

## A Late Eocene age proposal for the Loreto Formation (Brunswick Peninsula, southernmost Chile), based on fossil cartilaginous fishes, paleobotany and radiometric evidence

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**ABSTRACT.** We present new data on the paleoichthyology, paleobotany and radiometric results of the Loreto Formation in the Brunswick Peninsula of southernmost Chile, that allow us to propose a Late Eocene age. The rich diversity of fossil cartilaginous fishes (Chondrichthyes, Elasmobranchii) recognized in upper levels of this unit includes the taxa *Carcharias* aff. '*hopei*' (Agassiz), *Odontaspis* sp., *Carcharoides caticus* (Philippi), *Striatolamia macrota* (Agassiz), *Anomotodon* sp., *Macrorhizodus praecursor* (Leriche), *Galeorhinus* sp., *Abdounia* sp., *Hexanchus* sp., *Squatina* sp., Hexanchidae indet., *Myliobatis* sp., *Myliobatoidea* indet., and *Ischyodus dolloi* Leriche. This assemblage has clear ecological affinities with Eocene Tethyan fauna previously described in the Northern Hemisphere, and also has common elements with Eocene cartilaginous fishes from Antarctica. Additionally, a paleobotanic study of this unit identified leaf imprints of *Asplenium* sp., *Pteris* sp., *Podocarpus* sp., and abundant angiosperms including *Nothofagus lanceolata* Dusén, *N. simplicidens* Dusén, *N. variabilis* Dusén, *N. cf. alessandri* Espinosa, *N. subferruginea* (Dusén), *Hydrangea* sp. and *Phyllites* spp. Wood remains of *Nothofagoxylo scalariforme* Gothan and *Araucariaceae* cf. *Araucarioxylo* Kraus were also identified. Additionally, pollen grains indicate gymnosperms and angiosperms: *Podocarpidites otagoensis* Couper, *Retitricolpites* sp., *Tricolpites* sp., *Liliacidites* sp., *Polyporina* sp., *Nothofagidites cincta* Cookson, and *Nothofagidites cranwellae* Couper, having affinities with Eocene floras, and being consistent with the age of the fossil fishes. Finally, a SHRIMP U-Th-Pb analysis of two samples collected from the studied beds provided thirty-eight and sixty zircon grains, indicating a clear main peak at 36.48±0.47 Ma (MSWD=1.5) and 36.73±0.50 Ma (MSWD=0.65). The integrated results indicate that the upper part of the Loreto Formation has a minimum Priabonian age, supporting previous reassignments of this part of the formation into the Late Eocene, and differing from the Oligocene age proposed in its original definition.

**Keywords:** Fossil cartilaginous fishes, Paleobotany, Shrimp U-Th-Pb, Priabonian, Loreto Formation, Southernmost Chile.

**RESUMEN** Una edad eocena tardía propuesta para la Formación Loreto (península de Brunswick, extremo sur de Chile), basada en peces cartilaginosos fósiles, paleobotánica y evidencia radiógena. El presente estudio integra nueva evidencia paleoictiológica, paleobotánica y resultados radiométricos que en conjunto permiten proponer una edad eocena tardía para la Formación Loreto, en la península de Brunswick del extremo sur de Chile. La rica diversidad de peces cartilaginosos fósiles (Chondrichthyes, Elasmobranchii) reconocida en niveles superiores de la mencionada unidad incluye los taxa *Carcharias* aff. *hopei* (Agassiz), *Odontaspis* sp., *Carcharoides caticus* (Philippi), *Striatolamia macrota* (Agassiz), *Anomotodon* sp., *Macrorhizodus praecursor* (Leriche), *Galeorhinus* sp., *Abdounia* sp., *Hexanchus* sp., *Squatina* sp., Hexanchidae indet., *Myliobatis* sp., Myliobatoidea indet., e *Ischyodus dolloi* Leriche. Este conjunto muestra claras afinidades ecológicas con ictiofaunas del Eoceno tethyano previamente descritas en el Hemisferio Norte, a la vez que presenta elementos comunes con peces cartilaginosos del Eoceno de Antártica. Adicionalmente, el estudio paleobotánico en esta unidad identificó improntas referidas a *Asplenium* sp., *Pteris* sp. *Podocarpus* sp., y abundantes angiospermas, incluyendo *Nothofagus lanceolata* Dusén, *N. simplicidens* Dusén, *N. variabilis* Dusén, *N. cf. alexandri* Espinosa, *N. subferruginea* (Dusén), *Hydrangea* sp. y *Phyllites* spp. Además, se identificaron restos de troncos fósiles de *Nothofagoxylon scalariforme* Gothan y Araucariaceae cf. *Araucarioxylon* Kraus. Adicionalmente, se reconoció polen de las gimnospermas y angiospermas: *Podocarpidites otagoensis* Couper, *Retitricolpites* sp., *Tricolpites* sp., *Liliacidites* sp., *Polyporina* sp., *Nothofagidites cincta* Cookson y *Nothofagidites cranwellae* Couper, las que presentan afinidades con floras de edad eocena, siendo consistente con la edad de los peces fósiles. Finalmente, el análisis SHRIMP U-Th-Pb de dos muestras colectadas desde los estratos estudiados, han proporcionado 38 y 60 granos de circón respectivamente, indicando claros peaks principales en  $36,48 \pm 0,47$  Ma (MSWD=1,5) y  $36,73 \pm 0,50$  Ma (MSWD=0,65). Los resultados integrados indican que los estratos superiores de la Formación Loreto pueden ser acotados a una mínima edad priaboniana, siendo consistente con reasignaciones previas al Eoceno Tardío para esta parte de la formación, y difiriendo de la edad oligocena originalmente propuesta en su definición.

*Palabras clave:* Peces cartilaginosos fósiles, Paleobotánica, Shrimp U-Th-Pb, Priaboniano, Formación Loreto, Extremo sur de Chile.

## 1. Introduction

The Loreto Formation (Hoffstetter *et al.*, 1957) was previously known by several different informal names such as ‘Araucaria Stufe’, ‘Arenense’, ‘Banco de Gastrópodos’, ‘Banco de Venus’, ‘Capas de Loreto’, ‘Fagus Stufe’, ‘Magallaniano’, ‘Magallaniense’, ‘Magellanian beds’, etc. The first reference to these strata as the ‘Loreto Formation’ was in Hoffstetter *et al.* (1957), who proposed an Eocene age, but the description and definition of the unit was much generalized. Fasola (1969) was the first to propose a type locality and paralocalities for the Loreto Formation in the Los Ciervos River, Lynch River and Las Minas River valleys. This author measured a stratigraphic column in each of these areas and constructed a composite section showing sandstones with variable grain size and hardness, together with sporadic clay, conglomerate, concretionary and fossiliferous beds including carbonized wood, assigned by this author to the Oligocene based on palynomorphs. Subsequently, Charrier and Lahsen (1969) proposed a stratigraphic correlation chart indicating a Late Eocene age for the base of the Loreto Formation, while the rest of the formation remained in the Oligocene.

Since previous studies do not allow the age of the Loreto Formation to be precisely defined, this paper aims to constrain the age of this unit based on three available sources of information: **i.** An abundant fossil assemblage of cartilaginous fish teeth hosted by one particular bed in the studied locality, made it possible to obtain enough samples to interpret the different dental shapes belonging to certain genera and species. In this way, identifications based on isolated elements that usually lead to dubious taxonomical interpretations could be avoided. The identified taxa include several genera and species with good chronostratigraphic resolution; **ii.** Leaf imprints, wood remains and palynomorphs were collected from beds occurring stratigraphically below the teeth-rich beds; **iii.** In addition to the relative age obtained from the paleontological evidence, an absolute age of approximately 36-37 Ma was obtained by SHRIMP U-Th-Pb dating of detrital zircons.

Considering that the studied section of the Loreto Formation corresponds to its upper portion, and based on the new evidence presented here, a Late Eocene (Priabonian) age for most of the Loreto Formation can be proposed. This is the first age based on integrated and diverse data obtained from well-defined stratigraphic units within the formation.

## 2. Locality and geological setting

### 2.1. Locality

The studied materials were discovered during January 2007 and January 2008 in the Magallanes Reserve (53°08'18"S; 71°03'32"W), administrated by the Corporación Nacional Forestal (Conaf), located about 10 km west of Punta Arenas, in the Brunswick Peninsula (Fig. 1A). The host beds crop out on the upper slopes of the Las Minas River valley (locally known as Río de Las Minas, so called hereafter in the text). The studied succession forms part of the Loreto Formation (Hoffstetter *et al.*, 1957) assigned by these authors to the Eocene-Miocene, and later redefined and reassigned by Fasola (1969) to the Oligocene based on palynomorphs. The exposed lithology includes a coquina bed with abundant but poorly preserved oysters at the base of the valley slope, and several coal seams with frequent leaf imprints and carbonized wood remains exposed near the top, intercalated with strata that include fossil vertebrate remains. All these beds are consistent with the description of the Carbonoso Member of Hemmer (1935), as cited by Hoffstetter *et al.* (1957). In addition, the studied beds coincide with level K of Fasola (1969; Figs. 1 and 2), suggested by the latter author to belong to the upper portion of his measured stratigraphic section.

