

Paleontology and stratigraphic implications of a late Paleocene elasmobranch assemblage in Talcahuano, southcentral Chile

*Diego Rodríguez¹, David John Ward², Jorge Andrés Quezada³

¹ <http://orcid.org/0000-0003-2476-8172>, Chile.
diegorodz1996@gmail.com

² <http://orcid.org/0000-0002-3881-8970>, Department of Earth Sciences, Research associate, Natural History Museum, dirección, London, United Kingdom.
david@fossil.ws

³ Departamento de Ciencias de la Tierra, Facultad de Ciencias Químicas, Universidad de Concepción, dirección, Concepción, Chile.
jquezad@udec.cl

* Corresponding author: diegorodz1996@gmail.com

ABSTRACT. Late Paleocene elasmobranch findings are reported, along with reinterpretations of some previous taxonomic identifications in two main outcrops around Talcahuano area (Biobío region, Chile), and also delimiting the exposed lithostratigraphic units. Reviewed fossils are among 15 genera, comprising the species *Paraorthacodus clarkii*, *Squalus minor*, *Squalus orpiensis*, *Centrophorus* sp., *Squatina prima*, *Anomotodon novus*, *Striatolamia striata*, *Carcharias* spp., *Sylvestrilamia teretidens*, *Odontaspis winkleri*, *Palaeohypotodus speyeri*, *Palaeohypotodus rutoti*, *Isoiolamna inflata*, *Premontreia gilberti*, *Physogaleus secundus*, *Palaeogaleus vincenti* and *Hypolophodon sylvestris*. The main elasmobranch assemblage, collected from the San Martín outcrop, indicates deposition in a shallow lower shoreface-uppermost offshore marine environment and warm-temperate water. Moreover, this elasmobranch assemblage constrains the age of Pilpilco Formation into the middle-late Thanetian, which implies a latest Thanetian-early Ypresian age for the overlying Curanilahue Formation and a Danian-early Thanetian *hiatus* with the underlying Quiriquina Formation.

Keywords: Late Paleocene, Thanetian, Ypresian, Hiatus, Paleoenvironment, Elasmobranch, Talcahuano, Chile.

RESUMEN. Paleontología e implicancias estratigráficas de un conjunto de elasmobranquios del Paleoceno Superior en Talcahuano, Chile surcentral. Se reporta el hallazgo de elasmobranquios del Paleoceno Superior, junto con la reinterpretación de algunos taxones descritos previamente en dos afloramientos principales en el área de Talcahuano (región del Biobío, Chile), que también delimitan las unidades litoestratigráficas expuestas. Los fósiles descritos se encuentran entre 15 géneros y abarcan las especies *Paraorthacodus clarkii*, *Squalus minor*, *Squalus orpiensis*, *Centrophorus* sp., *Squatina prima*, *Anomotodon novus*, *Striatolamia striata*, *Carcharias* spp., *Sylvestrilamia teretidens*, *Odontaspis winkleri*, *Palaeohypotodus speyeri*, *Palaeohypotodus rutoti*, *Isoiolamna inflata*, *Premontreia gilberti*, *Physogaleus secundus*, *Palaeogaleus vincenti* y *Hypolophodon sylvestris*. El conjunto principal de elasmobranquios, obtenidos desde el afloramiento de Cerro San Martín, indica una deposición en un ambiente marino somero de *shoreface* inferior al *offshore* más superior, con una temperatura del agua templada cálida. Más aún, este conjunto de elasmobranquios acota la edad de la Formación Pilpilco al Thanetiano medio a tardío, subsecuentemente implicando una edad para la sobreyacente Formación Curanilahue entre finales del Thanetiano al Ypresiano temprano y un hiato Daniano-Thanetiano temprano con respecto a la subyacente Formación Quiriquina.

Palabras clave: Paleoceno Superior, Thanetiano, Ypresiano, Hiato, Paleoambiente, Elasmobranquios, Talcahuano, Chile.

1. Introduction

Paleocene elasmobranch's fossils are known in several worldwide outcrops, and have been reported at the Thanet Sands Formation of south-eastern England, Orp Member in the Heers Formation of Belgium, Sables de Bracheux of the Paleogene Paris basin at France, Aquia Formation of the United States, Phosphatic series of the Algerian-Tunisian border area, and in both Loburne Mudstone and Waipara Greensand layers of New Zealand (Herman, 1972; Ward, 1980; Ward and Wiest, 1990; Baut and Genault, 1995; Mannering and Hiller, 2008; Salim and Messaoud, 2018). From the late Paleocene sedimentary units, some frequent taxa comprise *Paraorthacodus clarkii*, *Squalus minor*, *Carcharias* spp., *Striatolamia striata*, *Sylvestrilamia teretidens*, *Myliobatis* spp., *Squalus orpiensis*, *Hypolophodon sylvestris*, *Anomotodon novus*, *Squatina prima*, *Palaeogaleus vincenti* and *Isoiolamna inflata* (Herman, 1972; Ward and Wiest, 1990; Baut and Genault, 1995; Smith *et al.*, 1999).

There's a relative lack of reliable up to date records of elasmobranch fossils late Paleocene, and even Paleogene from South America. Besides a few records on the outcrops discussed in this paper, there is a reworked assemblage with Paleocene-early Eocene affinity described by Otero *et al.* (2013) in southern Chile, and a preliminary report of Paleogene (in part Paleocene) taxa from the Salamanca Formation in Argentina (Bernárdez, 1997). Most of the publications are focussed on the Eocene, among which are the fossils of the Caballas Formation (Ypresian-Lutetian) of Perú and a few genera reported in the Man Aike Formation (middle-late Eocene) of Argentina (DeVries, 2017; Agnolin *et al.*, 2021).

In southernmost Chile there are also some papers dealing with middle-late Eocene elasmobranchs, reporting a couple of assemblages in the Río Baguales Formation of Sierra Baguales area, along with taxa from late Eocene layers at the Río Las Minas, Sierra Dorotea and Brunswick peninsula localities (Otero *et al.*, 2012, 2013; Otero and Soto-Acuña, 2015).

In southcentral Chile, other than from the outcrops discussed in this paper detailed systematic descriptions of Paleocene elasmobranch are scarce. Studies dealing with these very outcrops are Muñoz *et al.* (2007, 2008), Groz and Palma-Heldt (2013), Rodríguez (2022) and besides some unpublished reports. Particularly, Rodríguez (2022) in an unpublished graduate thesis described some of the fossil material in this paper,

but within a tectonostratigraphic focus and with a different emphasis.

The fossil assemblage described in this paper represents the first extensive listing of late Paleocene elasmobranch fauna not only from Chile, but also from South America. Besides this, the assemblage's geologic implications also comprise a narrower chronostratigraphic delimitation of the Paleogene layers in the Concepción-Talcahuano Bay area, and an improvement on the understanding of sedimentary facies and environment in the local marine Paleogene strata. In addition, the elasmobranch taxa show affinities with the European northwestern late Paleocene fossil record. The goal of this paper is to report and describe the late Paleocene elasmobranch fossils in the Talcahuano area, indicating the stratigraphic implications of this assemblage, precise lithostratigraphic units delimitations, and to confirm the existence of Paleocene strata in the outcrops.

2. Geological setting

In the locations around the elasmobranch-bearing outcrops (*ca.* 2 km around, Fig. 1) the basement is composed by metamorphic rocks, comprising phyllites, meta-sandstones and also schists (Frutos *et al.*, 1982). The age of these metamorphic rocks is reported to be late Paleozoic (Glodny *et al.*, 2008). Sedimentary layers include some conglomerates, shales and mainly sandstones, all of them ranging ages from the late Cretaceous to the Paleogene described generally as the Quiriquina (late Cretaceous) and Curanilahue (early Paleogene) formations (Salazar *et al.*, 2015; Inostroza, 2018; Rodríguez, 2022). The Curanilahue Formation is better known in the Arauco peninsula, with its three members Lota (continental), Intercalación (marine) and Colico (continental) (Muñoz-Cristi, 1956; Pineda, 1983).

The boundary between the Mesozoic and Cenozoic layers is not precisely documented, and for this set of outcrops it has been placed around a sandstone layer containing elasmobranch teeth, and above another sandstone stratum with detritus feeding bivalves and abundant trace fossils, which also overlies the uppermost ammonite bearing horizon (Biró, 1982; Frutos *et al.*, 1982; Muñoz *et al.*, 2007; Salazar *et al.*, 2015; Rodríguez, 2022).

The lowermost lithostratigraphic units is defined by different authors as the Quiriquina Formation (Biró, 1982; Salazar, 2004; Salazar *et al.*, 2015; Erices, 2018)

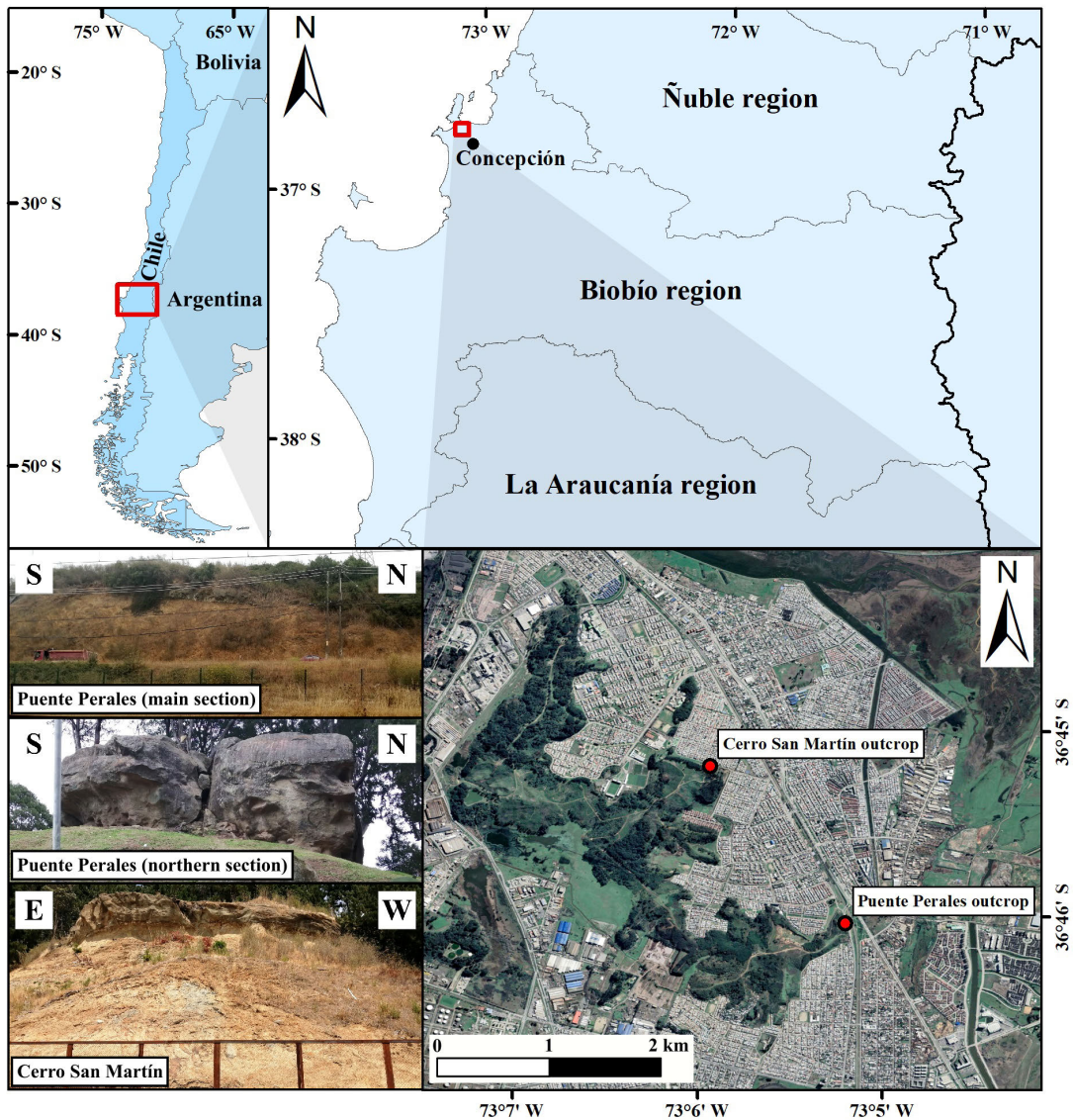


FIG. 1. Geographic location of both main outcrops, where paleontologic material was sampled. The lower left field pictures show the sections in Puente Perales, and in the Cerro San Martín outcrops.

which has a Maastrichtian age in the Talcahuano area (Salazar, 2004; Salazar *et al.*, 2015). This fossiliferous formation has a coastal shallow marine sedimentary environment, and its main lithofacies set begins with a basal conglomerate, laterally wedged and underlying a series of locally conglomeratic sandstones layers. These are under glauconitic sandstone strata that contain intercalated coquina layers. Overlying the glauconitic sandstone, are a set of horizons comprising a silty sandstone with fossiliferous calcareous concretions,

which is interdigitating with and underlying a bioturbated sandstone with fossil bivalves (Biró, 1982; Frutos *et al.*, 1982; Salazar *et al.*, 2015).

The main outcrops of Quiriquina Formation are located in the Concepción-Talcahuano Bay area, and in the eastern Arauco peninsula (Biró, 1982; Salazar *et al.*, 2015). Biró (1982) defined formally this unit and established its type locality in the northern Quiriquina island (Las Tablas Bay, near 20 km north of Concepción city).

The Paleogene Curanilahue Formation (locally former Cosmito Formation *sensu* Galli, 1967 in Inostroza, 2018), is in paraconformity over the Quiriquina Formation (Salazar *et al.*, 2015; Erices, 2018; Inostroza, 2018). In the Concepción-Talcahuano Bay area, the Curanilahue Formation is represented by conglomerates, sandstones, and shales from a laterally and vertically variable sedimentary environment, ranging from fluvial to marine strata (Gajardo, 1981; Inostroza, 2018).

