

Antarctic Paleontological Heritage: Late Cretaceous–Paleogene vertebrates from Seymour (Marambio) Island, Antarctic Peninsula

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Abstract Antarctica has significant environmental, scientific, historic, and intrinsic values, all of which are worth protecting into the future. This continent has a discrete number of places of scientific interest that exhibit great potential as natural heritage sites; its geodiversity is of fundamental importance to scientific values of the continent, and the pursuit of geological and paleontological knowledge has had a strong influence on its historical values. Seymour Island was once called the ‘Rosetta Stone’ of Southern Hemisphere paleobiology, because this small island provides the most complete and richly fossiliferous Late Cretaceous–Paleogene sequence in Antarctica. In particular, fossil vertebrates form part of the evidence used in reconstructing the history of life on Antarctica. Paleontological heritage is considered a subset of geo-heritage that embodies both natural and historical components which has received only indirect recognition. Seymour Island is an outstanding paleontological area with high heritage value of its Late Cretaceous/Paleogene vertebrates and should be considered for geo-conservation and protection. This paper reviews vertebrate fossil occurrences and outcrops on Seymour Island and discusses some threats to these fossil sites.

Keywords fossil vertebrates, geo-heritage, geo-conservation, Late Cretaceous–Paleogene, Seymour Island, Antarctica

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1 Introduction

Antarctica has a discrete number of places of scientific interest that exhibit great potential as natural heritage sites; its geodiversity is of fundamental importance to the environmental, scientific, wilderness and aesthetic values of the continent, and the pursuit of geological and paleontological knowledge has had a strong influence on its

historical values. The spectacular nature and aesthetic qualities of Antarctica can be attributed in part to the geology, paleontology and landforms of the region’s ice-free areas.

Seymour Island forms part of the Archipelago Ross and is situated northeast of the Antarctic Peninsula in the Weddell Sea (Figure 1). It is a rather small island, about 20 km long and 9 km wide, which is not covered by glaciers and is considered one of the most productive Paleogene/Late Cretaceous vertebrate sites in the Southern Hemisphere (Figure 2).

Seymour Island is an internationally well-known area in Antarctica because of its invertebrate and vertebrate fossils.

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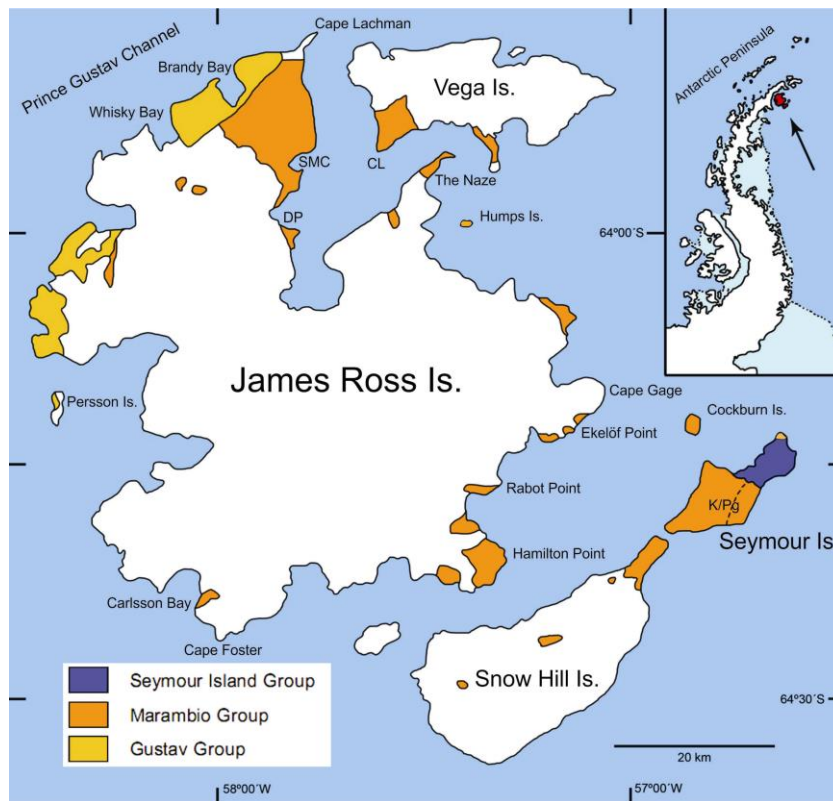


Figure 1 Location and stratigraphy of Seymour Island, Antarctic Peninsula. Schematic geological map of the James Ross Basin, Weddell Sea, north-eastern Antarctic Peninsula. Position of the Cretaceous–Paleogene boundary on Seymour Island indicated by the symbol K/Pg.

The Paleogene sequence of Seymour Island contains the only association of Cenozoic plants and land vertebrates known from anywhere in Antarctica. Although these fossils can be considered as part of the Antarctic geological heritage, they are facing some threats. Given the on-going increase in Antarctic tourism and scientific footprint, some high-quality geological and paleontological features may be vulnerable to human impact, such as damage due to the construction of logistical facilities, unregulated collection of paleontological specimens or oversampling for scientific purposes.

Fossil vertebrates form one of the most valuable paleontological resources which serve as important keys for

learning about the ancient environment, determining the age of strata and studying the past history of Antarctica. Seymour Island contains sites that are outstanding for their vertebrate species diversity and excellence of preservation. Also, fossil vertebrates from Seymour Island housed in existing collections of National repositories, rather than assembling new collections, could be used to estimate the geodiversity of these sites (Table 1). As Elliot (1988) wrote: “Seymour Island is surely destined to be recognized as one of the more important localities for Cretaceous and Paleogene paleontological research in the Southern Hemisphere, if not the world at large”.