### 2.2. Geological setting

The geology of the Brunswick Peninsula is characterized by thick sedimentary successions with a general SE strike, exposing the different units with decreasing age towards the NE (Fig. 1B). From the SW part of the peninsula to the NE (older to younger), the recognized units are, from top to base:

**Chorrillo Chico Formation** (Thomas, 1949): This is a 275 m thick succession (Charrier and Lahsen, 1968) of light brown, compact argillites, with sporadic lenses of glauconitic sandstones and lenticular, calcareous concretions. Charrier and Lahsen (1968, 1969) assigned the formation to the Late Maastrichtian-Early Paleocene, the lower limit being defined by the age of the Carrera Formation. A section of this formation was studied in the western part of Brunswick Peninsula, providing 27 taxa of dinoflagellates that support a middle to Late Paleocene age for this unit (Quatrocchio and Sarjeant, 2003).

**San Jorge Formation** (Thomas, 1949): This succession (about 400 m thick), is exposed along the eastern coast of the Brunswick Peninsula, about 2 km north of Punta Carrera. It is formed by soft-weathering brown argillites with abundant concretionary nodules of limestone and scarce fossils. The age proposed by Charrier and Lahsen (1969) is

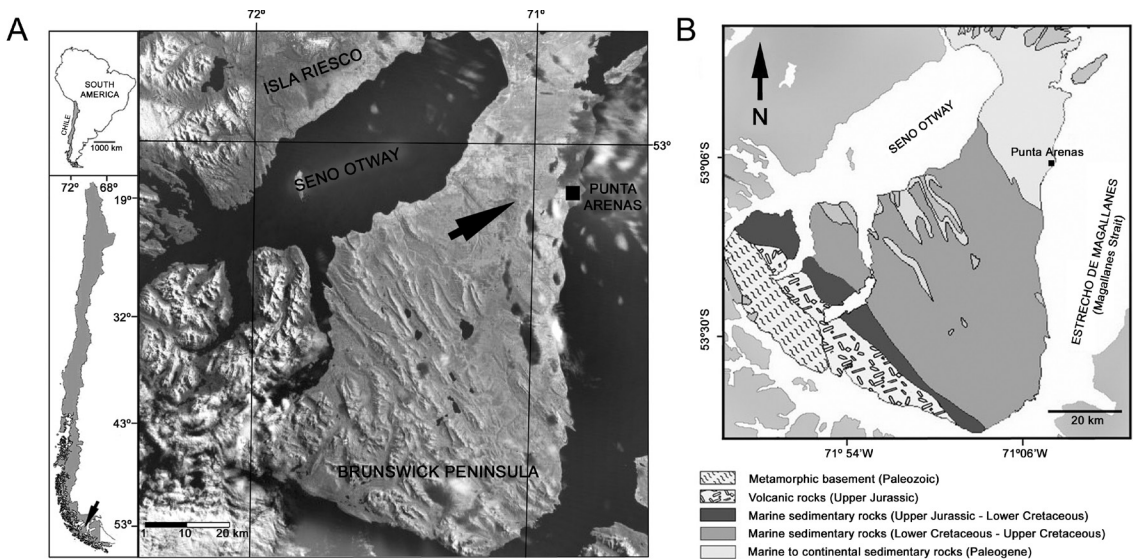


FIG. 1. A. Map of Brunswick Peninsula, southernmost Chile. The black arrow indicates the location of the Río de Las Minas study area. B. Schematic portrayal of the stratigraphic units exposed on the Brunswick Peninsula.

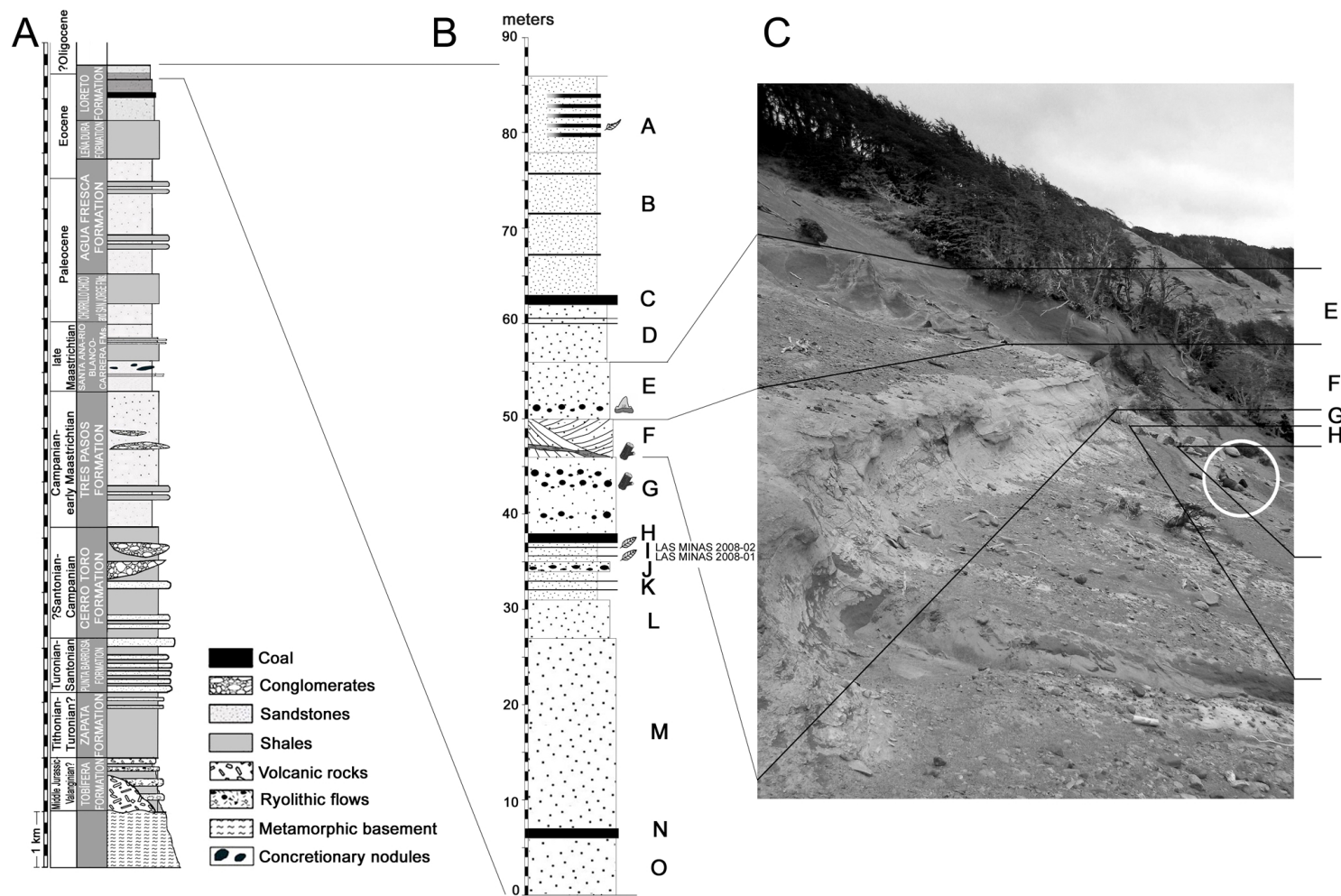


FIG. 2. **A.** Generalized stratigraphic column of the units exposed on the Brunswick Peninsula. The thickness of the units were taken from Katz (1963), Charrier and Lahsen (1969) and Fildani and Hassler (2005); **B.** Stratigraphic column based on the point 'K' of Fasola (1969), in the Río de Las Minas, Punta Arenas, adding the observations of the measured section of this study (points E to M in the figure). Host beds of the fossiliferous material described here and the location of the samples dated by SHRIMP are indicated. For further details on each bed, see the text; **C.** General eastward view of the studied section at Río de Las Minas. The lines represent the same levels indicated on figure 2. White circle indicates human scale.

Paleocene, as constrained by the age of the overlying Agua Fresca Formation.

**Agua Fresca Formation** (Hoffstetter *et al.*, 1957): This up to 2,000 m thick formation consists of marine deposits exposed in the eastern part of the Brunswick Peninsula, along the Agua Fresca River. It is formed by sandstones and mudstones with abundant microfossils. The age of the formation is assigned to the Late Palaeocene-Early Eocene based on microfossils (Charrier and Lahsen, 1968, 1969).

**Leña Dura Formation** (Natland *et al.*, 1974): This succession is about 640 m thick, consisting of grey, hard shales, with beds that include abundant concretions containing fossils. The age of the formation is assigned to the Late Eocene based on palynomorphs and invertebrate marine fossils (Fasola, 1969; Cookson and Cranwell, 1967).