In the Arauco peninsula, the Curanilahue Formation is above the marine Pilpilco Formation (which is also overlying Quiriquina Formation) and composed by (from base to the top) the Lota, Intercalación and Colico members with continental, marine and again continental sedimentary environments respectively (Muñoz-Cristi, 1956; Pineda, 1983). Martínez-Pardo (1968) portrays the Intercalación Member as an eastward and partial lateral equivalent of the marine Boca Lebu Formation (*sensu* Muñoz-Cristi, 1956), and also interdigitating with the Lota Member (lowermost member of the Curanilahue Formation). Tavera (1942) suggested a mainly early Eocene age for the Curanilahue Formation, as an interpretation of the lateral correlation between the Curanilahue and Boca Lebu formations, altogether with the marine fauna in the latter formation. More recently, Martínez-Pardo *et al.* (1997) infers from a foraminifera analysis, that all Pilpilco and Curanilahue (apart from the Colico Member) formations and most of the Boca Lebu Formation sedimentary age are late Paleocene, and the uppermost part of Curanilahue and Boca Lebu formations would be early Eocene.

3. Methodology

The elasmobranch sampling sites (Fig. 1), are in the southwestern margin of Talcahuano (near 7 km at the northwest of Concepción city) and inside the coastal zone of the Biobío region. For each sampling site (Puente Perales and Cerro San Martín), the location and a detailed stratigraphic section (comprising the main sedimentary lithofacies changes) is described. Also, those strata used for elasmobranch sampling are indicated in the description, and a maximum along with an average thickness is also supplied for them.

Elasmobranch fossils were sampled in situ or reviewed from the material collected by Muñoz *et al.* (2007), Groz and Palma-Heldt (2013) or unreported

field works. All these teeth are deposited in the “Profesor Lajos Biró Bagóczy” geological museum collections located in the Universidad de Concepción, at the Concepción city. Specimens were photographed using either a Panasonic DMC-FZ70 camera or a 10x loupe attached to a Huawei JKM-LX3 camera. Once identified, are listed in the same taxonomic sequence as Cappetta (2012), but the taxa with indeterminate family are listed just in the figures. Dental terminology (Fig. 2) is mainly based on Cappetta (2012).

Stratigraphic range of the taxa is obtained from reliable bibliographic records and sources, and also from the authors personal observations. All these data and records are analysed (if needed) within the discussion of each taxon. Once the ranges are obtained, a preliminary intersection's age is estimated, and then evaluated in regard to biostratigraphic and climatic aspects to obtain a wide and conservative age's range. The conservative range is narrowed down with the ranges of specific taxa, resulting a definitive range for the elasmobranch assemblage's age.

4. Elasmobranch sampling sites and detailed stratigraphy

4.1. Puente Perales outcrop

Stratigraphy (Fig. 3) of the main location at this outcrop (36°46'2" S/73°5'12" W) is, from base to the top: a first and basal section composed of a grey yellowish fine grain sized sandstone, with fossiliferous (marine invertebrates assemblage of bivalves, gastropods and ammonites) calcareous concretions, weakly marked planar bedding close to the top and a thickness of 11.7 m; a second section which comprise 1.3 m maximum thick layer (0.8 m average) of greenish glauconitic fine grain sized (structureless but with locally and weakly marked, low angle trough cross bedding) sandstone, the concretions right at the base are basally truncated following the contact surface, in its lateral continuations this layer can host coarser levels with elasmobranch teeth, and locally has interdigitations of very fine grain size; a third section (Puente Perales sampling level, PPSL) of 0.8 m thickness comprising four conglomeratic levels (0.05 m of maximum thickness each, the two topmost laterally wedged) hosting autochthonous elasmobranch fossils and intercalated with three fine-grained greenish glauconitic sandstone levels (0.2 m of thickness each) with common

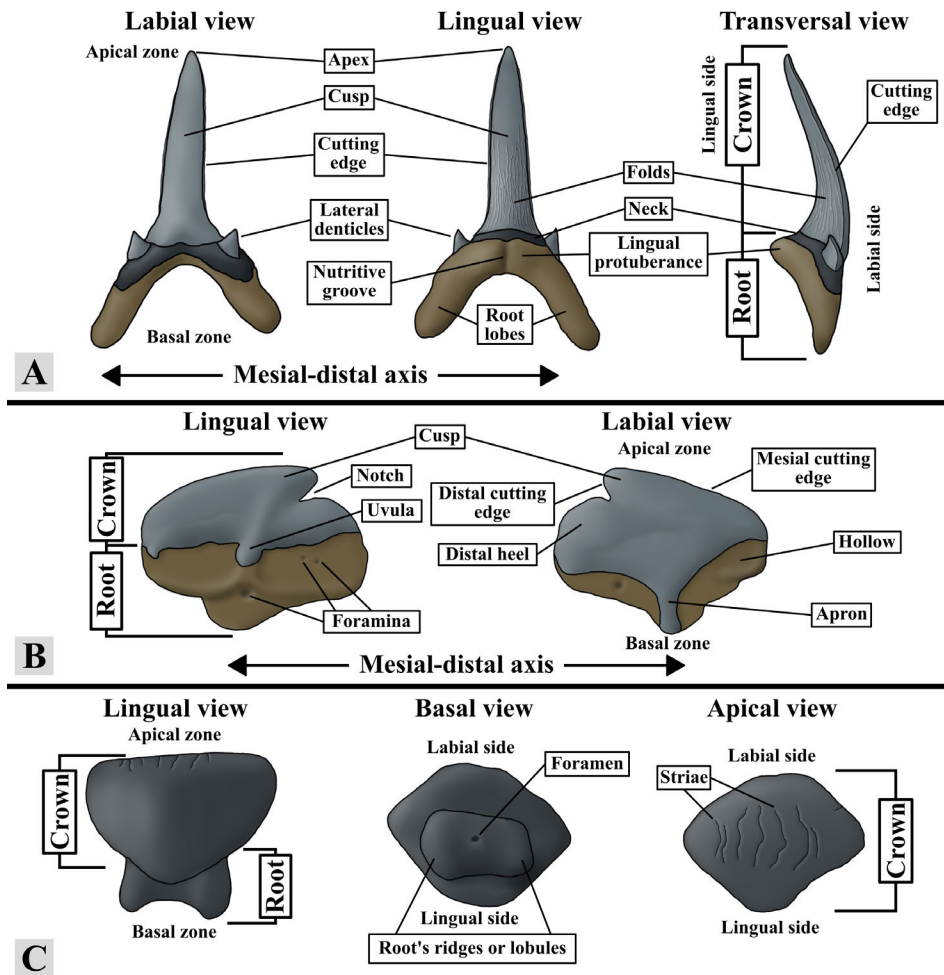
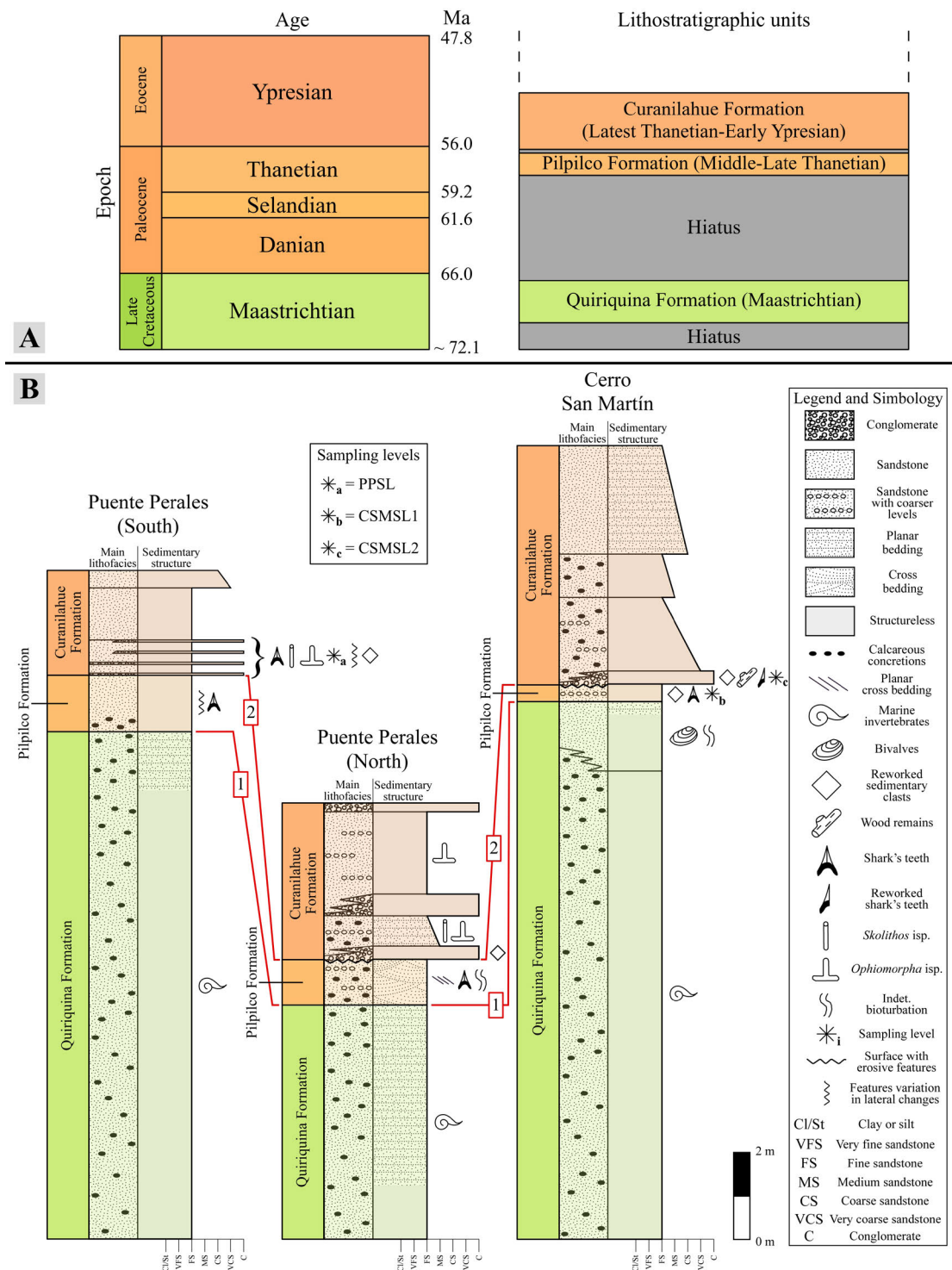


FIG. 2. Main terminology for elasmobranch's dental description, adapted from Cappetta (2012). A. Lamniform tooth. B. Squaliform tooth. C. Myliobatiform tooth.

Ophiomorpha isp. and *Skolithos* isp. trace fossils; a fourth section representing a 1.2 m thick layer of grey greenish glauconitic fine grain sized; and a finning upwards uppermost section of 0.4 m thickness, comprising a grey greenish sandstone, very coarse-grained at the base and coarse at the top. The layers from the third section and upwards are in lateral interdigitation with a 2.7 m thick stratum of brown greenish sandstone (coarse in the base and medium grain sized at the top) hosting levels of greater granulometry, reworked clasts of dark-grey mudstone (mostly near the base) and weakly marked planar bedding. The boundaries between the layers are generally planar and smooth surfaces, or at least slightly curved and predominantly smooth planar surfaces.

In the isolated northern outcrop (36°45'55" S/ 73°5'16" W), the stratigraphy (Fig. 3) comprise, from base to the top: a first and basal section composed of a 5.4 m thick layer with the same lithology of the basal stratum in the main location, but thought-out with planar bedding; a second section of grey greenish glauconitic fine grain sized sandstone with calcareous concretions, slightly marked and locally bounded planar cross bedding, indeterminate trace fossils, laterally wedged coarser levels, scarce autochthonous elasmobranch fossils, a mainly planar basal surface with minor erosive geometries or slight unevenness (Fig. 4) and a maximum thickness (at a small outcrop in between main section and the northern one) of 1 m (0.4 m average); a third section of 0.3 m maximum



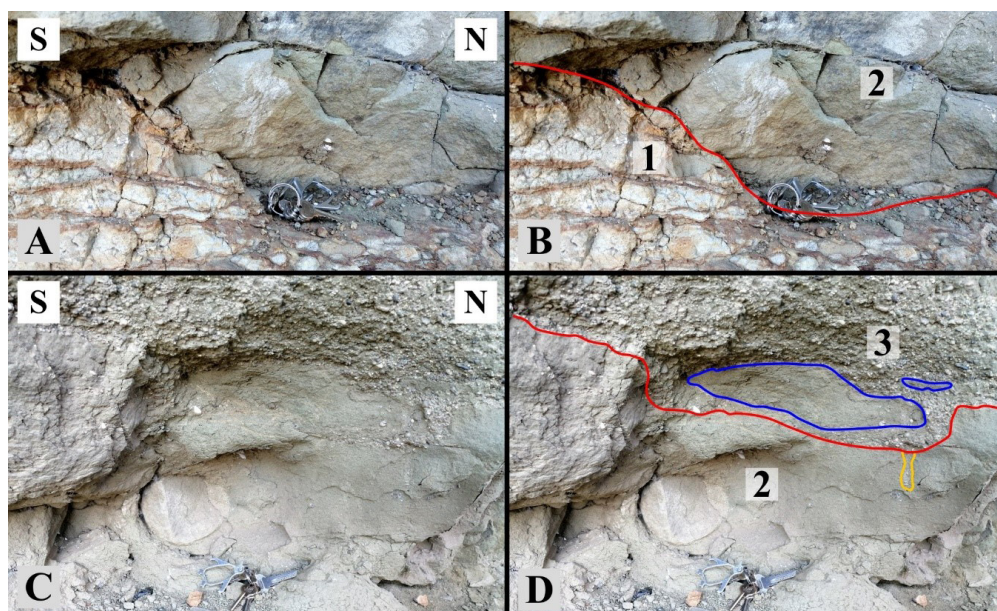


FIG. 4. Contact surfaces with erosive hints, in the isolated northern Puente Perales outcrop. **A.** General view of the contact between the first and the second lithologic sections in the location. **B.** The same previous view with a boundary line (red) delimitating the contact between the first (1) and the second (2) lithologic sections. **C.** General view of the contact between the second and the third lithologic sections in the location. **D.** The same previous view with a boundary line (red) delimitating the contact between the second (2) and the third (3) lithologic sections, intraclasts are marked with blue outline and bioturbation on the contact surface with an orange one.

thick stratum of a laterally wedged conglomerate with reworked intraclasts of the underlying sandstone and an erosive (but broadly planar) basal surface (Fig. 3); a fourth section of 0.7 m thick layer of a grey greenish, fining upwards concretionary sandstone of medium grain size in the base and fine near the top, altogether with coarser levels, weakly marked planar bedding besides of scarce *Skolithos* isp. and *Ophiomorpha* isp. trace fossils; a fifth section of 0.5 m maximum thick stratum of a conglomerate layer interdigitating with the overlying sandstone; a sixth section of 1.9 m thick layer of a yellow greenish fine grain sized sandstone with laterally wedged conglomeratic levels and scarce *Ophiomorpha* isp. trace fossils and finally a seventh section of 0.2 m maximum thick stratum comprising a conglomerate level.

