figure 7. This shows a bay head delta prograding from the south-southwest into an estuary partially protected from the open sea by sand spits at the entrance. Bay head deltas are commonly associated with wave-dominated estuaries (Reinson, 1992; Roy, 1994) and this sub-environment is here attributed to a high rate of sedimentation because of a surrounding mountainous terrain and possibly high, albeit sporadic rainfall. Separation of the tidal flats into slightly sandy mudflats and slightly muddy sandflats suggests wave action, which would have had a stronger winnowing effect near the delta itself where the waves would have suffered little refraction. Behind the sand spits at the entrance, an environment relatively protected from wave action probably existed so that muddy sediments accumulated on the flats.

5. Relative sea-level and climate changes

One of the key differences between deltas and estuaries is that the former are normally progradational sediment bodies showing a coarsening-upward succession, whereas estuaries are mainly aggradational, building up within a drowned river channel (Nichols, 1999). The base of the measured profile, unit 1, reflects an estuary mouth environment with barrier spits succeeding tidal inlet and flood tidal delta deposits, so that this part of the succession reflects marine transgression, probably accompanied by lateral migration of the inlet channel. Unit 2 is represented by distal, slightly sandy tidal mudflat and sub-tidal deposits, which occur landward of the barrier spits and so represent seaward progradation of the estuary complex. Nevertheless, the relatively great thickness of these deposits indicates the creation of new accommodation space, which could have been provided by tectonic subsidence and an increase in the relative water depth as the estuary itself migrated over and eroded its distal mudflats. The delta slope deposits of unit 3 must have prograded over sub-tidal sediments on the estuary floor in a water depth of at least 3 m. The superposition of 4 large-scale cross-bed sets indicates episodes of relative sea-level rise interrupted by pulses of delta progradation. The delta front deposits of unit 4, on the other hand, reflect seaward progradation accompanied by lateral migration of distributary mouth bars and channels that eroded gravel bars subject to wave action on the inner delta front. Unit 5 marks a return to slightly sandy tidal mudflats, but the latter in this case probably formed in a more proximal environment landward of the slightly muddy tidal sandflats flanking the delta, implying further seaward progradation. This is supported by the presence of tidal creek sandstones and the absence of bar-finger gravels in unit 5. The slightly sandy tidal mudflats were replaced by the slightly muddy tidal sandflats of unit 6, which suggests a renewed sea-level rise due to tectonic subsidence. Lateral migration of the delta, possibly accompanied by a continued rise in sea level, then temporarily replaced the slightly muddy tidal sandflats with delta front sedimentation as reflected in unit 7, before returning once again to slightly muddy sandflat deposition (unit 8). Unit 9 indicates initial slightly sandy tidal mudflat sedimentation followed by marine transgression to sub-tidal depths, as suggested by the presence of well-developed bar-finger gravels in the uppermost part of the succession. However, from this point in time the entire estuarine-delta system commenced to prograde seaward again, with sub-tidal deposits grading upward into slightly sandy tidal mudflats and finally the fluvial deposits of the Las Flores Formation.

Deep-sea $^{18}\delta O$ ice-volume records indicate that glacial-interglacial eustatic sea-level fluctuations of 10-40 m associated with orbital cycles occurred during the late Oligocene (Pekar *et al.*, 2006; Naish *et al.*, 2008), which probably account for the sea-level oscillations observed within the measured part of the Río Baguales Formation. Figure 3 of Naish *et al.* (2008) shows a regression from 23.8-23.5 Ma followed by a eustatic transgressive cycle from 23.5 Ma until 23.3 Ma, and then a marked sea-level drop commencing at 23.3 Ma. We correlate the first regression cycle with the more or less sustained fall in sea-level shown by units 2-8, whereas the marine transgression reflected by unit 9 possibly coincides with the sea-level rise between 23.5 and 23.3 Ma. The marked sea-level fall during the final stages of deposition of the Río Baguales Formation is consistent with evidence for a global marine regression straddling the Oligocene-Miocene boundary and commencing at 23.3 Ma. Known as the Mi-1 glaciation (Miller *et al.*, 1991) the growth of the East Antarctic Ice sheet caused a relative drop of about 50 m in sea-level at this time (Naish *et al.*, 2008). Various authors (*e.g.*, Shackleton and Kennett, 1975; Barker and Burrell, 1977) have linked this event to the opening of the Drake Passage between Antarctica and South America at the end of the Oligocene, which initiated the circum-Antarctic deepwater ocean current and caused cooling of the Antarctic landmass to its actual condition.

Acknowledgements

This study was completed as part of Project ARTG-04, Conexiones Geológicas entre Antártica Occidental y Patagonia desde el Paleozoico Tardío: Tectónica, Paleogeografía, Biogeografía y Paleoclima, carried out under the auspices of the World Bank, CONICYT and INACH. We are greatly indebted to Mr. J. Maclean for allowing us access to the 3R Ranch. Three reviewers (B. Flemming, H. Bahlburg and L. Spaletti) made very valuable comments that helped us to improve this paper considerably.

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Manuscript received: July 13, 2009; revised/accepted: November 13, 2009.