**Loreto Formation** (Hoffstetter *et al.*, 1957): This formation is about 800 m thick, being composed of well-sorted sandstones and including glauconitic and concretionary horizons with common intercalated beds containing fossil flora and several coal seams of variable thickness. It includes the Ciervos Member of Kniker (1949), assigned by this author to the Late Eocene based on microfossils. Martínez-Pardo *et al.* (1965) separated the basal part of the Loreto Formation (equivalent to the section measured at the Los Ciervos River by Fasola, 1969), raising it to formation status and assigning it to the Burdigalian based on taxonomic determinations of foraminifera referred to *Candeina nitida* D'Orbigny (= *Antarcticella antarctica* (Leckie and Webb); N. Malumián, personal communication, 2011), *Globigerina falconensis* Blow and *Globigerinoides triloba* immatura Le Roy. The latter genus was never found in the Magallanes Basin, and could in fact belong to *Globigerinaspis*, a taxon that disappeared near the Eocene/Oligocene boundary (N. Malumián, personal communication, 2011). The age of the formation was reassigned by Fasola (1969) to the Oligocene based on palynomorphs, while Biddle *et al.* (1986) assigned the lower part of the Loreto Formation to the Rupelian-Chatian, correlating it with the Leña Dura Formation and the Zona Glauconítica unit (Hauser, 1964) exposed in Argentina. Later, Martínez-Pardo and Martínez (1989) reaffirmed his proposal of a Miocene age for the Ciervos Member, based on the presence of foraminifers of the genus *Boltovskoyella*, associated to *Virgulinea severini* (Cañón and Ernst); nevertheless, *Boltovskoyella* has been considered by Malumián and Jannou (2010) as

an abundant, characteristic, and endemical taxon in the Atlantic transgression of the Magallanes Basin that occurred during the Eocene.

The fossil content of bivalves, gastropods (Fasola, 1969) and vertebrates (this study) and the presence of glauconite indicate that this unit was deposited in a shallow marine environment, although wood fragments and leaf imprints are also present.

### 3. The Río de Las Minas section of the Loreto Formation

A ca. 30 m thick stratigraphic section in the Río de Las Minas valley, which encompasses the beds containing vertebrate fossils and leaf imprints, was studied. It belongs to the upper part of the Loreto Formation according to the composite section of Fasola (1969), corresponding to point K of this author. According to Fasola's section, the strata that overlie the present studied profile are, from base to top, as follows (Fig. 2: B):

The beds underlying the studied section are exposed at the base of the cliff. Following Fasola (1969), from base to top these are:

- A. 6 m of massive sandstones.
- B. 0.8-1 m of coal.
- C. 20 m of coarse, greenish, very friable sandstones with thin intercalated conglomerates, some strata containing calcareous concretionary nodules.
- D. 4 m of massive sandstones with abundant concretionary nodules.
- E. 3 m of fine sandstones with scarce and fine coal seams.

From base to top, the beds of the studied section are:

- F. 1 m of massive sandstones with concretionary nodules at the base.
- G. 2 m of alternating dark grey, poorly consolidated sandstones and fine coal seams that include abundant leaf imprints. Sample LAS MINAS 2008-01 for zircon dating was collected here. The base includes ca. 1 m of light grey, poorly consolidated sandstones with abundant leaf imprints. Sample LAS MINAS 2008-02 for zircon dating was collected in this interval.
- H. 1 m of coal.
- I. 8 m of massive sandstones with abundant concretionary nodules.
- J. 4 m of sandstones showing large-scale cross-bedding with variable dip directions.
- K. 6 m of massive sandstones with some concretionary beds. This unit also includes fine conglomerate

lenses and abundant teeth of cartilaginous fishes, with less frequent bird bone fragments (Sallaberry et al., 2010).

**L.** 6 m of medium-grained, grey sandstones, with very fine coal intercalations.

**M.** 1 m of coal.

**N.** 15 m of massive sandstones with alternated, fine coal seams. At the base, the coal seams include fragmentary leaf imprints

Following Fasola (1969), and complemented with our own observations, the studied section is formed from top to base by (Fig. 2B and C):

**O.** 8 m of fine to medium sandstones including five prominent coal seams.

Our preliminary interpretation of the depositional environment is an estuary, based on the presence of shark teeth indicating a strong marine influence, coal seams representing stagnant marshes with abundant vegetation, and the large-scale cross-bedding of some sandstone units that is typical of Gilbert-type bayhead deltas or migrating barrier bars (e.g., Le Roux et al., 2010).

#### 4. Systematic paleontology

##### 4.1. Fossil cartilaginous fishes

**Chondrichthyes Huxley, 1880**

**Elasmobranchii Bonaparte, 1838**

**Subcohort Neoselachii Compagno, 1977**

**Order Lamniformes Berg, 1958**

**Family Mitsukurinidae Jordan, 1898**

**Genus *Striatolamia* Glikman, 1964**

**Type species:** *Otodus macrotus* Agassiz, 1843; Eocene. Paris Basin, France.

***Striatolamia macrota* (Agassiz, 1843)**

**Fig. 3: A-C**

**Materials:** SGO.PV.6513: (SGO.PV.=Institutional abbreviation for Área Paleontología, Museo Nacional de Historia Natural, Santiago): Seven anterior teeth; four lateral teeth; two postero-lateral teeth; one possible large lateral tooth.

**Description:** Teeth with high and slender crown, less sigmoidal in profile than *Odontaspis*, and with complete cutting edges that fade towards the base. The anterior teeth highly resemble *Odontaspis*, but differ in the presence of rough, well-marked striations that extend from the base and fade close to the top of

the crown over the lingual face. Lateral cusplets are small and recurved to the crown. The root shows an inverted 'V' shape, with separate branches. Lateral teeth have broader crowns, with soft striations on the lingual face. The cusplets are broad and short, with rounded tops, some having a pectinated aspect. The root is robust and the branches are massive and not separated like those seen in anterior teeth.

**Comments and age:** Cappetta (1987) indicates that during its stratigraphic history, the genus *Striatolamia* has shown a clear tendency to increase the size of its teeth, with a broadening of the main cusplet. This is particularly evident in later fossils of the species *S. macrota*. This author also points out for the lateral teeth of this species, that the lateral cusplets underwent a marked widening, becoming broad, short and rounded (pectinated aspect). They also display a fading of the striations on the lingual face, these becoming shorter, fading or even disappearing altogether. The species *S. macrota* has already been reported from the Loreto Formation by Suárez and Marquardt (2003) as a taxon with good chronostratigraphic value that indicates an Eocene age. The newly recovered material shows morphologies that resemble later members of the species. *S. macrota* has been reported in the Early Palaeocene-Late Eocene of the ex-U.S.S.R., North America, and the north and west of Africa (Cappetta, 1987). It is also known in the Eocene of Seymour Island, Antarctica (Long, 1992; Kriwet, 2005). Teeth of *S. macrota* with broad cusplets have furthermore been reported from the Middle Eocene of North Carolina (Case and Borodin, 2000) and the extreme south of South America (Arratia and Cione, 1996).

**Genus *Anomotodon* Arambourg, 1952**

**Type species:** *Anomotodon plicatus* Arambourg, 1952. Maastrichtian, Morocco.

***Anomotodon* sp.**

**Fig. 3: D**

**Materials:** SGO.PV.6514: A single anterior tooth.

**Description:** Small tooth with high and slender crown. The enamel extends laterally, having smooth cutting edges. No cusplets are noted. The root branches are thin, extended in antero-posterior direction, and widely separated.