4.2. Cerro San Martín outcrop

The outcrop's ($36^{\circ}45'11''$ S/ $73^{\circ}5'56''$ W) stratigraphy (Fig. 3) is, from base to the top: a first and basal section composed of a grey yellowish fine grain sized sandstone, with fossiliferous (bivalves,

gastropods and ammonites) calcareous concretions, and a thickness of 10.8 m; a second section of a yellow greyish fine grain sized sandstone, with plenty of bioturbation, scarce bivalve fossils, locally interdigitating with the underlying concretionary sandstone, planar bedding near to the top and a maximum thickness of 1.6 m; a third section of a 0.4 m maximum thick layer (0.3 m average, first Cerro San Martín sampling level, CSMSL1) comprising a grey greenish glauconitic fine grain sized sandstone, with isolated small pebbles or in small clusters, laterally wedged coarser levels hosting autochthonous elasmobranch fossils and scarce reworked-weathered clasts of the underlying sandstone, altogether with a predominantly planar basal surface (with minor erosive geometries or slight unevenness) (Fig. 5); a fourth section of a 0.3 m maximum thick layer (0.2 m average, second Cerro San Martín sampling level, CSMSL2) of a conglomerate with reworked intraclasts (underlying sandstone and dark-grey greenish mudstone), with also reworked (abraded and sometimes broken) elasmobranch fossils, carbonized wood remains,

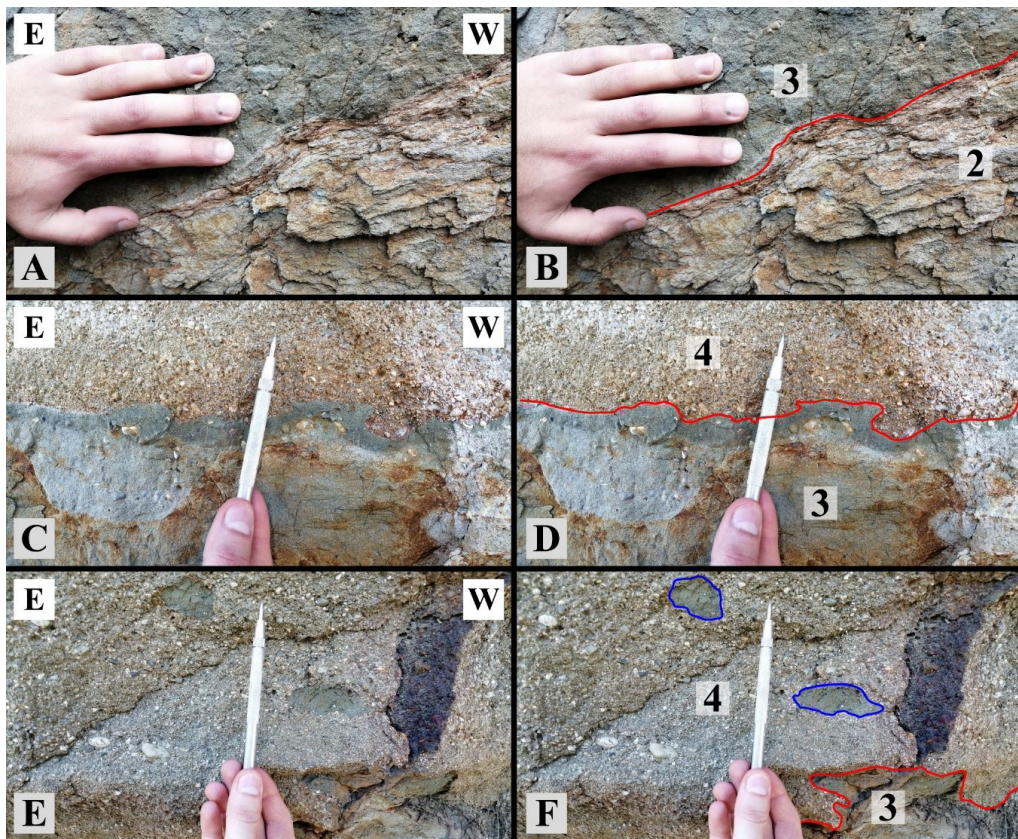


FIG. 5. Contact surfaces with erosive hints, in the Cerro San Martín outcrop. **A.** General view of the contact between the second and the third lithologic sections in the location. **B.** The same previous view with a boundary line (red) delimitating the contact between the second (2) and the third (3) (CSMSL1) lithologic sections. **C.** General view of the contact between the third and the fourth lithologic sections in the location. **D.** The same previous view with a boundary line (red) delimitating the contact between third (3) (CSMSL1) and the fourth (4) (CSMSL2), intraclasts are marked with blue outline. **E.** Another view of the same previous contact, with two sandstone intraclasts. **F.** The same, with a blue outline for the intraclasts and a red sections boundary.

a predominantly planar but uneven basal surface (Fig. 4), local lateral variations onto very coarse grain sized conglomeratic sandstones, and at the same time interdigitating with the overlying sandstone; a fifth section of a 1.7 m thick layer comprising a yellow greenish finning upwards concretionary sandstone of very coarse grain size in the base and fine near the top, altogether with coarser levels; a sixth section of a grey greenish finning upwards concretionary sandstone of medium granulometry in the base and fine near the top, with a thickness of 1 m; a seventh and uppermost section of a grey finning upwards sandstone of coarse grain size in the base and fine near the top, which has slightly marked planar bedding, levels with greater granulometry and also a thickness of 2.5 m.

5. Systematic paleontology

Class CHONDRICHTHYES Huxley, 1880
Subclass ELASMOBRANCHII Bonaparte, 1838
Subcohort NEOSELACHII Compagno, 1977
Superorder SQUALOMORPHII Compagno, 1973
Order SYNECHODONTIFORMES Duffin and Ward, 1993
Family PARAORTHACODONTIDAE Glikman, 1957
Genus *Paraorthacodus* Glikman, 1957
***Paraorthacodus clarkii* (Eastman, 1901)**

Fig. 6A-D, E-F and G-H

1901 *Synechodus clarkii* Eastman: p. 103, pl. 14, fig. 5, a-c.

1902 *Synechodus eocaenus* Leriche: pp. 29-30, pl. 1, figs. 24-26.

1964 *Paraorthacodus eocaenus* (Leriche); Glikman: pl. 20, fig. 18.

1993 *Paraorthacodus eocaenus* (Leriche); Cvancara and Hoganson: p. 10, fig. 2, L-M.

2007 *Paraorthacodus* sp. Muñoz et al.; p. 15, pl. 2, figs. I-L.

Material: 2 complete anterolateral teeth from CSMSL1: C.M/09 and Q/2846; 1 incomplete lateral tooth from CSMSL1: CPUC/4013; 1 incomplete anterior tooth from CSMSL2: C.M/01.

Dimensions: C.M/09: W=11.6 mm, H=8.2 mm (not figured); C.M/01: W=14.2 mm, H=1.3 mm; Q/2846: W=14.8 mm, H=8.4 mm; CPUC/4013: W=15 mm, H=14 mm.

Description: The teeth comprise a centrally placed, conical crown with between two and three pairs of laterally situated denticles or cusplets (Fig. 6E). The crown and lateral denticles are almost or completely separated at their bases. They bear vertical folds in both lingual and labial sides, and a cutting edge almost reaching the apex, more pronounced on the

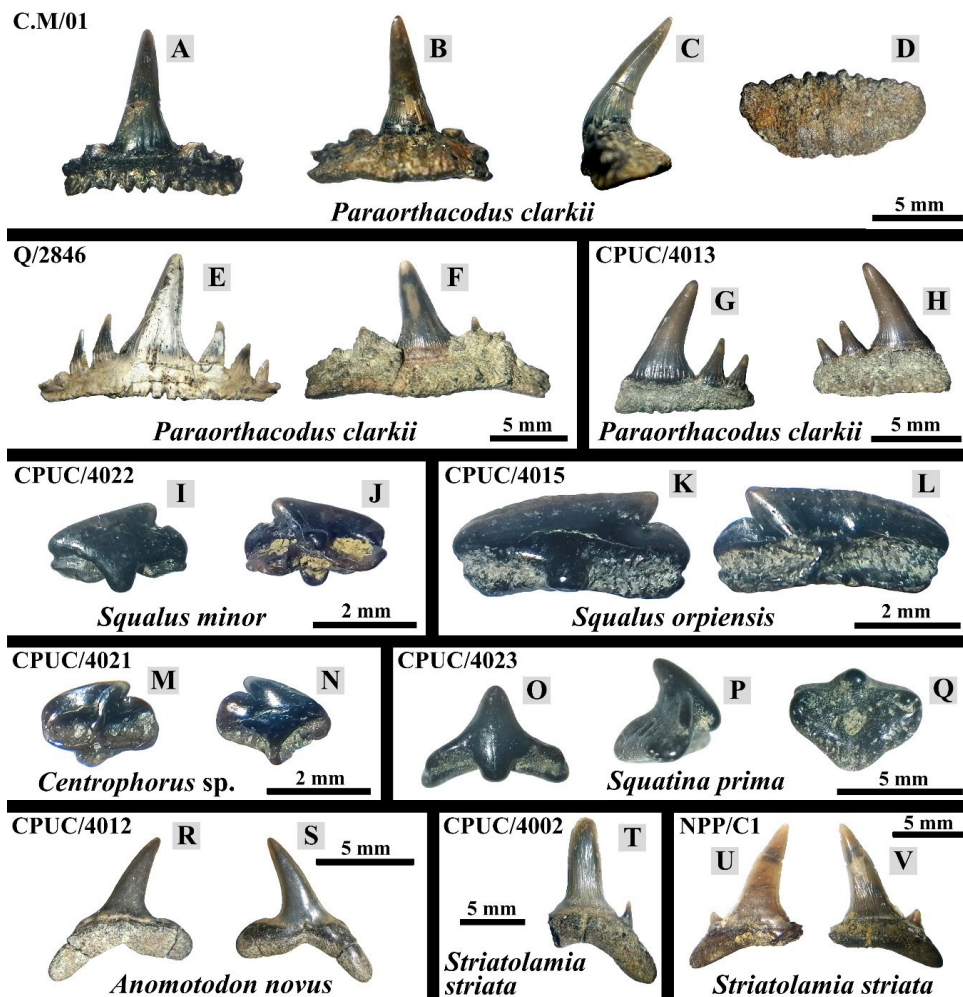


FIG. 6. *Paraorthacodus clarkii* C.M/01: A. Labial view. B. Lingual view. C. Lateral view. D. Basal view. *Paraorthacodus clarkii* Q/2846: E. Labial view without matrix. F. Lingual view. *Paraorthacodus clarkii* CPUC/4013: G. Labial view. H. Lingual view. *Squalus minor* CPUC/4022: I. Labial view. J. lingual view. *Squalus orpiensis* CPUC/4015: K. Labial view. L. lingual view. *Centrophorus* sp. CPUC/4021: M. Lingual view. N. Labial view. *Squatina prima* CPUC/4023: O. Labial view. P. Lateral view. Q. Basal view. *Anomotodon novus* CPUC/4012: R. Lingual view. S. Labial view. *Striatolamia striata* CPUC/4002: T. Lingual view. *Striatolamia striata* NPP/C1: U. Labial view. V. Lingual view.

more convex lingual face (Fig. 6G). The crown enameloid does not overhang the root labially. The root is wide and basally flattened, its base bears a series of deep grooves originating on the labial margin and terminating in foramina (Fig. 6D).

Discussion: In the Paleogene, with its “*Hybodus*-like” morphology, *Paraorthacodus* is difficult to mistake for any other genus except for *Synechodus*, with which it shares a similar stratigraphic range (Cappetta, 2012). *Synechodus* differs in having a fused crown and lateral denticles and labial crown enameloid overhanging the root, especially in anterior teeth. In his description of “*Synechodus*” *clarkii*, Eastman (1901) held the opinion that despite being abraded, his unique specimen was still sufficiently distinctive to form the basis of a new species, but Leriche (1902) held the contrary view. He regarded Eastman’s specimen as being rolled, incomplete and devoid of sufficient characters of specific taxonomic value. The three specimens figured by Leriche (1902), presumably his best, were scarcely better. One, an anterolateral tooth in Leriche (1902) is relatively complete, the other two are broken fragments. Subsequent figures of “*Synechodus*” *eocaenus* are much more comparable with Eastman’s original figure (Priem, 1908; Casier, 1967; Herman, 1977) leading it to be regarded as a junior synonym of *Paraorthacodus clarkii* (Ward and Wiest, 1990).