**Comments and age:** The shape of the tooth from Punta Arenas is highly similar to the species *A. novus*.

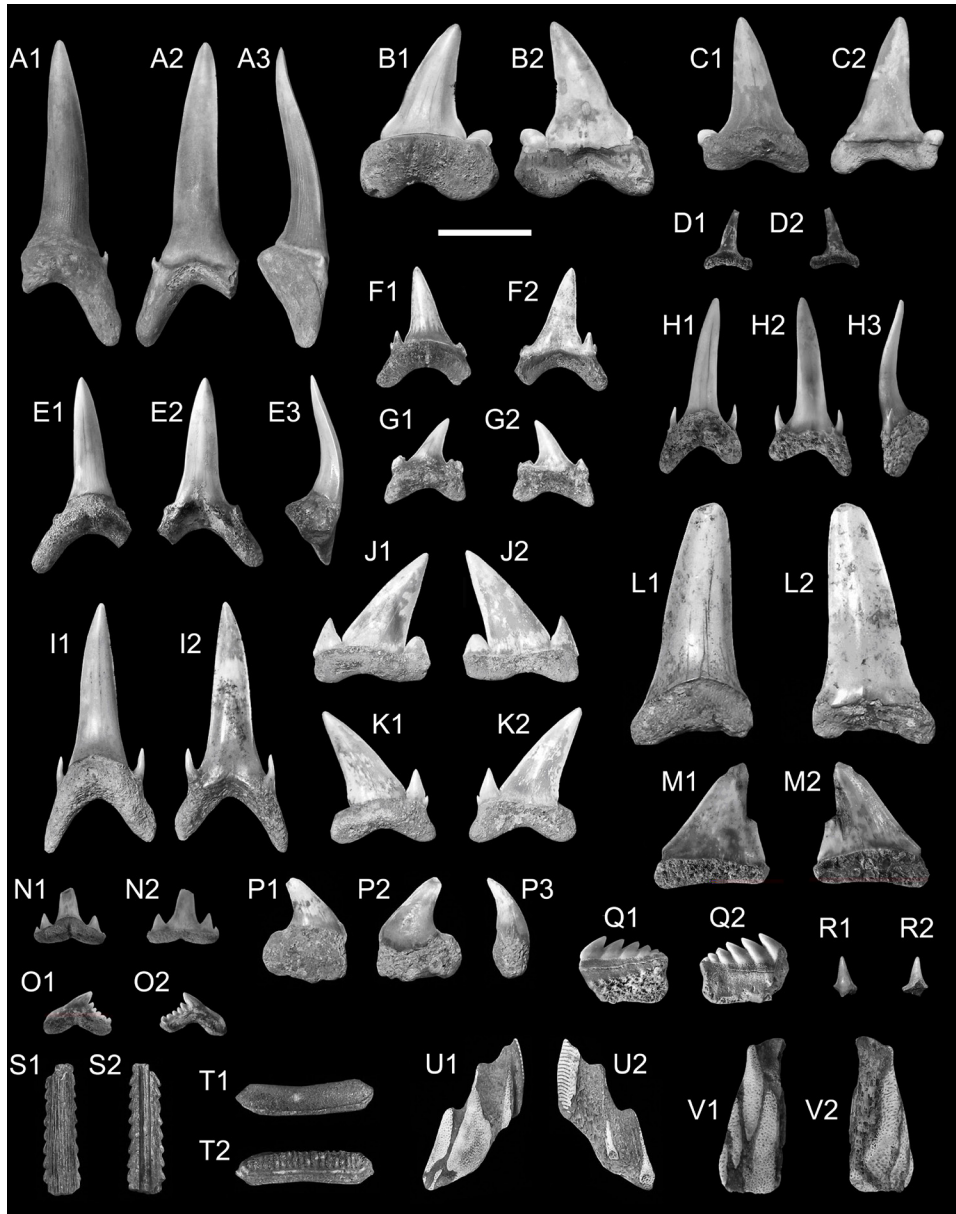


FIG. 3. SGO.PV.6513: *Striatolamia macrota* (Agassiz, 1843). A1. Anterior tooth in lingual view; A2. labial view; B1, C1. postero-lateral teeth in lingual views; B2, C2. labial views. SGO.PV.6514: *Anomotodon* sp. D1. Anterior tooth in lingual view; D2. labial view. SGO.PV.6510: *Carcharias* aff. '*hopei*' (Agassiz). E1. Anterior tooth in lingual view; E2. labial view; E3. profile view; F1, G1. lateral teeth in lingual view; F2, G2. labial views, SGO.PV.6511: *Odontaspis* sp. H1. Anterior tooth in lingual view; H2. labial view; H3. profile view. SGO.PV.6512: *Carcharoides catticus* (Philippi, 1846). I1. Upper anterior tooth in lingual view; I2. labial view; J1, K1. lateral teeth in lingual views; J2, K2. labial views. SGO.PV.6515: *Macrorhizodus (Isurus) praecursor* (Leriche, 1905). L1. Anterior lower tooth in lingual view; L2. labial view; M1. lateral upper tooth in lingual view; M2. labial view. SGO.PV.6517: *Abdounia* sp; N1. Anterior tooth in lingual view; N2. labial view. SGO.PV.6516: *Galeorhinus* sp. O1. Lateral tooth in lingual view; O2. labial view. SGO.PV.6518: Hexanchidae indet. M1. Upper anterior tooth in lingual view; M2. labial view; M3. profile view. SGO.PV.6519: *Hexanchus* sp. N1. Lateral lower tooth in lingual view; N2. labial view. SGO.PV.6520: *Squatina* sp. R1. Antero-lateral tooth; R2. labial view; P. lingual view. SGO.PV.6521: Myliobatoidea indet. S1. Distal fragments of caudal spine in dorsal view; S2. ventral view. SGO.PV.6522: Myliobatis sp. T1. Medial tooth in occlusal view; T2. basal view. SGO.PV.6524: *Ischyodus dolloi* Leriche, 1902. U1. Left mandibular plate in occlusal view; U2. basal view; V1. right palatine in occlusal view; V2. basal view. Scale bar=1 cm.

Nevertheless, the absence of more dental pieces prevents its identification as the same species. The genus is known since the Lower Cretaceous to the Early Miocene in Europe, North America, north and west Africa and Japan. Eocene reports come from Belgium, the ex-U.S.S.R. and England (Cappetta, 1987), as well as Seymour Island, Antarctica (Long, 1992; Kriwet, 2005) where the species *A. multidenticulatus* was identified.

### Family Odontaspidae

Müller and Henle, 1839

### Genus *Carcharias* Rafinesque, 1810

**Type species:** *Synodontaspis hopei* (Agassiz, 1843), Eocene. England, France, Belgium and Morocco.

#### *Carcharias* aff. 'hopei' (Agassiz)

Fig. 3: E-G

**Materials:** SGO.PV.6510: Four anterior teeth, lacking lateral cusplets in most cases; six lateral teeth, with partial cusplets; two intermediate teeth, with partially preserved cusplets; two complete latero-posterior teeth; one symphyseal tooth, lacking cusplets.

**Description:** Anterior teeth with high cusp, thin and slender, with a sigmoidal profile and 'V' shaped root. The crown has complete cutting edges, fine striations on its lingual face and enamel rifts. The labial face has enamel with soft folds close to the root. Two lateral cusplets are present on each side, but they have been lost in most cases due to erosive processes. The root has two separate branches and shows a bulk with a medial nutritious groove. Intermediate teeth show a lower crown but a very similar root to anterior ones. The lateral cusplets are present in most cases, being robust and joined to the crown, having a continuous enamel surface between the cusp and the lateral cusplets on the labial face. Posterior teeth are similar, but with a crown recurved backwards. The symphyseal tooth shows a bulky root, high and broad in the labial-lingual direction. Despite the fact that only one root branch is preserved, they are not broadly separated.

**Comments and age:** The recovered teeth from Punta Arenas are very similar to those figured by Cappetta and Nolf (2005, p. 260) referred to as *Carcharias* sp. These authors indicate that their tooth set has affinities to the recent species *C. taurus*, being morphologically more similar to the latter than the

fossil *C. acutissima*. They also indicate that their materials probably share the systematic attributes of *C. hopei*, but specific identification is discarded because they consider that the species *hopei* is still not clearly described. Following this, the identification of the tooth set from Punta Arenas is included in the genus *Carcharias*, noting its high similarity to the 'hopei' taxon, but refraining from a more specific identification.

Kent (1994) indicates that the genus *Carcharias* has a cosmopolitan distribution in the Campanian-Recent. Regionally, fossil *Carcharias* species are reported from the Cenozoic of Ecuador, Peru and Chile (Cione et al., 2007). The presence of the genus *Carcharias* in Chile has been documented since the Campanian-Maastrichtian, from the Quiriquina Formation and equivalent units (Suárez et al., 2003, Table 1; Muñoz-Ramírez et al., 2007). In addition, it was previously reported from the Eocene of the Loreto Formation (Suárez and Marquardt, 2003), and is also present in the Early Miocene of the Navidad Formation (Suárez et al., 2006), at least one species having been identified as *C. cuspidata* Agassiz. The youngest report of the genus *Carcharias* in Chile belongs to Late Miocene-Early Pliocene deposits of the Bahía Inglesa Formation (Suárez et al., 2004). Concerning the species *C. hopei*, it is known from the Early Eocene of England, and the Eocene of the French-Belgian Basin and Morocco (Cappetta, 1987). Ward (1988) also indicates its occurrence in the Late Paleocene of England, the Paleocene, as well as the Middle Eocene of Belgium and the Eocene of Maryland.

### Genus *Odontaspis* Agassiz, 1838

**Type species:** *Squalus ferox* (Risso, 1810). Recent, warm waters of the northeastern Atlantic, Pacific Indian, and Mediterranean Oceans.