The tooth morphology fits the type description (Leriche, 1902) with a cusp and lateral denticles of smaller size (Fig. 6E-H), that are lingually inclined, all well developed and with a conical-slender shape (Fig. 6A-H). Another characteristic for the identification of *P. clarkii* (*sensu* this work) pointed out by Leriche (1902) is the presence of folds in both tooth’s faces, corroborated in the samples just described (Fig. 6A-H). Detailed shape of the folding and the basal grooves can be distinguished from the fossil’s images in Casier (1967), being again homologous to the described teeth. Some of the features described by Eastman (1901) are also presents, like a symmetrical shape with recurved, gently tapering cusp, but are much better represented in the anterior tooth C.M/01 (Fig. 6A-D).

The appearance of *P. clarkii*, the only species of *Paraorthacodus* known from the Paleogene, is synchronous in the European and North American Paleocene at the base of the Thanetian at (approximately) the top of nannofossil zone NP6 (Ward, 1980; Casier, 1967; Ward and Wiest,

1990). The youngest European record (specimen PV P 75130, Natural History Museum, London: Ward, 2013, personal observation) is from the early Eocene, basal NP10 Orwell Member of the Harwich Formation at Herne Bay, United Kingdom (King, 2016). This is the first published reliable record and description of *P. clarkii* (*sensu stricto*) from the southern hemisphere. Rodríguez (2022) identified CPUC/4013 as *Paraorthacodus eocaenus*, junior synonym of *P. clarkii*. It is noteworthy that the genus *Paraorthacodus*, and thus *P. clarkii*, has not been recorded in Europe south of the Paris Basin in early Paleogene layers, nor any of the north African Paleogene phosphate deposits, suggesting that it preferred cooler waters.

Order SQUALIFORMES Goodrich, 1909

Family SQUALIDAE Bonaparte, 1834

Genus *Squalus* Linnaeus, 1758

Squalus minor (Daimeries, 1888)

Fig. 6I-J

1874a *Notidanus orpiensis* (in part) Winkler: p. 12, pl. 1, figs. 16-17 (non 13-15).

1888 *Biforisodus minor* Daimeries: pp. 43 and 45-46, *nom. nud.*

1902 *Acanthias minor* Leriche: pp. 16 and 27, pl. 1, figs. 9-16.

1977 *Squalus minor* (Leriche); Herman: p. 134; pl. 5; fig. 7.

Material: 1 complete lateral tooth from CSMSL1: CPUC/4022.

Dimensions: W=2.9 mm, H=1.9 mm.

Description: The single tooth is moderately rolled and has a mesio-distally long crown with a distally directed cusp and a single small distal heel or cusplet. The labial surface bears a large, slightly rounded V-shaped labial flange or “apron” that extends below the level of the root base (Fig. 6I). Small foramina are present in the labial root mesial and distal to the flange. The lingual face bears a small flange or uvula (Fig. 6J). The notch is short and rounded, and the distal heel is mildly elongated towards the apical zone. The root base is relatively flat; on its lingual aspect has a single large foramen or infundibulum below the uvula. The root also has two extensions or enlargements coming out into the mesial and distal directions (Fig. 6J).

Discussion: Specimen CPUC/4022 conforms to the general shape of the early Paleogene species *Squalus*

minor, with a typical mesio-distally elongated crown, distally directed cusplet, smooth mesio-distal borders and a flattened root. Teeth of genus *Squalus* exhibit little heterodonty compared with lamniform teeth, and upper teeth are slightly narrower than lowers.

Because “*Biforisodus minor*” is a *nomen nudum* (Daimeries, 1888), we rely on the description and figures of the teeth of “*Acanthias minor*” by Leriche (1902). According to Leriche (1902), the identification characteristics (apart from the unreliable size criteria) of *S. minor* (*sensu* this work) are the smooth mesio-distal borders, a slightly curved cusp, a convex mesial margin, and an apically high, convex and very distally rounded distal heel. Regardless Leriche (1902) description were mainly made to be compared with *Squalus orpiensis* specimens, it fits the CPUC/4022 shape and features (Fig. 6I-J). It is remarkable that this lateral tooth has two well marked root extensions (Fig. 6J), corresponding to the description made by Baut and Genault (1995) on lateral teeth of *S. minor*.

The species *S. smithi* described in Herman (1982) is regarded as a junior synonym of *S. minor* as it has no specific characters separating it from *S. minor* other than size (Migom et al., 2021). Because of the close similarity in tooth morphology between Recent species of *Squalus*, it would be unwise to assume the fossil species *Squalus minor* represents a single biological species. Recent species of *Squalus* are common in inner to middle shelf fully marine habitats (Ebert et al., 2021). *Squalus minor* ranges in North America and Europe from the early Paleocene (Danian) to the middle Eocene, in nannofossil zones NP3-NP16 (Casier, 1967; Ward and Wiest, 1990; Cappetta, 2012). This is the first published and reliable record of *S. minor* from the southern hemisphere, and also the first mention in Chile. This taxon is only reported before in South America at the Paleogene of southern Argentina, in the preliminary report made by Bernárdez (1997).

***Squalus orpiensis* (Winkler, 1874a)**

Fig. 6K-L

- 1874a *Notidanus orpiensis* (in part) Winkler: p. 12, pl. 1, figs. 13-15 (non 16-17).
 1902 *Acanthias orpiensis* (Winkler); Leriche: p. 40, p. 14, pl. 1, figs. 1-8.
 1931 *Squalus orpiensis* (Winkler); White: p. 67, figs. 25-26.
 1982 *Megasqualus orpiensis* (Winkler); Herman: p. 2, pl. 1, fig. 6.

Material: 1 complete lateral tooth from CSMSL1: CPUC/4015.

Dimensions: W=3.9 mm, H=1.9 mm.

Description: The tooth has a mesio-distally long crown with a distally directed cusp and a single distal heel. The mesial and distal border of the cusp has slightly crenulated or serrated cutting edges, feature which is also stronger in the mesial cutting edge (Fig. 6L). The labial apron is more U-shaped than V-shaped and barely protrudes below the base of the root (Fig. 6K). The notch is well marked, and triangular shaped. The distal heel is well rounded and slightly elongated into the distal direction. The root base is flattened; on its labial side has some foramina covered with matrix (Fig. 6K). The base of the crown in its lingual side contains mild crenulations, more evident towards the mesial direction (Fig. 6L).

Discussion: Teeth of *Squalus orpiensis* conform closely to those of Recent *Squalus* species, and can be readily separated from those of *Squalus minor* in being mesio-distally longer, having slightly serrated mesial and distal cutting edges, larger and more labial foramina, and a finely crenulated lingual crown base (Fig. 6L). As the genus *Megasqualus* was restricted to a single species with no obvious ancestors nor descendants and did not significantly depart from the *Squalus* morphotype, it is regarded as a junior synonym of the genus *Squalus* (*sensu* Linnaeus, 1758). *Squalus orpiensis* ranges in Europe from the middle Paleocene, (Selandian) to early Eocene, (Ypresian), nannofossil zones from NP5 to basal NP10 (Herman, 1982; Cappetta, 2012; Ward, 2013, personal observation), although verifiable Eocene records are rare. Muñoz et al. (2007) referred as *Squalus* sp. the tooth CPUC/4015. This is the first published record of *S. orpiensis* from the southern hemisphere.

Family CENTROPHORIDAE Bleeker, 1859

Genus *Centrophorus* Müller and Henle, 1837

***Centrophorus* sp.**

Fig. 6M-N

Material: 1 abraded but complete anterolateral tooth from CSMSL1: CPUC/4021.

Dimensions: W=2.2 mm, H=1.7 mm.

Description: Lower tooth, labio-lingually slim, deeper than they are wide, with a distally inclined cusp and a large distal heel. The mesial cutting edge is smooth. The labial surface has a large V-shaped

apron which terminates just above the base of the root flange, and also a marked hollow in the distalmost root zone (Fig. 6N). Several foramina are present on either side of the apron below the root-crown junction. The lingual surface has a small uvula with a large infundibulum almost immediately below, and an evident longitudinal ridge partially interrupted by the infundibulum or central lingual foramen, below the ridge (Fig. 6M).

Discussion: Unlike those of *Squalus*, teeth of *Centrophorus* display a high degree of heterodonty. Lower teeth are labio-lingually compressed, with a mildly distally inclined cusp, mesial cutting edge may be straight or have serrations, also with a high distal heel and convex shaped, a large apron, and a relatively small uvula (Cappetta, 2012). The distal part of *Centrophorus* root is larger than the mesial part, and the infundibulum opens below the uvula and longitudinal ridge (Long, 1992; Cappetta, 2012). Upper anterior teeth are smaller and much narrower than lower teeth, and almost symmetrical. More lateral teeth are like the lower ones but smaller and with a slightly concave mesial cutting edge. The single tooth from CSMSL1 is typical of a lower tooth of *Centrophorus* and fits the diagnostic criteria of Cappetta (2012), and also the features pointed out by Long (1992) in Eocene Antarctic *Centrophorus* teeth. However, it is too abraded and polished to refer to a Recent or fossil species.

Teeth of *Centrophorus* are known from the Maastrichtian and Danian of New Zealand (Keyes, 1984), the Eocene of Antarctica (Welton and Zinsmeister, 1980; Long, 1992) and the Paleocene Lodo Formation in California (Welton, 1974). It is relatively common in the early Eocene Rosnaes and Lillebaelt formations in Denmark (Ward, 1988, personal observation) and middle Eocene of Landes, SW France (Adnet, 2006). Known Recent species of *Centrophorus* generally live in middle to outer shelf fully marine habitats (Ebert *et al.*, 2021). This is the first report of the *Centrophorus* genus in Chile's mainland.

Superorder SQUATINOMORPHII Compagno, 1973

Order SQUATINIFORMES De Buen, 1926

Family SQUATINIDAE Bonaparte, 1838

Genus *Squatina* Duméril, 1806

Squatina prima (Winkler, 1874a)

Fig. 6O-Q

1874a *Trigonodes primus* Winkler: p. 14, pl. 1, figs. 18-21.

1886 *Squatina prima* (Winkler); Noetling: p. 16.

1905 *Squatina crassa* (Daimeries); Leriche: p. 96, pl. 4, figs. 6-7.

2021 *Squatina prima* (Winkler); Migom *et al.*: p. 21, pl. 7, figs. 1-6, pl. 8, figs. 1-6.

Material: 1 highly abraded but complete anterior tooth from CSMSL1: CPUC/4023.

Dimensions: W=5.8 mm, H=4.3 mm.

Description: The crown bears a single upright cusp with wide heels and a distinct cutting edge that is continuous over the principal cusp. The labial crown is wide and has a centrally placed, rounded labial flange (Fig. 6O). The lingual crown enamel covers the upper part of the lingual protuberance. The root is triangular to diamond-shaped, basally flattened or concave and at right angles to the principal cusp, and there is a central hollow in the basal root's surface, which shallows labially into which foramina open (Fig. 6Q).

Discussion: Specimen CPUC/4023 resembles the Winkler (1874a) holotype in size and proportions and can confidently be referred to the species *S. prima*. Angel sharks (genus *Squatina*) are flat-bodied benthic sharks; their teeth are distinctive and have not changed significantly since first appearing in the Jurassic. Their size varies from about 4 mm wide to 12 mm.

The specimen CPUC/4023 has been previously figured by Muñoz *et al.* (2007) as *Cretorectolobus* sp. This was probably because abrasion had removed from the basal surface the medial vascular canal giving the tooth a hemiaulacorhize appearance. The degree of lingual curvature is consistent with small anterior teeth of both fossil and Recent species.

Squatina teeth from the Paleocene and Eocene of Europe are generally referred to the "species" *Squatina prima* (*sensu* Winkler, 1874a). There is some variation in morphology between stratigraphic horizons, late Paleocene-early Eocene teeth are generally robust and larger when compared to the middle-late Eocene teeth (White, 1931; Casier, 1946, 1966, 1967). It is very likely that a number of species are housed under this name. As Daimeries (1888) did not figure *S. crassa*, designate a holotype or a type locality, it remained a *nomen nudum* until figured and described by Leriche (1905) to whom the "species" must be credited. In our opinion its morphology falls within the range of variation seen in *S. prima* from the Late Paleocene

and early Eocene. *Squatina prima* (*sensu lato*) ranges from the middle Paleocene (Selandian) to the late Eocene (Cappetta, 2012). This is the first published record of *S. prima* from the southern hemisphere.

Superorder GALEOMORPHII Compagno, 1973

Order LAMNIFORMES Berg, 1958

Family MITSUKURINIDAE Jordan, 1898

Genus *Anomotodon* Arambourg, 1952

Anomotodon novus (Winkler, 1874b)

Fig. 6R-S

1874b *Oxyrhina nova* Winkler: p. 20, pl. 2, fig. 8.

1962 *Isurus novus* (Winkler); Gurr: p. 427, pl. 21, figs. 1-3.

1967 *Oxyrhina nova* (Winkler); Casier: p. 27; pl. VII, figs. 8-9.

1995 *Anomotodon nova* (Winkler); Baut and Genault: p. 202, pl. 5, figs. 5-8.

2012 *Anomotodon novus* (Winkler); Cappetta: p. 184 (name only).

Material: 1 complete lateral tooth from CSMSL1: CPUC/4012.

Dimensions: W=6.8 mm, H=7.5 mm.

Description: Lamniform tooth, narrow crowned, in the shape of an inverted “Y”. Crown’s lingual basal side has a few and very fine striae. The cusp is distally curved towards the apex and at its base is slightly inclined on this same axis. There are no lateral cusplets present, and the two root lobes are slender, asymmetrical, widely spaced and with a shallow lingual nutritive groove (Fig. 6R). At the base of the labial crown there is a small protuberance (Fig. 6S). The single specimen from CSMSL1 is probably a lateral tooth from the upper dentition.