#### *Odontaspis* sp.

Fig. 3: H

**Materials:** SGO.PV.6511: Four antero-lateral teeth, one of them with cusplets.

**Description:** High crown, slender and sharp, thinner and sharper than those seen in the genus *Carcharias*, and with a sigmoidal shape in profile. It shows soft striations at the base of the lingual face and some grooves, while the labial face is completely smooth. The labial face is flattened at the top and, in cross



**TABLE 1. SYNTHESIS OF THE KNOWN STRATIGRAPHIC DISTRIBUTION OF THE MOST EXCLUSIVE TAXA OF FOSSIL CARTILAGINOUS FISHES (CHONDRICHTHYES) RECOVERED AT PUNTA ARENAS, SOUTHERNMOST CHILE. FOR DETAILS, SEE THE TEXT FOR EACH TAXON.**

	Upper Cretaceous	Paleocene				Eocene			Oligocene		Miocene		
	Maastrichtian	Danian	Selandian	Thanetian	Ypresian	Lutetian	Bartonian	Priabonian	Rupelian	Chatthian	Aquitanian	Burdigalian	Langhian
<i>Carcharias</i> . ‘hopei’													
<i>Odontaspis</i> sp.													
<i>Carcharoides caticcus</i>													
<i>Striatolamia macrota</i>													
<i>Anomotodon</i> sp.													
<i>Macrorhizodus (Isurus) praecursor</i>													
<i>Galeorhinus</i> sp.													
<i>Abdounia</i> sp.													
<i>Hexanchus</i> sp.													
<i>Myliobatis</i> sp.													
<i>Ischyodus dolloi</i>													

section displays a rounded shape near the base. The cutting edges extend from the top, but fade before reaching the base. The contact between the crown and the root has a neck, causing the enamel to slightly overhang the root.

**Comments and age:** A typical character of the genus *Odontaspis* is the incomplete cutting edges that do not reach the base of the cusp (Cappetta, 1987; Kent, 1994). This allows their distinction from other odontaspids such as *Carcharias*, where the cutting edges are complete. Teeth of the genus *Carcharias* commonly found in the Loreto Formation allow their comparison with those of SGO.PV.6511, which highlights the different cutting edges. Due to the incomplete preservation of the teeth and the lack of more complete samples, specific identification was not attempted.

*Odontaspis* is known since the Campanian to Recent in Europe, northern and western Africa, North America (Cappetta, 1987) and the south of South America, (Arratia and Cione, 1996). In Chile, fossil specimens are mentioned in the Eocene of Lebu (Oliver-Schneider, 1936), referred to as the species *O. elegans* (Agassiz). Furthermore, the genus is reported in the Late Miocene-Early Pliocene Bahía Inglesa Formation (Suárez *et al.*, 2004). Finally, the species

*O. ferox* Risso was reported in the Early Miocene of the Navidad Formation (Suárez *et al.*, 2006).

**Genus *Carcharoides* Ameghino, 1901**

**Type material:** *Carcharoides caticcus* (Philippi, 1846). ‘Tertiary’ of Europe.

***Carcharoides caticcus* (Philippi, 1846)**

**Fig. 3: I-K**

**Materials:** SGO.PV.6512: Two complete anterior teeth; four upper lateral teeth, only one complete; three teeth preserving only one lateral cusplet; two upper posterior teeth.

**Description:** Anterior teeth with high, straight and slender crown, becoming recurved backwards and broader in the posterior teeth. The lingual face is slightly convex, while the labial face is very flat, both faces having soft enamel with no striations. In profile, some teeth show a slightly sigmoidal aspect. All teeth have two cusplets with soft and flat faces, those of the anterior teeth being very thin and sharp, while those of the lateral and posterior teeth are broad and triangular in shape. Two lateral teeth show incipient secondary cusplets. The cutting

edge is continuous in all cases, fading near the base of the cusp. The root has short separated branches with a medial constriction at the base, and lingually displays a single nutritious groove in a central position. In most of the teeth, this groove is not evident, due the erosion suffered by the root.

**Comments and age:** The genus *Carcharoides* includes only two known species: *C. totuserratus* Ameghino, 1901 and *C. caticus* (Philippi, 1846). The first species was reported exclusively from the Southern Hemisphere, particularly in the Late Oligocene of Australia (Chapman, 1913; Fitzgerald, 2004), the Early Miocene of Argentina (Cione, 1978; Cione and Expósito, 1980) and the Early Miocene of Chile (Suárez et al., 2006). The second species, *C. caticus*, can be diagnosed by anterior odontospidid-like teeth and lamnoid lateral teeth, the latter with a triangular cusp and one triangular cusplet on each side, bent lingually (Cappetta, 1987), and having a smooth cutting edge that frequently does not reach the base. These teeth have compressed cusps, while the roots branches are short and well separated. The species has been reported from the Oligocene-Miocene of Europe and west Africa (Cappetta, 1987). Finally, Werner (1989) referred some dubious materials from the Cenomanian of Egypt to *Carcharoides*.

**Family Lamnidae (Müller and Henle, 1838a)**  
**Genus *Macrorhizodus* Glikman, 1964**

**Type species:** *Isurus praecursor* (Lerliche, 1905). Middle Eocene, Belgium.

***Macrorhizodus (Isurus) praecursor* (Lerliche, 1905)**  
**Fig. 3: L, M**

**Materials:** SGO.PV.6515: One anterior lower tooth; one lateral upper tooth.

**Description:** High, slender and triangular crown that becomes broader towards the base, being labio-lingually compressed. The labial face is flat, with soft enamel and smooth folds near the root. The lingual face is convex and the enamel shows some rifts.

**Comments and age:** The species *Macrorhizodus praecursor* (= *Isurus praecursor*) was previously reported from Eocene deposits in Belgium, Syria, Egypt, Nigeria, Togo, Guinea Bissau and England (Cappetta, 1987). It was also reported from the Middle-Late Eocene of Chesapeake Bay, U.S. (Kent,

1994), and the Middle-Late Eocene of Seymour Island, Antarctica (Cione and Reguero, 1994).

**Order Carcharhiniformes Compagno 1973**  
**Family Carcharhinidae Jordan & Evermann, 1896**

**Type species:** *Eugaleus beaugei* Arambourg, 1935. Lower Eocene, Morocco.

**Genus *Abdounia* Cappetta, 1980a**  
***Abdounia* sp.**

**Fig. 3: N**

**Materials:** SGO.PV.6517: A single tooth.

**Description:** Small tooth with moderately high crown and two lateral cusplets with triangular shape on each side. The labial face is flat and the lingual face has a soft convexity. The top of the crown and one of the distal cusplets are absent. The cusplets are slightly recurved to the crown. The enamel is smooth and continuous from the main cusp to the lateral cusplets. Cutting edges are smooth and complete over all of the crown. The root is robust, with separated branches and one medial, well-marked groove.

**Comments and age:** The genus can be diagnosed by the small-sized teeth, with a relatively triangular cusp, broader near the base, having a flat labial face and a slightly convex lingual face, displaying one or more lateral cusplets and a crown that does not overhang the labial face of the root. This latter has branches transversely extended, with a well-marked, deep groove (Cappetta, 1987), typical of carcharhinid sharks. The genus is known in the Early-to-Late Eocene of Europe, North America, North and West Africa (Cappetta, 1987) and in the Early Eocene of India (Rana et al., 2004).

**Family Triakidae Gray, 1851**  
**Genus *Galeorhinus* de Blainville, 1816**

**Type species:** *Squalus galeus* Linnaeus, 1758. Recent, all seas.

***Galeorhinus* sp.**  
**Fig. 3: O**

**Materials:** SGO.PV.6516: One complete tooth.

**Description:** Small tooth with broad, low crown and broad root. The crown has a main cusp, recurved backwards, with a smooth anterior cutting edge and

five cusplets in the distal portion. The crown extends over the root onto the labial face. The root has separate branches and a well-developed medial groove. **Comments and age:** Its known biocron ranges from the Eocene to Recent. Eocene reports come from Egypt, the United States (Cappetta, 1987), Belgium (Nolf, 1988) and India (Rana *et al.*, 2004). The genus is also reported from the Eocene of Seymour Island (Kriwet, 2005). In Chile, it was previously reported from Campanian-Maastrichtian beds at Talcahuano Bay (Muñoz *et al.*, 2007) and from the Neogene of the Bahía Inglesa Formation (Long, 1993).

**Order Hexanchiformes de Buen, 1926**  
**Suborder Hexanchoidei Garman, 1913**  
**Family Hexanchidae Gray, 1851**  
**Hexanchidae gen. et sp. indet.**  
**Fig. 3: P**

**Materials:** SGO.PV.6518: Single upper anterior tooth. **Description:** Acrocone (main cusp) robust, recurved backwards and also lingually, with complete anterior cutting edge, smoothly serrated, and no cutting edge along posterior margin. On lingual face, smooth grooves are noted at the base and the enamel overhangs the root.

**Comments and age:** Apparently, the tooth has no secondary cusplets. Nevertheless, the preservation of the root is poor, and it is difficult to establish whether there was a loss of secondary cusplets by erosive processes. Nevertheless, the presence of smooth serrations on the anterior cutting edge is common in teeth of hexanchid sharks and some squaliformes, but the absence of a posterior cutting edge is unusual. Cappetta (1987) indicates that in larger individuals of the genus *Notorhynchus*, this posterior cutting edge often disappears close to the base. The poor preservation and lack of additional teeth from this locality do not allow an accurate generic identification.

**Genus *Hexanchus* Rafinesque, 1810**

**Type species:** *Squalus griseus* Bonaterre, 1788. Recent, all seas.

***Hexanchus* sp.**  
**Fig. 3: Q**

**Materials:** SGO.PV.6519: Single lateral lower tooth. **Description:** Incomplete tooth lacking the main cusp (acrocone). Its general shape is expanded in

the antero-posterior sense and compressed in the labial-lingual sense. The crown preserves six cusplets (accessory cones), these being recurved backwards and decreasing in size towards the posterior portion. The root has a rectangular shape with a rift near its contact with the crown.

**Comments and age:** The genus is known since the Early Jurassic to Recent (Cappetta, 1987), with a cosmopolitan distribution. Regionally, Eocene *Hexanchus* has been described from Seymour Island, Antarctica (Cione and Reguero, 1994).

**Order Squatiniformes de Buen, 1926**  
**Family Squatinidae Bonaparte, 1838**  
**Genus *Squatina* Duméril, 1806**

**Type species:** *Squalus squatina* Linnaeus, 1758. Recent, all tropical seas.

***Squatina* sp.**  
**Fig. 3: R**

**Materials:** SGO.PV.6520: One antero-lateral tooth. **Description:** Small tooth with relatively high and sharp crown. This is slightly recurved backwards and has a ventral extension over the root. The lateral flanks are partially preserved, but in all species it extends for almost the whole length of the tooth, having a continuous cutting edge. The root is absent, nevertheless. All the species have two well-separated branches and a lingual bulk.

**Comments and age:** The genus was previously reported since the Oxfordian to Recent (Cappetta, 1987), and has a cosmopolitan distribution. Regionally, it was previously reported from Upper Cretaceous beds in central Chile (Suárez *et al.*, 2003) and from probable Paleocene beds in south-central Chile (Muñoz-Ramírez *et al.*, 2008). Furthermore, it was reported from the Eocene of Seymour Island, Antarctica (Welton and Zinsmeister, 1980).

**Superorder Bathomorphi Cappetta, 1980b**  
**Order Myliobatiformes Compagno, 1973**  
**Superfamily Myliobatoidea Compagno, 1973**  
**Myliobatoidea indet.**

**Fig. 3: S**

**Materials:** SGO.PV.6521: Five fragments of caudal spines.

**Description:** Elongated spines, with broad proximal portion and thinner distal end. The lateral flanks are

serrated, fading close to the insertion area (proximal end). They differ by the presence of profuse striations on the dorsal surface and a ventral keel in the distal portion, while other samples have soft striations and a shallow ventral groove at the distal end. The fragmentary condition of the material prevents the observation of the complete morphology of the caudal spines. The two different striated fragments are a proximal and distal end respectively, probably belonging to the same taxon and indicating the general shape of this morphotype.

**Comments and age:** Myliobatoids are known since the Campanian to Recent, with a cosmopolitan distribution (Cappetta, 1987). Also, they have been recognized on Seymour Island, Antarctica (Kriwet, 2005).

**Family Myliobatidae Müller and Henle, 1837**  
**Genus *Myliobatis* Cuvier, 1817**

**Type species:** *Raja aquila* Linnaeus, 1758. Recent, all warm seas.

***Myliobatis* sp.**  
**Fig. 3: T**

**Materials:** SGO.PV.6522: Four medial teeth.

**Description:** Teeth broader than length, with hexagonal contour. The crown is flat and quite convex, being displaced anteriorly with respect to the root. The latter shows multiple parallel grooves disposed in an antero-posterior direction.

**Comments and age:** The recovered materials show a general small size for all the individuals. Cappetta (1987) indicates that the numerous myliobatid species diversified since the Eocene possess teeth with a thick and granular enameloid, this also being noted in the Chilean material.

The genus *Myliobatis* is known since the Early Paleocene to Recent, with a cosmopolitan distribution (Cappetta, 1987).

**Subterbranchialia Zangerl, 1979**  
**Holocephali Bonaparte, 1832**  
**Order Chimaeriformes Obruchev, 1953**  
**Suborder Chimaeroidei Patterson, 1965**  
**Family Callorhynchidae Garman, 1901**  
**Genus *Ischyodus* Egerton, 1843**

**Type species:** *Ischyodus dolloi* Leriche, 1902. Paleocene, Belgium.

***Ischyodus dolloi* Leriche, 1902**

**Fig. 3: U, V**

**Materials:** SGO.PV.6524: Two left mandibular plates, one right palatine and one left palatine.

**Description:** SGO.PV.6524: Massive mandibular plate, rhomboidal in shape, with two embayments along the occlusal margin. The symphyseal tritor is laminated and located in the anterior end of the symphyseal margin. The larger medial tritor is broad near the basal end and thinner close to the occlusal end. The outer posterior tritor is elongated over the occlusal margin. The smaller tritors are the anterior inner tritor, the anterior outer tritor and the accessory median tritor. The palatine plates have a larger size and more robust tritors. The apical margins show differences in wearing and the basal margins have a distinct, broad shape.

**Comments and age:** The species *I. dolloi* has been reported in the Late Cretaceous (Stahl and Chatterjee, 2003) and from the Eocene of Seymour Island, Antarctica (Ward and Grande, 1991). The material from Punta Arenas is very similar to that figured by these authors (p. 329, Fig. 6b), in particular the Chilean mandibular plates have an occlusal end with comparatively more wear, and part of the basal end being absent. Comparing both Chilean mandibular plates, the configuration and relative position of all the tritors are broadly similar; nevertheless, they appear to be slightly different in that the median and anterior inner tritors show a distinct development. In addition, the size of the plate is different and one apical margin is less sharp, suggesting that this belongs to a younger individual. Ward and Grande (1991) indicate that the growing of dental plates of *Ischyodus* occurs on the basal surface, giving the plate a basal margin narrower than the apical, which causes a change in the general shape and a rotation of the plate in different stages of the ontogeny, becoming broader and less slender (Ward and Grande, 1991; Fig. 3). The recovered mandibular plates from Punta Arenas preserve the configuration of the tritors seen in *I. dolloi*, but the differences between both plates can be interpreted as resulting from different ontogenetic stages.

The type material of *I. dolloi* is reported from the Paleocene of Belgium and France (Leriche, 1902). The species is also known from the Eocene of England (Ward, 1973), Paleocene of North Dakota (Cvancara and Hoganson, 1993), the Paleocene-Eocene of Russia (Popov 1996) and the Late Eocene of Seymour Island, Antarctica (Ward and Grande, 1991). The earliest

report comes also from this locality, where Stahl and Chatterjee (2003) identified the species in lower Maastrichtian deposits, this being its oldest known record and suggesting that its origin was in southern high latitudes. *Ischyodus* cf. *dolloi* is also reported from the Neogene of Australia (Fitzgerald, 2004).

## 4.2. Paleobotany

Macroflora are especially abundant in level H (Fig. 2B) of the studied section, but the hosting beds are formed by poorly consolidated sediments, making it difficult to obtain complete samples. Identified leaf imprints indicate the presence of Pteridophytes of the genera *Asplenium* sp. and *Pteris* sp. Additionally, pinophytes of the genus *Podocarpus* were recognized. The angiosperms are the most abundant assemblage, including *Nothofagus lanceolata* Dusén; *N. simplicidens* Dusén; *N. variabilis* Dusén; *N. cf. alessandri* Espinosa (= *Betuliphyllum patagonica* Dusén); *N. subferruginea* (Dusén); *Hydrangea* sp. and *Phyllites* spp. Although wood remains seem to be scarce, samples collected from coal seams near the base of the measured section were identified as *Nothofagoxylon scalariforme* Gothan, which display well-marked growth rings. A different taxon referred to Araucariaceae cf. *Araucarioxylon* Kraus was recognized from the same strata, being very similar to previously reported material from the northern outcrops of the Loreto Formation, referred by Terada *et al.* (2006) to *Araucarioxylon pichasquense* Torres and Rallo.

Three samples considered for palynologic analysis were collected from level E, H and J of the succes-

sion, although level E did not show any evidence of palynomorphs (Torres *et al.*, 2008). Level H includes spores of *Dicellaesporites* sp., *Multicellaesporites* sp., trilete spores of pteridophytes, mainly *Cyathidites* spp. and *Laevigatosporites ovatus* Wilson and Webster. Gymnosperms are represented by *Podocarpidites otagoensis* Couper while angiosperms include *Retitricolpites* sp., *Tricolpites* sp. and *Liliacidites* sp. Finally, Caryophyllaceae are represented by *Polyporina* sp. Level J includes palynomorphs and cuticles, stromes of *Callimothallus*, spores of *Dicellaesporites* sp., *Multicellaesporites* sp., and *Granatisporites* sp. Additionally, it includes pteridophytes such as *Cyathidites minor* Couper, *Cyathidites australis* Couper and *Laevigatosporites ovatus* Wilson and Webster. Gymnosperms are represented by *Podocarpidites otagoensis* Couper and Angiosperms by *Nothofagidites cincta* Cookson, *Nothofagidites cranwellae* Couper and psilated *Tricolpites*.