Discussion: Teeth of *Anomotodon* are characterised by a lack of lateral denticles or cusplets, and a fine striation on the basal half of the labial crown mostly in anterior teeth. Like most lamniform sharks, the teeth display marked disjunct monognathic, dignathic and a degree of ontogenetic heterodonty resulting in a wide range of morphologies (Van den Eeckhaut and De Schutter, 2009).

The diagnostic features from the upper lateral CPUC/4012 tooth of *Anomotodon novus* when compared to *Anomotodon sheppeyensis*, are the rounded-slender shape termination of the root lobes of *A. novus* against the wider termination of the root lobes in *A. sheppeyensis* lateral teeth of the upper dentition in Cappetta (1976), and the root lobes of

the latter are also more symmetrical and spaced than the ones figured of CPUC/4012. The upper lateral teeth of the Late Cretaceous species *Anomotodon plicatus* figured in Arambourg (1952) show stronger ornamentation at the base of the lingual crown, and relatively shorter root lobes than those of *A. novus*.

Anomotodon novus ranges from the late Paleocene (Thanetian) to the middle Eocene in Europe and North America (Cappetta, 2012). *A. novus* has only been recorded before in Chile by Rodríguez (2022), corroborating this taxonomic identification on this very specimen.

Family ODONTASPIDIDAE Müller and Henle, 1839

Genus *Striatolamia* Glickman, 1964

Striatolamia striata (Winkler, 1874a)

Fig. 6T and U-V; Fig. 7A-C and D-E

1874a *Otodus striatus* Winkler: p. 8, pl. 1, figs. 7-9.

1931 *Odontaspis* (*Synodontaspis*) *macrota* (Agassiz), premut. *striata* (Winkler); White: p. 58, pl. 45-74.

1952 *Odontaspis macrota* premut. *striata* (Winkler); Arambourg: p. 62, figs. 58-67.

1964 *Striatolamia striata* (Winkler); Glickman: p. 121, pl. XX, figs. 35-37 and 39-40.

Material: 1 complete anterolateral tooth from CSMSL1: C.M/03; 2 incomplete lateral teeth from CSMSL1: CPUC/4002 and CPUC/4003; 1 lateral tooth from PPSL: NPP/C1; 1 incomplete anterolateral tooth from CSMSL2: Q/3729; 1 incomplete lateral tooth from PPSL: CPUC/4033.

Dimensions: C.M/03: W=9.9 mm, H=17 mm; CPUC/4002: W=8.4 mm, H=12.7 mm; CPUC/4003: W=8.2 mm, H=9.8 mm; NPP/C1: W=7.8 mm, H=9.9 mm; Q/3729: W=9.1 mm, H=17.1 mm (not figured); CPUC/4033: W=3.1 mm, H=4.1 mm (not figured).

Teeth vary greatly in size depending on their position in the jaw. Anterior teeth of adult individuals reach 40 mm in height while posterior teeth may only reach a few mm.

Description: The teeth are “Y”-shaped with widely spaced root lobes and a slender crown. Lateral teeth have lower crowns which in upper teeth are inclined distally. The lingual crown bears several fine but distinct vertical folds (Fig. 7A). There is a lingual protuberance (Fig. 7B) with a well-marked nutritive groove (Fig. 7A). The lateral denticles or cusplets have different shapes, ranging between conical

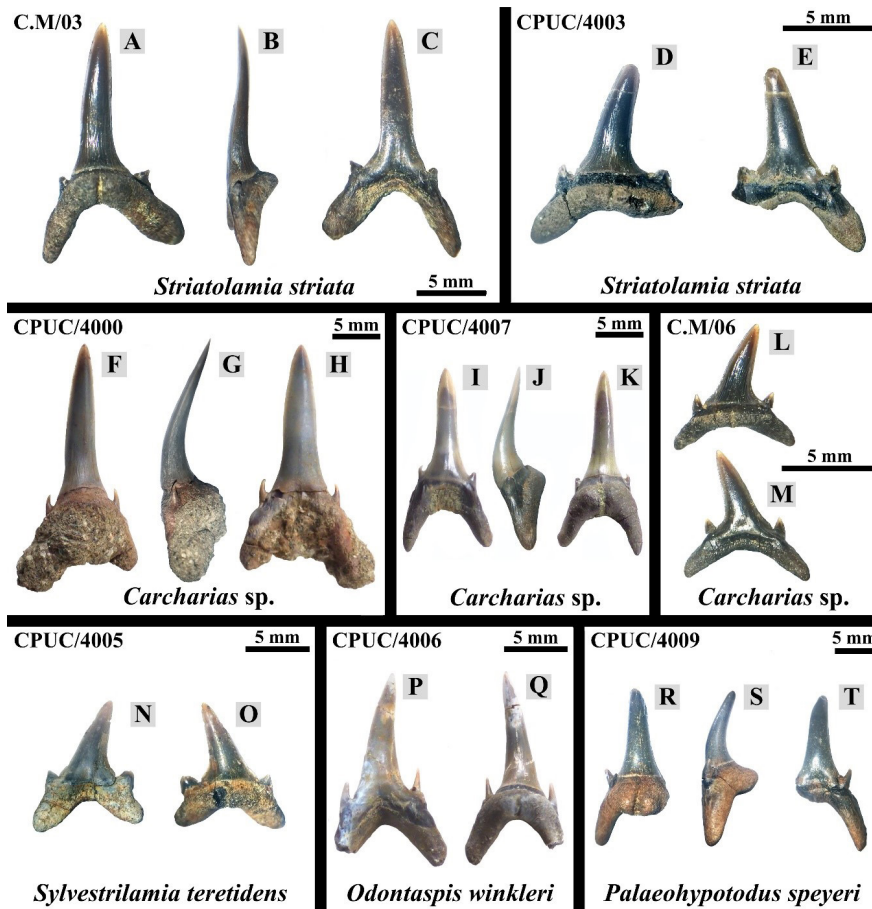


FIG. 7. *Striatolamia striata* C.M/03: A. Lingual view. B. Lateral view. C. Labial view. *Striatolamia striata* CPUC/4003: D. Lingual view. E. Labial view. *Carcharias* sp. CPUC/4000: F. Lingual view. G. Lateral view. H. Labial view. *Carcharias* sp. CPUC/4007: I. Lingual view. J. Lateral view. K. Labial view. *Carcharias* sp. C.M/06: L. Lingual view. M. Labial view. *Sylvestrilamia teretidens* CPUC/4005: N. Labial view. O. Lingual view. *Odontaspis winkleri* CPUC/4006: P. Labial view. Q. Lingual view. *Palaeohypotodus speyeri* CPUC/4009: R. Lingual view. S. Lateral view. T. Labial view.

shaped (Fig. 6T), broad-triangular shaped (Fig. 6V), or spade-like ones (Fig. 7D).

Discussion: Teeth of *Striatolamia* sp., a very common Paleogene sand tiger shark, closely resemble those of the Recent sand tiger shark *Carcharias taurus* Rafinesque (1810) (Cunningham, 2000). Like most lamniforms they exhibit marked disjunct monognathic and dignathic heterodonty. The main feature separating *S. striata* from other sand sharks with a similar morphology is the presence of numerous fine vertical folds that cover the labial crown surface.

Striatolamia striata is the name conventionally given to the middle and late Palaeocene representatives of the *Striatolamia* lineage which extends from the middle Paleocene (Selandian) to the middle or late

Eocene. The early Eocene representative is either *S. elegans* Agassiz (1843) or *S. macrota* Agassiz (1843) depending on one's taxonomic opinion (Zhelezko and Kozlov, 1999). Siverson (1995) referred the genus *Striatolamia* to the Mitsukurinidae *sensu lato*, arguing that the iconic wide and flattened lateral cusps could easily be derived from the blade-like shoulders of an *Anomotodon*. However, we do not find this convincing. The cusplets on lower lateral teeth closely resemble those of *Carcharias* and other members of the Odontaspidae. *S. striata* has only been recorded before in Chile by Rodríguez (2022), describing another specimen from Talcahuano area, sampled at an outcrop different than Puente Perales or Cerro San Martín.

Genus *Carcharias* Rafinesque, 1810***Carcharias* spp.**

Fig. 7F-H, I-K and L-M

Material: 2 complete anterior teeth from CSMSL1: CPUC/4000, CPUC/4007; 1 complete lateral tooth from CSMSL1: C.M/06; at least fifty whole and damaged teeth from CSMSL1, CSMSL2 and PPSL, of which 7 are fairly complete teeth.

Dimensions: CPUC/4000: W=12.6 mm, H=24.4 mm; CPUC/4007: W=9.3 mm, H=19.2 mm; C.M/06: W=6.3 mm, H=7 mm.

As with all sand tiger sharks, size depending on their position in the jaw. Anterior teeth of adult individuals reach 30 mm in height while posterior teeth may only reach a few mm.

Description: Anterior teeth may have medially interned lateral cusplets and very fine lingual folds on the basal half of the lingual crown, as in specimen CPUC/4000 (Fig. 7F-H), or be smooth as in CPUC/4007 (Fig. 7I-K), but they all have a slightly sigmoidal profile (Fig. 7G, J) and a cutting edge that does not extend into the base of the cusp. Upper lateral teeth as C.M/06 (Fig. 7L-M), is labio-lingually slim and have wider root lobes and needle-like or slightly spatulate lateral cusplets, and fine lingual folding in the cusp, which is also distally inclined. The root lobes of the upper lateral teeth are widely spaced and symmetrical, while the ones from the very anterior positions teeth figured show only a mild asymmetry. The lingual protuberance is well developed (Fig. 7G, J) and hosts a notoriously marked nutritive groove (Fig. 7K-L).

Discussion: Specimen CPUC/4000 fits the description of anterior teeth of *Carcharias* sp. (*sensu* Cappetta and Nolf, 2005), including the fine folding that is more evident in the basal distal and mesial zones of the lingual cusp, whether CPUC/4007 does not match that feature. The upper lateral tooth C.M/06 has folding in its lingual cusp, a feature not present in the teeth figured by Cappetta and Nolf (2005). Thus, it is likely that there are, at least, 2 species of *Carcharias* present in the studied assemblage.

The genus *Carcharias* has been recorded before at these same outcrops by Muñoz et al. (2007, 2008), Groz and Palma-Heldt (2013) and Rodríguez (2022). Apart from these, in Chile the Paleogene *Carcharias* is recorded by Otero et al. (2012, 2013), altogether with Otero and Soto-Acuña (2015), all of them in middle-late Eocene deposits from the Chile's

southernmost area. Neogene *Carcharias* has been recorded from the Neogene of South America by Long (1993), Suárez et al. (2006), and Villafañá et al. (2019).

Genus *Sylvestrilamia* Cappetta and Nolf, 2005***Sylvestrilamia teretidens* (White, 1931)**

Fig. 7N-O

1931 *Odontaspis* (*Synodontaspis*) *cuspidata* (Agassiz), praemutation *teretidens* White: p. 53, figs. 16-44.

1946 *Odontaspis* (*Synodontaspis*) *teretidens* (White); Casier: p. 69, pl. 2, fig. 3.

2005 *Sylvestrilamia teretidens* (White); Cappetta and Nolf: p. 250, figs. 1-8.

Material: 1 complete lateral tooth from CSMSL1: CPUC/4005.

Dimensions: W=8.6 mm, H=10.2 mm.

Description: Small upper lateral *Carcharias*-like tooth, with distally-directed triangular crown and large spatulate lateral denticles. The lingual surface of the cusp is almost completely smooth (Fig. 7O), with a few very fine striae that do not go higher than midway up the cusp. The lingual protuberance is mildly developed, but evident, and it bears a slightly marked nutritive groove (Fig. 7O). The cutting edge extends into the lateral denticles, which have a convergent direction into the root. The root lobes are almost symmetrical and well-spaced.

Discussion: Anterior teeth of *Sylvestrilamia teretidens* often have slightly folded lingual crowns. Upper lateral teeth have broad spatulate lateral cusplets sometimes slightly serrated, as in CPUC/4005 (Cappetta and Nolf, 2005). For most of the cases, *S. teretidens* teeth differ from others in the very frequent presence of several fine folds at the lingual side of the cusp, but less markedly than in *Striatolamia* (Nolf, 1988).

This species is frequently recorded from the late Paleocene (Ward, 1980; Dutheil, 1991; Baut and Genault, 1995). It is relatively infrequent in open marine deposits but extremely common in inshore and marginal marine deposits. *S. teretidens* ranges from the middle Thanetian into the early Eocene (Ypresian) (Smith et al., 1999; Cappetta, 2012; White, 1931). This is the first published and reliable record of *S. teretidens* from the southern hemisphere, and the first mention in Chile. This species is recorded from the Paleogene of southern Argentina, in the preliminary report made by Bernárdez (1997), as "*Carcharias teretidens*".

Genus *Odontaspis* Agassiz, 1843
***Odontaspis winkleri* (Leriche, 1905)**

Fig. 7P-Q

1905 *Odontaspis winkleri* Leriche: pp. 74 and 117,
 pl. 6, figs. 1-12.

1990 *Odontaspis winkleri* (Leriche); Kemp *et al.*:
 p. 9, pl. 4, figs. 1-3.

Material: 1 complete anterior tooth from CSMSL1:
 CPUC/4006.

Dimensions: W=9.1 mm, H=15.2 mm.

Description: Medium-sized anterior tooth lacking the tip of the mesial root lobe. The crown is unornamented with large paired lateral denticles or cusplets, apically directed or slightly inturned. The cutting edge does not extend to the base of the cusp (Fig. 7P), and at the base of the crown is a well-marked neck. There is a pronounced lingual protuberance and nutritive groove on this anterior tooth (Fig. 7Q). The complete root lobe is elongated, straight and is moderately spaced with respect to the broken one.