## 5. SHRIMP U-Pb dating of detrital zircons

Detrital zircons from two fine-grained sandstone beds from the Río de Las Minas section were separated for dating, with the main purpose of contributing to the age determination of the succession. The position of the samples in the stratigraphic column is shown in figure 2B.

### 5.1. Methodology

The zircon concentrates were prepared at the Departamento de Geología, Universidad de Chile.

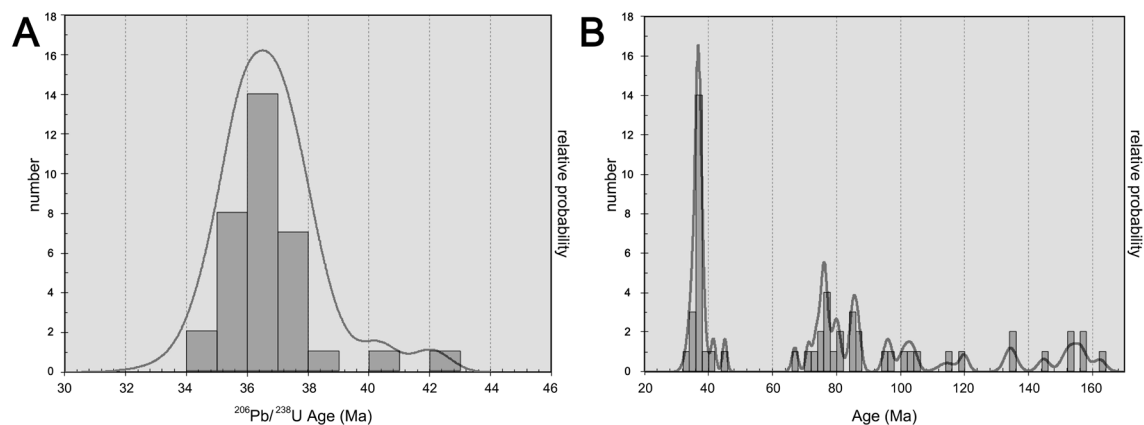


Fig. 4. A. Age versus probability diagram for the younger zircons from sample Las Minas 2008-01; B. Age versus probability diagram for the Mesozoic and Cenozoic zircons from sample Las Minas 2008-02.

The U-Pb-Th SHRIMP ages determined during this investigation were obtained using SHRIMP I, II and RG at the Research School of Earth Sciences, Australian National University, Canberra. The measurement techniques employed followed those of Williams (1998). FC1 was used as the standard throughout, and the data were processed using the SQUID Excel Macro of Ludwig (2001). Thirty-eight (sample Las Minas 2008-01) and 60 (sample Las Minas 2008-02) grains were analyzed, in each case with four-scan data. The respective results are indicated as age probability plots for individual samples shown in Fig. 4, A and B. The Geological Time Scale used throughout the text is that of Gradstein *et al.* (2008).

## 5.2. Results

All analysed zircon grains are igneous, as revealed by typical zoning in CL images (not shown). Thirty-eight zircon grains were analysed from sample Las Minas 2008-01, 32 of which form a very well-defined peak at  $36.48 \pm 0.47$  Ma (MSWD=1.5). An additional small grouping of 3 grains (74 to 77 Ma), and single dates at 42 Ma and 619 Ma are also present.

Sixty zircon grains from the more complex Las Minas 2008-02 sample were analysed. A dominant peak of 19 grains at  $36.73 \pm 0.50$  Ma (MSWD=0.65) groups the youngest grains. Two somewhat older grains (42 and 45 Ma), a relevant scatter of 32 grains in the age interval 67 to 162 Ma, and isolated grains with Paleozoic (3 grains), Proterozoic (3 grains) and Archean (1 grain) ages complete the age spectrum obtained. The analytical data for each sample are included in Appendices I and II, respectively.

## 6. Discussion

### 6.1. Fossil cartilaginous fishes

Few occurrences of Paleogene elasmobranchs are known in Chile. Muñoz-Ramírez *et al.* (2008) reported probable Palaeocene chondrichthyan fauna from the coast of the Biobío Region in south-central Chile. In the same region, at Lebu, an uncertain and not figured tooth referred to *Odontaspis elegans* was reported by Oliver-Schneider (1936) from Eocene beds. Eocene myliobatid tooth plates were also mentioned by Suárez and Marquardt (2003) from the Valparaíso Region of central Chile. The southernmost known Eocene elasmobranchs were recovered from Punta Arenas in the Magallanes Region, where Suárez and

Marquardt (2003) identified the presence of three elasmobranch families that include one genus with good chronostratigraphic resolution, allowing these authors to propose an undifferentiated Eocene age for the host beds.

Previous studies have cited the presence of elasmobranch fishes in the Brunswick Peninsula. Tavera (1946) described a single tooth identified as *Lamna?* sp. (Fig. 130, plate IX). The material was poorly presented and no indication about its final repository was provided, nevertheless, it probably belongs to an anterior tooth of *S. macrota*, associated with abundant Eocene invertebrate fauna. Fasola (1969) also includes material of elasmobranchs identified as *Oxyrhina* sp. (*nomen vanum*), but this was not figured or described (only his unpublished doctoral thesis includes a picture of the tooth, which probably is a lateral tooth of *Striatolamia macrota*). The most recent publication dealing with elasmobranchs from the Loreto Formation is that of Suárez and Marquardt (2003) indicating the presence of the species *S. macrota* (Agassiz), *Carcharias* sp., teeth of myliobatids, and fragments of dorsal spines of indeterminate holocephalian fishes. The presence of all these taxa is confirmed by the present study.

The recovered materials studied by us include two taxa known since the Eocene (*Galeorhinus* and *Abdounia* sp.) and two taxa that remain unreported after the Eocene (*S. macrota*, and *I. dolloi*). The presence of *C. catticus* suggests an age close to the Eocene/Oligocene boundary, while the remaining taxa do not provide a finer resolution. This new information allows us to constrain the host beds as Eocene, confirming the previous proposal of Suárez and Marquardt (2003), but adding more precision on the stratigraphic position of this unit.

### 6.2. Paleoecology

Considering the newly collected materials and comparing them with Eocene elasmobranch assemblages worldwide (Table 2), closer faunal affinities are observed with the assemblages from the European basins, where almost all of the genera and species are known from the Eocene. Also, a clear affinity is observed with the elasmobranch diversity reported from the Atlantic coast of North America, with similarities in ten of the twelve taxa. When they are compared with the Eocene north African elasmobranch fauna, eight of the twelve taxa are similar. The same is the case with the elasmobranch

**TABLE 2: GEOGRAPHIC DISTRIBUTION OF THE STUDIED FOSSIL TAXA OF CARTILAGINOUS FISHES (CHONDRICTHYES) IN THE MAIN MARINE PROVINCES DURING THE EOCENE. FOR DETAILS, SEE THE TEXT FOR EACH TAXON.**

	Eastern North Atlantic		Western North Atlantic	Eastern North Pacific	Eastern South Pacific	Western South Pacific		Western North Pacific		
	Europe	North Africa	West Africa	North America		South America	Antarctica	Australia	India	Japan
<i>Carcharias</i> aff. 'hopei'	X	X		X						
<i>Odontaspis</i> sp.	X			X		X	X			
<i>Carcharoides caticus</i>	X		X							
<i>Striatolamia macrota</i>	X	X	X	X		X	X			
<i>Anomotodon</i> sp.	X						X			X
<i>Macrorhizodus (Isurus) praecursor</i>	X	X	X	X			X			
<i>Galeorhinus</i> sp.	X	X		X					X	
<i>Abdounia</i> sp.	X	X	X	X			X		X	
<i>Hexanchus</i> sp.	X	X		X			X			
<i>Myliobatis</i> sp.	X	X	X	X		X	X			
<i>Ischyodus dolloi</i> Leriche, 1902	X	X		X			X			

diversity in the Eocene of Antarctica. However, common elements with Indo-Pacific records are scarce. This suggests a closer connection between Tethyan elasmobranch fauna and those assemblages from Seymour Island and southernmost Chile, instead of a direct connection with elasmobranch faunas from the Pacific Ocean. The situation seems to be consistent with the conditions of oceanic currents before the Early Oligocene, before the opening of the Drake Passage and the Australian-Antarctic Gulf caused important variations in the seaways in the circum-Antarctic region (Lawver and Gahagan, 2003) and consequently, important climatic changes.

### 6.3. Paleoclimate and paleoenvironment

An estimation of climatic conditions can be obtained by evaluating the habitat of the extant elasmobranchs present in the Eocene of southernmost Chile. Extant hexanchid sharks inhabit cold temperate to tropical seas (Compagno, 1984), while odontaspids are tropical to warm-temperate, inshore to offshore, littoral and deepwater sharks. Additionally, squatinids have a broad distribution in cool temperate to tropical waters (Compagno,

2001). Triakids such as *Galeorhinus* as well as myliobatids are found in warm-temperate waters. This indicates a range of temperate waters for the marine environmental conditions during deposition of the sediments in the studied section of the Loreto Formation. Additionally, comparison of the studied taxa with the environmental conditions of their closest extant species, provides information about the depth in which their host beds were deposited. The most frequent sharks recovered are the odontaspids, represented mainly by *Carcharias* aff. 'hopei' and scarce teeth of *Odontaspis* sp. Odontaspids are frequent in depths ranging 15 to 25 m (Compagno, 2001). Other frequent remains are myliobatids, represented by the genus *Myliobatis*. The latter is known in shallow depths up to 20 m. On the other hand, inhabitants of deeper water are scarcely represented. Such is the case of *Squatina* sp. that dwells from the surf line to a depth of several hundred meters, being represented in the recovered material by a single fragmentary tooth. This suggests that the habitat of the assemblage correspond to shallow, littoral waters. Although no detailed sedimentological study was carried out, we tentatively interpret the paleoenvironment as

an estuary. This is suggested by the presence of coal seams, which may have originated as poorly drained marshes. The large-scale cross-laminated sandstones can possibly be attributed to either migrating barrier bars at the estuary entrance or to bayhead deltas where the river entered the system (Le Roux *et al.*, 2010). The stratigraphy of the studied section also supports this notion, displaying strata with wood remains and leaf imprints located stratigraphically close to the host beds of the elasmobanch assemblage.

#### 6.4. Relative age

The evaluation of the known biochron (Table 1) shows that *M. praecursor* is the only species exclusively constrained to the Eocene (Cappetta, 1987). On the other hand, the youngest known records of *Ischyodus dolloi* are restricted to the Late Eocene (Ward and Grande, 1991), whereas the genera *Abdounia* and *Galeorhinus* are only known since the Early Eocene (Cappetta, 1980b; Cappetta, 1987). The only exception is constituted by *Carcharoides caticus*, previously described in Oligocene-Miocene beds in both hemispheres (Philippi, 1846; Cappetta, 1987). This could be interpreted as the oldest known record of this species (or, alternatively, the youngest records of *M. praecursor* and *I. dolloi*). The presence of serrated cutting edges on *Carcharoides totuseerratus* could be interpreted as a derived character from a taxon without serrations (such as *C. caticus*). A similar situation is seen between *Carcharodon carcharias* Linnaeus, 1758 and *Cosmopolitodus hastalis* (Agassiz, 1843), the latter possibly being the ancestor of the former (Nyberg *et al.*, 2006). Furthermore, it is consistent with the presence of the derived species *C. totuseerratus* exclusively in the Southern Hemisphere during the Oligocene-Miocene, with two records in the Pacific (Fitzgerald, 2004; Suárez *et al.*, 2006) and one in the Atlantic Ocean (Cione and Expósito, 1980).

#### 6.5. Paleobotany

The relative abundance of pteridophytes, pino-phytes and angiosperms of the genus *Nothofagus*, indicates environmental requirements of humidity and temperature compatible with a temperate and wet climate, similar to that recognized during the Eocene on Seymour Island, Antarctica (Askin, 1989; Cione *et al.*, 2007), suggesting that this floristic

assemblage existed previous to the large climatic changes registered since the Eocene/Oligocene boundary (Lawver and Gahagan, 2003). However, the recognized diversity cannot provide more accurate chronostratigraphic information, although all the recognized taxa are known during the Eocene (Barreda and Palazzesi, 2007). On the other hand, Torres *et al.* (2009) recognized a rich diversity of palynomorphs in lower levels of the Loreto Formation, including 40 continental taxa of pteridophytes, and pollen of pinophytes and angiosperms, while recovered macroflora were represented by 30 leaf imprints with an abundant content of *Nothofagus lanceolata* Dusén, *N. variabilis* Dusén, and *N. subferruginea* Dusén, together with *Hydrangea inserta* Berry, and *Araucaria pichileufensis* Berry. According to this diversity from lower levels of the Loreto Formation, there is thus no conflict with the present age proposal.

#### 6.6. U-Th-Pb data

Both analysed samples have a very precise concordant dominant Late Eocene (Priabonian) grouping of detrital zircon grains. This is interpreted as the maximum possible sedimentation age of the rocks in which they occur. The relative probability pattern of the detrital ages, with the maximum peak being the youngest, suggests that very probably sedimentation took place at around this time. Surprisingly, no rocks with similar ages have been found in the South Patagonian Batholith (SPB, Hervé *et al.*, 2007), lying ca. 100 km to the west and southwest, which would be the most obvious source of clastic material for the Rio de Las Minas depositional area. However, the 67 to 162 Ma zircon ages in the Las Minas 2008-02 sample, testify to a provenance from the SPB rocks, as the bulk of the batholith formed during that time span. A hitherto undated part of the SPB, or a different, not presently exposed (?) magmatic (volcanic?) body, must be considered to explain the presence of the Late Eocene igneous detrital zircons in the Rio las Minas studied succession. Further consideration of the provenance and tectonic implications of the detrital zircon assemblage will be given elsewhere.

#### 6.7. Associated vertebrate fauna

Two bone fragments of fossil penguins were recovered from the Loreto Formation and described by Sallaberry *et al.* (2010). The material includes an



ungual phalanx (SGO.PV.6652) and a tarsometatarsal fragment (SGO.PV.6653), but the fragmentary condition of these remains does not allow them to be identified to genus or species level. Nevertheless, the ungual phalanx SGO.PV.6652 is identical to one figured by Jadwiszczak (2006; Fig. 19, i-j), and identified as an indeterminate spheniscid. On the other hand, the size of the tarsometatarsus matches that of endemic spheniscid penguins only known in the Late Eocene of the La Meseta Formation of Seymour Island in Antarctica. This group includes the species *Mesetaornis polaris*, *Delphinornis gracilis*, *Delphinornis larseni*, *Delphinornis arc-towskii*, *Delphinornis* sp., and *Marambiornis exilis*, all characterized by a distinctively smaller size in comparison with common, larger Eocene penguins of the Weddellian Biogeographic Province. Additionally, the presence of well-fused metatarsals in SGO.PV.6653 compared to Neogene and extant species of spheniscids, indicates that this specimen has affinities with Paleogene members of this clade (Simpson, 1946; Acosta Hospitaleche *et al.*, 2007). What is more, strongly fused metatarsals such as those of SGO.PV.6653 are a common character of all Eocene penguins (*e.g.*, Clarke *et al.*, 2007; Myrcha *et al.*, 2002), this character is absent from crown spheniscids such as those from the Neogene (Göhlich, 2007) and extant species. Eocene penguins had a widespread distribution in the Southern Hemisphere, contrary to the scarce, known Paleocene distribution of these birds. In southernmost Chile other fossil spheniscids are represented by at least one genus, namely *Palaeudyptes* Hector (SGO.PV.6585) recovered from Eocene beds of the Río Turbio Formation. All these data partially support the proposed Eocene age in this paper.

## 7. Conclusions

The fossil cartilaginous fishes from Río de Las Minas constitute the southernmost assemblage of this group in South America. The presence of *Carcharias* aff. '*hopei*' (Agassiz), *Striatolamia macrota* (Agassiz), *Macrorhizodus praecursor* (Leriche), *Abdounia* sp. and *Ischyodus dolloi* Leriche supports an Eocene age for the hosting strata, while the presence of *Carcharoides caticus* (Philippi), previously known in Oligocene beds of the Northern Hemisphere (except for one dubious record in the Cenomanian of Egypt), suggests the relative age of the assemblage closer to the Eocene/Oligocene boundary. Additionally, this

diversity seems to be typical of cold to temperate, shallow waters not deeper than 30 m, being consistent with climate and seaway models during the Eocene and previous to the major changes experienced in the Southern Hemisphere during the Oligocene. The associated penguin bones found in the same beds are very fragmentary, although the presence of strongly-fused metatarsals can be distinguished, these being observed only in Eocene penguins from the Southern Hemisphere. The rich paleobotanic assemblage recognized in the Loreto Formation does not conflict with the relative age based on fossil vertebrates, although it cannot provide a more precise age due to poor chronostratigraphic resolution of the taxa. Finally, the absolute age obtained from the analyzed zircon grains indicates a very well defined peak at  $36.48 \pm 0.47$  Ma (MSWD=1.5). Considering the stratigraphic position of the studied section in the upper part of the Loreto Formation, all the data presented above indicate that most of this unit can be constrained to a minimal Priabonian age, but without discarding the eventual presence of Oligocene beds in the uppermost section. These remaining units are located several meters above the studied section, being mostly covered by vegetation, and represent a very minor portion of the whole formation.

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