Discussion: Teeth of *Odontaspis winkleri* closely resemble those of the Recent species *Odontaspis ferox*. They differ from each other in the more robust crown and better developed root lobes of *O. ferox*, (Leriche, 1905). Teeth of *O. winkleri* also vary from *Palaeohypotodus*, and in general from other Odontaspididae, in lacking basal lingual crown folds and having long apically-directed lateral cusplets with sharply pointed tips.

The specimen CPUC/4006 has been previously figured by Muñoz *et al.* (2007) as *Carcharias* sp. The species *O. winkleri* ranges from the late Paleocene (Thanetian) into the late Eocene (Smith *et al.*, 1999; Kriwet, 2005; Casier, 1967). This is the first published and reliable record of *O. winkleri* in South America, because the figure at Priem (1911) of an *Odontaspis aff. winkleri* tooth from Argentina, shows only the lingual view and it does not fit the features of this taxon.

Family JAEKELODONTIDAE Glickman, 1964

Genus *Palaeohypotodus* Glickman, 1964

***Palaeohypotodus speyeri* (Dartevelle and Casier, 1943)**

Fig. 7R-T

1943 *Odontaspis speyeri* Dartevelle and Casier:
 p. 116, pl. IV, figs. 1-13.

1952 *Odontaspis speyeri* (Dartevelle and Casier);
 Arambourg: p. 74, pl. X, figs. 1-38.

1994 *Palaeohypotodus speyeri* Zhelezko: p. 50,
 pl. 1, figs. 1-3.

1995 *Odontaspis speyeri* (Dartevelle and Casier);
 Siverson: p. 7, fig. 3, G-J.

Material: 1 incomplete anterior tooth from CSMSL2:
 CPUC/4009.

Dimensions: W=(incomplete), H=19.7 mm.

Description: Medium-sized upper anterior tooth, lacking the mesial root lobe and lateral cusp. The upright crown is smooth, rounded in section and lingually recurved (Fig. 7S). The lateral cusp or denticle is outwardly directed. The robust root lingually bears a prominent protuberance divided by a nutritive groove (Fig. 7R).

Discussion: Anterior teeth are similar to those of *Odontaspis winkleri* but overall, more robust and with smaller and more divergent lateral cusplets. Juvenile teeth are coarsely folded along the base of the labial crown in a similar manner to *P. rutoti* (Siverson, 1995). A more detailed description was made by Arambourg (1952).

This is a common early Paleocene (Danian) species in Morocco (Arambourg, 1952), and also occurs in middle-late Danian from southern Sweden (Siverson, 1995). It also occurs in the base of the Upnor Formation in the United Kingdom (Ward, 2023, personal observation) which is late Paleocene, in the early half of nannozone NP9 (King, 2016). This is the first published record of *P. speyeri* in South America.

***Palaeohypotodus rutoti* (Winkler, 1874a)**

Fig. 8A-B

1874a *Otodus rutoti* Winkler: p. 6, pl. 1, figs. 3-4.

1902 *Odontaspis rutoti* (Winkler); Leriche: pl. 1,
 figs. 37-44.

1964 *Palaeohypotodus rutoti* (Winkler); Glickman:
 p. 136, pl. 18, figs. 1-20.

1977 *Palaeohypotodus rutoti* (Winkler); Herman:
 p. 232, pl. 10, fig. 3.

2007 *Palaeohypotodus* sp. Muñoz *et al.*: p. 13,
 pl. 2, figs. G-H.

Material: 1 incomplete lateral tooth from CSMSL1:
 C.M/08.

Dimensions: W=8.9 mm, H=(incomplete).

Description: Upper lateral tooth lacking its crown tip and root lobes. The labial crown base bears numerous fine vertical folds which slightly overhang the root (Fig. 8B). The lingual crown base bears a



FIG. 8. *Palaeohypotodus rutoti* C.M/08: A. Lingual view. B. Labial view. *Isurolamna inflata* CPUC/4011: C. Lingual view. D. Labial view. *Premontreia gilberti* CPUC/4016: E. Basal view. F. Labial view. *Physogaleus secundus* CPUC/4032: G. Lingual view. H. Labial view. *Physogaleus secundus* CPUC/4031: I. Labial view. *Palaeogaleus vincenti* Q/3726: J. Labial view. K. Lingual view. *Hypolophodon sylvestris* CPUC/4034: L. Occlusal view. M. Basal view. N. Labial view. O. Lingual view. P. Lateral view. *Hypolophodon sylvestris* CPUC/4035: Q. Occlusal view. R. Basal view. S. Labial view. T. Lingual view. U. Lateral view. *Myliobatid indet.* C.M/07: V. Occlusal view. W. Lingual view. X. Basal view. *Myliobatid indet.* CPUC/4017: Y. Basal view. Z. Labial view. AA. Occlusal view. AB. Lingual view. *Myliobatiform caudal sting spine* CPUC/4018: AC. Dorsal view. Undetermined neoselachian vertebra CPUC/4030: AD. Axial view. AE. Opposite axial view. AF. Lateral view.

few very fine striae (Fig. 8A). There are two pairs of slightly incurved lateral cusps, the mesial pair being the larger. The robust lingual surface of the root bears a large protuberance divided by a nutritive groove (Fig. 8A).

Discussion: *P. rutoti* has very distinguishable teeth with a well-marked lingual protuberance, vertical folds in the base of the labial crown and one or two pairs of incurved lateral cusplets. A more detailed description of this taxon's teeth is made by Cappetta (2012).

P. rutoti ranges in Europe from the middle Paleocene to the base of the Ypresian, where teeth lack the distinctive labial folds (Dutheil *et al.*, 2006; Cappetta, 2012). *P. rutoti* teeth are also recorded from the Ypresian-Lutetian of Antarctica and the Paleocene of Greenland (Bendix-Almgreen, 1969; Long, 1992). Otero and Soto-Acuña (2015) reported *P. rutoti* in the Bartonian-Priabonian of southernmost Chile. This taxon has only been (mistakenly) identified before in these outcrops (PPSL) by Rodríguez (2022) as an isolated tooth, in this work considered a *Striatolamia* sp. tooth. Therefore, this is the first reliable Paleocene record of *P. rutoti* in South America.

Family LAMNIDAE Müller and Henle, 1838

Genus *Isurolamna* Cappetta, 1976

Isurolamna inflata (Leriche, 1908)

Fig. 8C-D

1905 *Lamna vincenti* var. *inflata* Leriche: p. 76, *nom. nud.*

1908 *Lamna vincenti* var. *inflata* (Leriche); Leriche: p. 11, pl. 1, fig. 9.

1936 *Lamna inflata* (Leriche); Leriche: p. 296.

1946 *Odontaspis hopei* var. *affinis* Casier: p. 65, pl. 2, fig. 11, b-c (non 11a).

1976 *Isurolamna affinis* (Casier); Cappetta: pl. 2, figs. 1-8.

Material: 1 incomplete lateral tooth from CSMSL1: CPUC/4011.

Dimensions: W=9.2 mm, H=10.2 mm.

Description: Lateral tooth missing mesial root lobe and lateral cusplet or denticle. The crown is a low upright one, unornamented with the cutting edge extending down to just above the root-crown junction (Fig. 8D). The root is wide rectangular root with a pair of low, triangular lateral cusp, almost separated from the principal cusp.

Discussion: Teeth of *Isurolamna inflata* exhibit a moderate degree of monognathic heterodonty, with the anterior teeth being quite different from the lateral files. This can result in misidentification and under reporting (Cappetta, 1976, 2012).

Isurolamna inflata ranges from the middle Paleocene (Selandian) to the middle Eocene (Bartonian) of Belgium, but the Paleocene morphotype is smaller than the Eocene form (Ward and Wiest, 1990; Cappetta, 2012). As indicated by the synonymy, the species *I. affinis* is considered a junior synonym of *I. inflata*. This is the first published record of *I. inflata* in South America.

Order CARCHARHINIFORMES Compagno, 1973

Family SCYLIIORHINIDAE Gill, 1862

Genus *Premontreia* Cappetta, 1992

Premontreia gilberti (Casier, 1946)

Fig. 8E-F

1946 *Scyliorhinus gilberti* Casier: p. 59, pl. 1, fig. 14.

1995 *Scyliorhinus gilberti* (Casier); Baut and Genault: p. 204, pl. 17, figs. 1-3.

2006 *Premontreia (Oxyscyllium) gilberti* (Casier); Adnet: p. 84, figs. 6-8.

Material: 1 complete anterior tooth from PPSL: CPUC/4016.

Dimensions: W=2.55 mm, H=3.55 mm.

Description: Small tooth with upright unornamented crown and paired apically directed lateral cusps. The wide labial crown base bears vertical folds on either side of the principal cusp (Fig. 8F). Lingual side of the cusp is unornamented. The root is basally flat with a deep nutritive groove and prominent lingual protuberance (Fig. 8E).

Discussion: This subgenus ranges from the Danian to the late Eocene (Cappetta, 2012). Teeth with a morphology very close to CPUC/4016 occur in the late Eocene, Thanetian and the early Eocene of north-western Europe (Ward, 1980; Baut and Genault, 1995). Rodríguez (2022) identified this same specimen as *Pachyscyllium gilberti*.

Family CARCHARINIDAE Jordan and Evermann, 1896

Genus *Physogaleus* Cappetta, 1980

Physogaleus secundus (Winkler, 1874b)

Fig. 8G-H and I

1874b *Trigonodus secundus* Winkler: p. 5, pl. 1, figs. 4-5.

1905 *Physodon secundus* (Winkler); Leriche: p. 132, pl. 8, figs. 1-18.

1980 *Physogaleus secundus* (Winkler); Cappetta: p. 38, fig. 5.

Material: 2 complete lateral teeth from CSMSL1: CPUC/4032 and CPUC/4031.

Dimensions: CPUC/4032: W=4.4 mm, H=3.1 mm; CPUC/4031: W=4.8 mm, H=3.7 mm.

Description: A small tooth with a distally directed triangular crown and a single distal heel. The labial face of the crown is flat to slightly convex (Fig. 8H-I). The root's lingual surface bears a relatively large protuberance and an evident nutritive groove (Fig. 8G).

Discussion: *Physogaleus* is an extremely heterodont genus; the nominal species *P. secundus* probably incorporates several biological species. Stratigraphically younger teeth may have more serrations on the mesial cutting edge and the distal heel (Cappetta, 1980; Ward, 1990, personal observation).

It is recorded from the late Paleocene of France (Thanetian, NP9 zone) to the middle Eocene of Belgium (Bignot et al., 1994; Baut and Genault, 1995; Smith et al., 1999; Dutheil et al., 2002; Van den Eeckhaut and De Sutter, 2009). Specimen CPUC/4031 was figured by Muñoz et al. (2007) as “*Galeorhinus* sp.”. This is the first published record of *P. secundus* from South America.

Genus *Palaeogaleus* Gurr, 1962
***Palaeogaleus vincenti* (Daimeries, 1888)**

Fig. 8J-K

1902 *Scyllium vincenti* Leriche: p. 18, pl. 1, figs. 31-6.
1951 *Scyllium vincenti* (Leriche); Leriche: p. 496.
1962 *Palaeogaleus vincenti* (Leriche); Gurr: p. 429, pl. 22, figs. 1-17.

Material: 1 complete lateral tooth from CSMSL1: Q/3726.

Dimensions: W=3.8 mm, H=2.75 mm.

Description: Small abraded tooth with a distally directed triangular crown, 2 distal heels (Fig. 8J), and lacking part of the lingual root (Fig. 8K). The mesial cutting edge in the crown is slightly concave. There are 2 relatively small root lobes and also a longitudinal ridge (partially broken) following the basal root shape. The lingual side of the root bears various foramina (mainly in the basal distal lobe) and also a nutritive groove interrupting the longitudinal ridge (Fig. 8K). The tooth is wider around the root-crown junction axis, with a prolongation of the crown's mesial and distal basal most zones, further than the most distal and mesial ends of the root at the root-crown junction axis (Fig. 8J). Mesial prolongation of the labial crown base is slightly swollen (Fig. 8J).

Discussion: Teeth of *Palaeogaleus vincenti* possess fine vertical folds on the base of the labial crown, which separates them from those of *Physogaleus*. The crown is labio-lingually slim, similar in shape to *Physogaleus* but with a prominent distal cusplet. These are not visible on specimen Q/3726. Teeth of *P. vincenti* are more mesio-distally wider than those of *Physogaleus* teeth (Gurr, 1962; Nolf, 1988; Baut

and Genault, 1995; Cappetta, 2012). The longitudinal ridge can also be used for distinguishing *P. vincenti* teeth from other similar carcharhiniforms (Maisch et al., 2019). Moreover, lateral *P. vincenti* teeth with similar shape and little to no folding in the labial crown, have been reported from Paleocene sediments by Maisch et al. (2019).

Another specimen of *P. vincenti* was figured by Muñoz et al. (2007) as “*Palaeogaleus* sp.”, for these same outcrops. Rigorous *P. vincenti* record comprises from the late Danian of Belgium and Greenland, to the late Thanetian (NP9 zone) of France (Bendix-Almgreen, 1969; Baut and Genault, 1995; King, 2016).

Superorder BATOIDEA Compagno, 1973
Order MYLIOBATIFORMES Compagno, 1973
Superfamily DASYATOIDEA Whitley, 1940
INCERTAE FAMILIAE

Genus *Hypolophodon* Cappetta, 1980
***Hypolophodon sylvestris* (White, 1931)**

Fig. 8L-P and Q-U

1931 *Hypolophus sylvestris* White: p. 70, figs. 94-104.
1946 *Platyrrhina ypresiensis* Casier: p. 23, pl. 3, figs. 5a-v.
1962 *Hypolophus farreri* Gurr: p. 432, pl. 26, 2a-3b, fig. 5A.
1962 *Hypolophus sylvestris* (White); Gurr: p. 433, fig. 5B.
1980 *Hypolophodon sylvestris* (White); Cappetta: p. 39, fig. 6.
2007 *Myliobatiformes* indet. Muñoz et al.: p. 16; pl. 3; figs. H-K.

Material: 1 complete lateral tooth from CSMSL1: CPUC/4035; 1 complete anterior tooth from CSMSL2: CPUC/4034. Ten whole and damaged teeth from CSMSL1.

Dimensions: CPUC/4034: W=4.3 mm, H=2.7 mm; CPUC/4035: W=3.5 mm, H=1.7 mm.

Description: Small unornamented crown. The occlusal surface is sub-hexagonal, slightly convex with rounded edges (Fig. 8L, Q). There is a small lingual flange present in most specimens (Fig. 8O, T). The root is bilobed, does not extend beyond the crown width and has a wide median groove (Fig. 8M, R).

Discussion: The specimen CPUC/4034 was figured by Muñoz et al. (2007) as “*Myliobatiformes* indet.”. *Hypolophodon* is relatively uncommon in

the European Paleocene but extremely common in the basal Eocene Blackheath Formation at Abbey Wood, south-eastern England, it is because of the absence of tail spines at this locality that this species is placed in open nomenclature rather than in the *Dasyatidae* (Ward, 1975, personal observation).

H. sylvestris ranges from the middle-late Danian of France, the early Paleocene of the United States, and the Ypresian of England and Europe (Herman, 1977; Ward and Wiest, 1990; Baut and Genault, 1995; Case, 1996; Smith *et al.*, 1999; Cappetta, 2012; Ward, 1975, personal observation). *H. sylvestris* has also been recorded from Argentina, from the top of the Jagüel Formation (Maastrichtian) by Bogan and Gallina (2011), but with uncertain stratigraphy. Cione *et al.* (2013) referred them (and other earliest Paleocene specimens) to *Hypolophodon patagoniensis*. Thus, for this work a first occurrence of *H. sylvestris* remains from the middle Danian. *H. sylvestris* has not been recorded in Europe south of the Paris Basin in early Paleogene strata, nor any of the north African Paleogene phosphate deposits, suggesting that it preferred cooler waters.

This is the first published record of *H. sylvestris* in Chile, and the first reliable one from South America.

Superfamily MYLIOBATOIDEA Compagno, 1973

Family MYLIOBATIDAE Bonaparte, 1838

***Myliobatidae* indet.**

Fig. 8V-X and Y-AB

Material: 1 isolated complete symphyseal tooth from CSMSL1: C.M/07; 1 complete tooth from lateral file, from CSMSL1: CPUC/4017; numerous fragments.

Dimension: C.M/07: W=13 mm, H=3.2 mm; CPUC/4017: W=4.4 mm, H=3 mm.

Description: Specimen C.M/07 is a small, slightly rolled but well-preserved median chevron. The occlusal surface is slightly convex and lacks enameloid (Fig. 8V). The root is polyaulacorhize and basal to the crown (Fig. 8W-X). Specimen CPUC/4017 and the other fragmentary ones are teeth from lateral files and have sub-hexagonal or trapezoidal occlusal surfaces (Fig. 8AA).

Discussion: *Myliobatidae* dental elements and whole palates of this morphotype are usually placed in the nominal species *Myliobatis dixonii* Agassiz (1843), which ranges from the Middle Paleocene (Selandian) to the late Eocene.

There are two genera of Recent *Myliobatiform* ray; *Myliobatis* Cuvier (1817) and *Aetomylaeus* Garman (1908). The genus *Pteromylaeus* is regarded as a junior synonym of *Aetomylaeus* (Last *et al.*, 2016). Villafaña *et al.* (2019) point out that Neogene dental plates and isolated teeth traditionally referred to *Myliobatis* could also be from *Aetomylaeus*. Because of this is likely to apply to Paleogene dental elements, these fragmentary remains are left in open nomenclature.

6. Lithochronostratigraphic discussion and assemblage analysis

6.1. Local lithostratigraphic correlations and erosive surfaces

The basal most sections of the three columns in both sampling sites are referred to into the same lithostratigraphic unit (lowermost lithostratigraphic unit), with a sedimentary lithofacies composed by a calcareous-concretionary and fine-grained sandstone. Locally, this concretionary and fossiliferous stratum can be overlain by an interdigitating layer of a bioturbated fine grain sized sandstone with some bivalve fossils and local planar bedding, which must also belong to the same unit.

Above the uppermost part of these strata, there is an erosive surface that represents a *hiatus* between these layers and the Paleogene sediments (Figs. 3, 4, and 5). The existence of a *hiatus* in this broadly planar limit is also supported by the presence of reworked-weathered clasts from the underlying sandstone (Cerro San Martín outcrop), and the reworked glauconite found by Rodríguez (2022), both, in the glauconitic sandstone (with coarser levels) above the concretionary sandstone and overlying the upwards-interdigitated sandstone. In both outcrops, there's also minor erosive morphologies along the surface, further supporting an erosive stage between the final sedimentation part of the underlying fossiliferous layers and the earliest sedimentary lapse of the overlying glauconitic sandstone. Additionally, the concretions at the base of the overlying lithostratigraphic unit have a truncated lowermost zone limited by the first erosive surface, suggesting that during the diagenetic process of these strata the underlying unit have already a significantly lower permeability, implying that in this period the basal most unit was already a lithified sediment.

Overlying the first (lower) erosive surface, there is a glauconitic and fine-grained sandstone with

laterally wedged greater granulometric levels hosting elasmobranch fossils (intermediate lithostratigraphic unit). This layer is in all the outcrops, but in southern Puente Perales, has no greater granulometric levels and is laterally interdigitating with a similar lithofacies that also contains calcareous concretions (towards the northern area). The concretionary lithofacies and the one with just basal concretions comprise an individual lithostratigraphic unit (Fig. 3), between two erosive surfaces. The upper limit of this lithostratigraphic unit is in both outcrops marked by a very uneven but planar-trend surface (Figs. 3, 4, 5) that separates the underlying elasmobranch bearing sandstones from the overlying and coarser strata (uppermost lithostratigraphic unit). In this upper and coarser strata, there are intraclasts (with an even coarser size) of the glauconitic sandstone and of a dark-grey mudstone that does not appear in any point near (at least 5 km around) in a similar stratigraphic position (above the glauconitic sandstone and under the second erosive surface) that in the two locations, thus further indicating an erosive process capable of erode completely the dark-grey mudstone's layers in a time lapse in between both sedimentation processes, and at least a sedimentary sequence boundary (Suter, 2006).

The section over the second (upper) erosive surface comprises, in both outcrops, a transgressive conglomerate (absent in the southern part of the Puente Perales outcrop) underlying and interdigitating a set of sandstones with some laterally wedged conglomerates. All these lithologies above the second erosive surface, comprise a different lithostratigraphic unit.

6.2. Assemblage's subsets, paleoecology and sedimentary environment

The lithostratigraphic correlations imply that there are two assemblages comprising all the reviewed material. A first and main one, which essentially comes from the Cerro San Martín outcrop (CSMSL1 between the two erosive surfaces, and CSMSL2 above the second one), and a second assemblage from southern Puente Perales outcrop (PPSL, above the second erosive surface).

The host lithology for the autochthonous main assemblage (CSMSL1, intermediate lithostratigraphic unit) with a fine sandstone granulometry, laterally wedged coarser levels and isolated small pebbles, indicates correlation with sedimentary facies of lowermost shoreface-upper offshore (*i.e.*, lowermost

shoreface-inner shelf, offshore-transition) in a high energy pebbly coast, wave-dominated, shallow marine environment (Ando, 1990; Reading and Collinson, 1996; Clifton, 2019). Laterally wedged coarser levels also suggest that deposition took place with certain storm influence and above the storm wave base depth (Reading and Collinson, 1996). In the correlative's layers from southern Puente Perales location, the lithologic features have affinity with uppermost offshore sedimentary facies, due to the lack of coarser levels and interdigitations with very fine grain size layers, but also these facies can laterally also turn into lower shoreface, as appear the wedged coarser levels (Reading and Collinson, 1996; Clifton, 2019). Similarly, the northern Puente Perales outcrop intermediate lithostratigraphic unit can portray lower shoreface facies because of the lithology, planar cross bedding and coarser levels (Ando, 1990; Reading and Collinson, 1996; Clifton, 2019).

The elasmobranch assemblage composition from CSMSL1 and CSMSL2 comprise genera with no precise nor conclusive bathymetry bounding elements (when compared to sedimentary facies constraints), among which are *Striatolamia striata*, *Physogaleus secundus*, *Squatina prima*, *Palaeogaleus vincenti*, *Palaeohypotodus rutoti* and *Squalus orpiensis*, as seen in an extensive bathymetric table with most of the taxa from the main assemblage made by Dutheil *et al.* (2006).

In the main assemblage, only the presence of the genus *Centrophorus* indicates at least a possible proximity to open shelf environments (Ebert *et al.*, 2021; Ward, 2013, personal observation), as already discussed from the sedimentary facies data. Furthermore, the relative predominance of Odontaspidae teeth over Dasyatidae or Myliobatidae may also imply that this specific environment was deeper than completely shallow shoreface-related conditions (below normal wave base depth), as seen in north-western European early Paleogene strata (Ward, 1988, personal observation).

The absence of typical tropical and subtropical water Paleogene taxa such as *Cretalamna* spp. or *Otodus obliquus*, altogether with the presence of warm-temperate water related taxa as *Paraorthacodus* genus, *Isurolamna inflata*, *Hypolophodon sylvestris* and *Physogaleus secundus* indicates that the most reasonable water temperature determination from the sampled main assemblage is warm-temperate conditions (Smith *et al.*, 1999; Salim and Messaoud, 2018). Rodríguez (2022) reported a mistakenly identified, isolated tooth of *Cretalamna* sp. from

these outcrops, but it was from PPSL and in this work it is considered as a mildly abraded posterior tooth of *Carcharias* genus. The main assemblage from Cerro San Martín is particularly correlatable in morphology with the teeth found in the late Thanetian unit Bracheux Formation (Baut and Genault, 1995; King, 2016), and are similar in taxa diversity with the basalmost part of Bracheux Formation, Sables de Rollet (Baut and Genault, 1995; Mathis and Moreau, 1997; Smith *et al.*, 1999), both in the Paleogene Paris basin (north-eastern France).

The PPSL's assemblage does not give further constrains for paleobathymetric estimations because of the scarcity of specimens, and just *Premontreia gilberti* (a member of the Scyliorhinidae) could suggest slightly deeper water than just shoreface conditions, when compared with modern Scyliorhinidae (Smith *et al.*, 1999). Exposed lithofacies of conglomerate and coarse-fine grained sandstone just above the second erosive surface (in northern Puente Perales and Cerro San Martín) could broadly correlate with upper shoreface-foreshore facies, in a similar environmental setting than the underlying unit's sedimentary cycle, but shallower and more storm influenced, implied from the conglomerate layers (upper shoreface-foreshore), coarse to fine-grained sandstones (essentially upper shoreface) with continuous coarser levels and planar stratification (Reading and Collinson, 1996; Clifton, 2019). Only those correlative layers in southern Puente Perales shows locally affinity with facies of lower shoreface-uppermost offshore (laterally changing onto upper shoreface facies), also with fine-grained sandstones hosting a few coarser wedged and continuous levels, just as in the top of Cerro San Martín stratigraphic column (Ando, 1990; Reading and Collinson, 1996; Clifton, 2019). At the uppermost layer in southern Puente Perales, coarser local lithofacies vaguely suggests shallower conditions than lower shoreface facies.

6.3. Age of the main elasmobranch assemblage

The main assemblage (from CSMSL1 and reworked specimens from CSMSL2) has taxa with chronostratigraphic ranges comprising the Paleocene and Eocene, related with the CSMSL1 sedimentary cycle. However, intersection of each species range leads to a preliminary late Thanetian age without reaching the end of it (Fig. 9, white background highlight), and this subsequently allows the analysis of the assemblage's age more accurately.

Regardless this, there are some considerations needed to be discussed before a definitive age determination. Despite the chronostratigraphic range of each taxon is known, mostly from north-western Europe, it is still not clear how much effect climatic conditions and geographic distance could have on elasmobranch stratigraphic distribution between South America and Europe. It is likely that due to South America isolation from Antarctica and North America in the Paleogene, at least a seasonal climatic opportunity for the species displacement could be possible. This implies that instead of having an effect on first occurrences for most elasmobranch, the climatic changes would mainly cause latitudinal chronostratigraphic offsets (between the low, mid and high latitude zones) in the last occurrences.

Once discussed this, the first step is to delimitate a very broad and conservative age for the assemblage. A first bounding element is the climate, pointed out from the assemblage itself, with warm-temperate waters. Indirectly, this suggests an age previous to the Paleocene-Eocene Thermal Maximum (Fig. 9, red highlight, labelled as PETM), and to the subsequent warming in early Eocene, when temperatures would raise higher than pre-PETM times. This is consistent with some considerations of the water temperature in middle latitudinal Europe made by Smith *et al.* (1999), working also with similar taxa and an age around the Thanetian-Ypresian. Thus, a very conservative climatic-biostratigraphic bounding (Fig. 9, yellow highlight) for the assemblage would be a simply Thanetian age, comprising a relevant amount of the taxa first and last occurrences (Fig. 9).

A definitive age constraint (Fig. 9, green highlight) for the assemblage's range should then be fully constrained inside the Thanetian, ruling out any Ypresian age option also by the last occurrences of *P. speyeri* and *P. vincenti*, and discarding an early Thanetian age due to the occurrence of *S. teretidens* and *P. secundus*, implying an assemblage age constrained in the middle-late Thanetian. It is worth noting that this range is also considered conservative enough for climatic small occurrences offsets, being also wider than the preliminary range.

6.4. Lithostratigraphic units determination and chronostratigraphic delimitations

The lowermost lithostratigraphic unit is referred to the Quiriquina Formation (Fig. 10), as pointed out by Salazar *et al.* (2015) and Rodríguez (2022) for

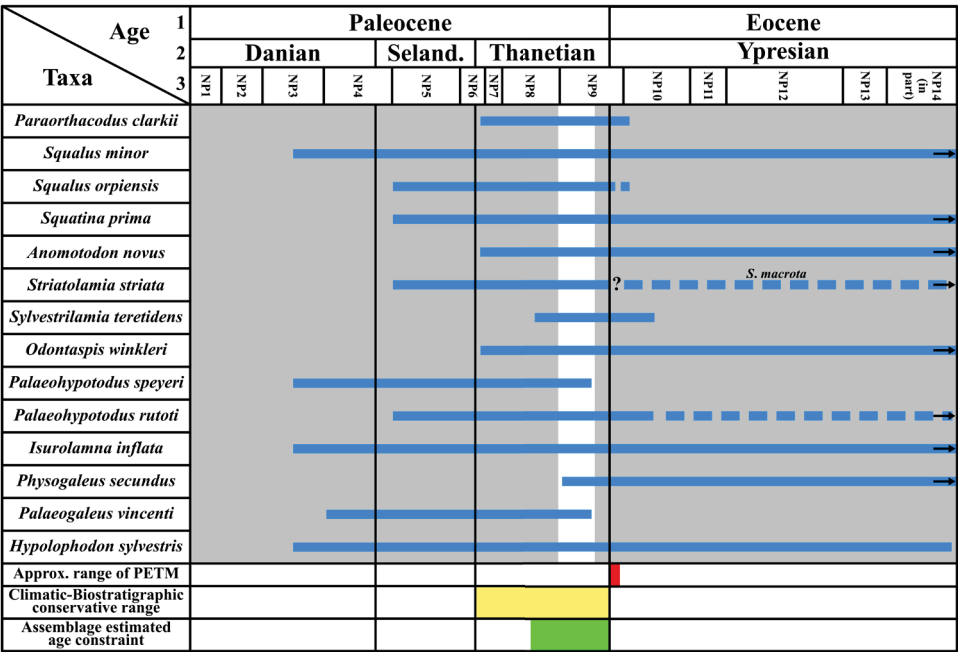


FIG. 9. Stratigraphic distribution of the species identified in the main assemblage's taxa. The known distribution is marked by continuous blue bars, and arrows indicate ranges that go further than the Ypresian. Scarce data, dubious presence or not well-defined transition with other taxa is labelled by dashed bars, and the in last case an interrogation mark and additional taxa name are also used. The epoch (1), chronostratigraphic age (2) and Martini (1971) approximated calcareous nannofossils zones (3), after King (2016) and Faris *et al.* (2021), are included. Approximated range of Paleocene-Eocene Thermal maximum (PETM) is obtained from Zeebe and Lourens (2019). White highlight background shows preliminary common range of the taxa, in yellow is the climatic conservative common range, and in green the definitive assemblage estimated age constraint.

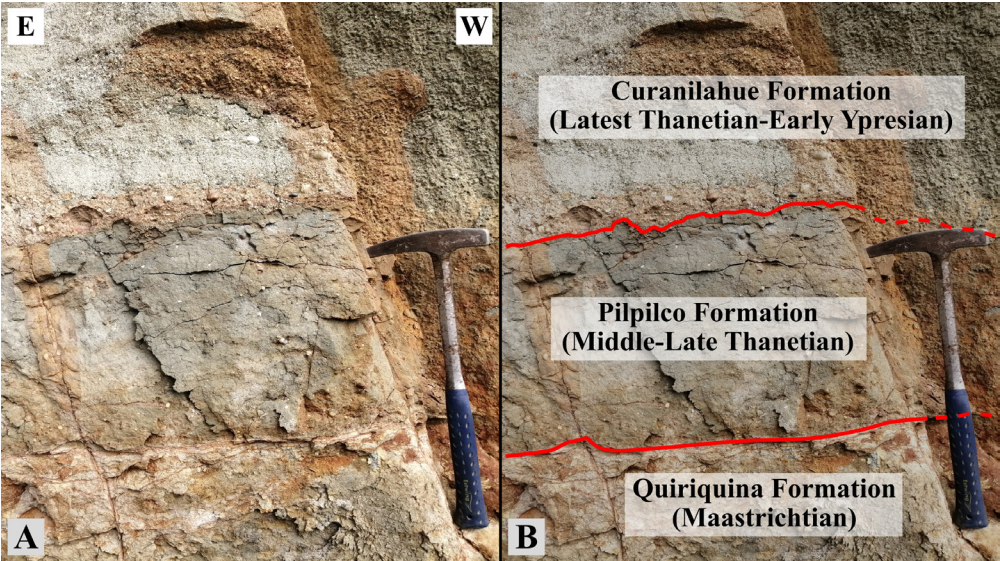


FIG. 10. Exposed section in the Cerro San Martín outcrop, comprising at least a part of all the lithostratigraphic units reviewed in this work. **A.** General view of the section. **B.** The same but with the red lines (dashed for unclear continuation) delimitating the contacts and also erosive surfaces, between the Quiriquina Formation, Pilpilco Formation (CSMSL1) and Curanilahue Formation (CSMSL2).

these strata around the two outcrops. The age of the Quiriquina Formation in its type-area can be obtained directly from Salazar (2004), being bounded inside the Maastrichtian (from the late part of the early Maastrichtian into the latest Maastrichtian without reaching the end of it), and this age constraining can also be extended for this formation's layers in Concepción and Talcahuano localities (Salazar *et al.*, 2015).

The first layer of glauconitic sandstones with coarser levels are allocated above the first erosive surface and under the second erosive surface, implying that this intermediate lithostratigraphic unit is bounded in its lower and upper limits by two *hiatuses*, as already described. This hypothesis is also supported in the first erosive surface case, by the age obtained from the elasmobranch fauna for the intermediate lithostratigraphic unit (and corresponding sedimentary cycle), constrained in the middle-late Thanetian.

The first elements that must be analysed for the Paleogene units determination are the contact surface between both units and the unweathered sandstone intraclasts above this surface. The contact surface tends to be planar but with erosive geometries, indicating as detailed previously, the existence of an erosive time lapse after the sedimentary cycle of the intermediate lithostratigraphic unit and before the sedimentation of the uppermost one. The consideration of this erosive *hiatus*, altogether with the unweathered sandstone intraclasts (of the glauconitic sandstones with conglomeratic levels and dark-grey mudstones) hosted in the overlying coarser layers, suggests a relatively brief (when compared with the previous one) erosive period and intense enough to completely erode the dark-grey mudstones layers. Furthermore, this brief erosive *hiatus* also indicates that the intermediate sedimentary unit should lithostratigraphically correlate with a formation completely bounded inside the late Paleocene, and also implying that the uppermost unit correlation is a formation directly above the correlative Paleocene unit, in the Concepción-Talcahuano Bay area stratigraphic schemes, or homologously in the described formations set around the Arauco peninsula. From the previous analysis, the previous determination for both units is simplified to the search of the geological setting's best described formations that satisfy the required conditions, and also with a sufficient amount of lithostratigraphic correlative features.

For the intermediate lithostratigraphic unit determination, the first broad constraining is the sedimentary age, just to ensure there's not a local *hiatus* in between the sedimentary cycles corresponding to both of the units (theoretical one and targeted one, for each unit). A broad age of Thanetian-Ypresian is used to find a unit in this time lapse with at least some relevant portion of it in the Thanetian. Consequently, in this interval the Pilpilco, Curanilahue (Lota Member) and Boca Lebu (or Intercalación Member of the Curanilahue Formation) formations should be considered, from the age constraints in Martínez-Pardo *et al.* (1997). The specifics of the sedimentary lithofacies in the outcrops around the elasmobranch's sampling points, proof the existence of lateral interdigitations between marine lithofacies (at the base shallower than the intermediate unit) and continental sedimentary rocks in levels laterally equivalent to the uppermost lithostratigraphic unit (described as Cosmito Formation, or Curanilahue Formation) of this work (Inostroza, 2018; Rodríguez, 2022). This implies that the correlation with the eastern part of the Paleogene Arauco peninsula sedimentary record is more accurate than with the western portion of it.

According to the lateral equivalency and interdigitation relations used by Martínez-Pardo *et al.* (1997), the Intercalación Member (marine laterally equivalent of the Boca Lebu Formation inside the Curanilahue Formation) in the eastern part of the Arauco peninsula, has near its base the first appearance of *Pseudohastigerina wilcoxensis* and *Discoaster diastypus*. The planktonic foraminifera *P. wilcoxensis* has a first appearance calibrated in 55.4 Ma (Berggren and Pearson, 2005; Pearson *et al.*, 2006), but also its first occurrence has a constraint in the first half of the magnetochron C24r (Berggren and Pearson, 2005), and considering C24r *sensu* Ogg (2020) this lapse should comprise the range 57.1-55.5 Ma. Following Martínez-Pardo *et al.* (1997), the first occurrence of calcareous nannofossil *D. diastypus* is at similar levels than *P. wilcoxensis*, and it's calibrated in 54.13 Ma by Agnini *et al.* (2014). This first occurrence is restricted inside the second half of C24r, and again following the recalibrations of Ogg (2020) the time range of the first appearance should be around 55.5-53.9 Ma.

Thus, these age constraints ensure that eastward enough in the Arauco peninsula (or in a correlatable lithofacies evolutionary trend) and following the

lithofacies changes inside the units interdigitation proposed by Martínez-Pardo (1968) and Pineda (1983), the maximum age for the Intercalación Member basal zone (local equivalent of the Boca Lebu Formation in the eastern Arauco peninsula) is the early Ypresian. Recalling target set definition for the intermediate lithostratigraphic unit, rules out the Boca Lebu Formation from it. Examining the two possibilities left, the intermediate unit must belong to the Pilpilco Formation, with an (locally constrained) age bounded inside the middle-late Thanetian (from the main elasmobranch assemblage), this determination also implies that the uppermost unit gets referred to the Lota Member of the Curanilahue Formation (Fig. 3), a statement consistent with the lithochronostratigraphic correlation made between the Cosmito and Curanilahue formations by Tavera (1947) from a marine interdigitation paleontologic samples, Inostroza (2018) with an analysis of stratigraphic data altogether with previous authors considerations, and Rodríguez (2022) after evaluating the lithostratigraphic units around the sampling outcrops.

The minimal age of the Curanilahue Formation in the sampling outcrops gets bounded by the maximal age that Intercalación Member could have in this lithostratigraphic context, which is early Ypresian. Maximal age bound of the Curanilahue Formation comes directly from the Pilpilco Formation local age, implying that the oldest hypothetical period of time for the Curanilahue Formation sedimentation must be after the time period of the *hiatus* established between these units, and considering a Pilpilco Formation bounded in the Thanetian. Thus, the most reasonable Curanilahue Formation maximal age considering the continuation of the deposition after the uppermost Pilpilco Formation and the subsequent erosive period, is the latest Thanetian. Zambrano et al. (2014) dated by U-Pb a late Thanetian detrital zircon from the base of the Curanilahue Formation (*sensu* this work), implying a maximal age of 57 Ma for the CSMSL2 layer (Cerro San Martín outcrop), where the zircon sampling was carried out (personal communication, Zambrano, 2022). This radiometric result supports the assumption of a maximal age in the latest Thanetian for Curanilahue Formation and indirectly also suggests a Thanetian age for Pilpilco Formation, below the geologically-brief *hiatus*.

These determinations imply that in the layers around the sampling outcrops, and as particularly well exposed in Cerro San Martín outcrop (Fig. 10),

Quiriquina Formation (Maastrichtian) is under Pilpilco Formation (middle-late Thanetian), separated by a Danian-early Thanetian *hiatus* (Figs. 3, and 10). Furthermore, there's a second and brief *hiatus* in between the Pilpilco Formation and the Curanilahue Formation (latest Thanetian-early Ypresian) with a transgressive lag (Figs. 3, and 10) in two out of three described stratigraphic columns (and coarser levels in all of them), proving the existence of a transgressive base in a shallower marine environment that the one in Pilpilco Formation, and once more corroborating the assumptions made for the lithostratigraphic considerations and determinations.

7. Conclusions

This study described the precise lithostratigraphic units delimitations in the Cretaceous-Paleogene sedimentary rocks exposed in the southwestern area of Talcahuano, and corroborated the existence of Paleocene layers. The elasmobranch teeth taxa indicate a middle-late Thanetian age for the Pilpilco Formation, which was deposited in a coastal shallow marine environment, near to the open shelf. Two *hiatuses* are identified, one of them having an age bounded in the Danian-early Thanetian. This new information also pushes the age of the overlying Curanilahue Formation into the latest Thanetian-early Ypresian.

Several species in this study are also identified and correspond to their first record either in Chile, South America or even in the southern hemisphere. The main assemblage comprises *Paraorthacodus clarkii*, *Squalus minor*, *Squalus orpiensis*, *Centrophorus* sp., *Squatina prima*, *Anomotodon novus*, *Striatolamia striata*, *Carcharias* spp., *Sylvestrilamia teretidens*, *Odontaspis winkleri*, *Palaeohypotodus speyeri*, *Palaeohypotodus rutoti*, *Isurolamna inflata*, *Premontreia gilberti*, *Physogaleus secundus*, *Palaeogaleus vincenti*, *Hypolophodon sylvestris*, Myliobatidae indet., and a myliobatiform caudal sting. These records represent important progress in the understanding of South American early Paleogene elasmobranch, until now better understood during the Neogene, including the chondrichthyans in the central and northern Chile's Neogene localities. Moreover, even the records with indeterminate family in this work, correspond to the first published Paleogene myliobatiform caudal sting record from South America (CPUC/4018, sampled at CSMSL1), and also the first published Paleogene

neoselachian vertebra from Chile (CPUC/4030, sampled at PPSL).

The systematic paleontology also shows a main assemblage (Cerro San Martín) with a quantity-predominance of the Odontaspidae family, and similar with the late Thanetian fauna described in north-western Europe, especially with the Bracheux Formation of France.

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