Table 1 National repositories (museums, universities, institutes, etc.) housing scientific collections of fossil vertebrates from Seymour Island

Nation	Acronym	Repositories
Argentina	MLP	Museo de La Plata, La Plata, Argentina
	IAA-PV	Repositorio Antártico de Colecciones Paleontológicas y Geológicas, Instituto Antártico Argentino (IAA), Buenos Aires, Argentina
Chile	SGO	Museo Nacional de Historia Natural, Santiago, Chile
Poland	IB/P/B	Institute of Geological Sciences, Polish Academy of Sciences, Krakow, Poland
Sweden	NRM	Stockholm, Sweden
United Kingdom	BAS	British Antarctic Survey, Cambridge, UK
	BM	Natural History Museum, London, UK
	UCR	University of California, USA
United States	TTU	Museum of Texas Tech University, USA
	USNM	Smithsonian National Museum of Natural History, Washington, USA

Seymour Island paleontological sites contain well-preserved fossil vertebrate accumulations of high species diversity which in combination best document the story of community and environmental change through time. Late Cretaceous to Paleogene vertebrates in Antarctica are well documented in the rocks and sediments of Seymour Island. Such deposits are very well exposed in spectacular and varied geological landscapes having been shaped and modified by repetitive processes of deposition and erosion. The human impacts may result in loss or damage to, important fossils, remodeling of natural topography, loss of access or visibility, interruption of natural processes, pollution, or visual impacts.

Within the Antarctic Treaty, the designation of particular areas, initially to protect scientific research and then to conserve outstanding examples of Antarctic habitats, was a cause supported by the Scientific Committee on Antarctic Research (SCAR) and agreed by Treaty Parties in the form of Sites of Special Scientific Interest (SSSI) and then Specially Protected Areas (SPA). The Protocol on Environmental Protection to the Antarctic Treaty agreed in 1991 attempted to rationalize the protected area system by merging all these particular areas, SSSI and SPA sites, into a single system called Antarctic Specially Protected Areas (ASPAs) and redefining the scope to allow outstanding geological, paleontological and geomorphological areas to be considered. This opened the way for earth scientists to propose geological and paleontological sites for protection, such as important fossil sites, but there was concern that this approach might attract attention to important sites and result in increased damage and souveniring from tourism. Nevertheless, geological heritage (or ‘geo-heritage’) has remained almost completely outside the formal protected area system (Carson et al., 2018).

The Protocol on Environmental Protection to the Antarctic Treaty puts in place a framework for the protection of Antarctica’s environmental, scientific, historic, wilderness and aesthetic values. However, the Antarctic Protected Area system is still immature and further implementation of existing management tools may be required to protect the diverse range of vulnerabilities, qualities and spatial scales represented in the geology, paleontology and geomorphology of Antarctica. The recently established SCAR Action Group on Geological Heritage and Geo-conservation undertake detailing research, protection and ongoing management on and in areas of geological, paleontological and geomorphological significance within Antarctica.

For the purposes of this paper it is necessary to distinguish the concepts of geodiversity, geo-conservation and geo-heritage. Sharples (2002) defined them as follows: (1) “Geodiversity”—the natural quality that we want to protect; (2) “Geo-conservation”—our endeavor to try to protect “geodiversity”; and (3) “Geo-heritage”—includes concrete examples of the significance of our efforts to preserve geodiversity. One of the main targets on

geo-conservation is to define which paleontologically important sites should be conserved. The way to solve this issue is to promote geosites selection by means of inventory (Henriques et al., 2011; Brilha, 2016).

This paper tries to highlight the high geo-heritage value of the fossil vertebrates and the sites registered on Seymour Island and the vulnerabilities and threats to the geodiversity of the island using existing scientific and public information and discussing the utility of such an initiative, aiming to contribute to the protection and conservation of the paleontological heritage in Antarctica.

2 Historical background of the fossil vertebrates collected on Seymour Island

The Antarctic Peninsula (West Antarctica) is the region that has provided and that will likely continue to provide the most informative fossil vertebrate remains from the Cretaceous–Paleogene of this continent. In particular, during the past three decades, geological and paleontological explorations of the James Ross Basin (del Valle et al., 1992), Weddell Sea, have revealed that this basin, located off the northeast tip of the Antarctic Peninsula (West Antarctica), contains one of the most important records of Late Cretaceous and early Paleogene life in the Southern Hemisphere (Figure 2). Knowledge of the existence of fossils in Antarctica goes back to the early 19th century, when James Eights described in situ fossilized wood from the South Shetland Islands (Eights, 1833). The first documented collection of fossils from Antarctica was made by the Norwegian whaling Captain Carl Anton Larsen on Seymour Island during the austral summer of 1892–1893 (Larsen, 1894). These fossils were studied and reported by Sharman and Newton (1894).

Since the beginning of the 20th century, geological and paleontological explorations on Seymour Island have demonstrated that this island contains one of the most important records of the Late Cretaceous and Paleogene life in the Southern Hemisphere. The early explorer and scientist Otto Nordenskjöld, leader of the Swedish South Polar Expedition of 1901–1903, recognized the paleontological and biogeographical importance of this island. The Swedish South Polar Expedition was the first to collect Antarctic vertebrate fossils on Seymour Island. The site, indicated as ‘fossil locality no. 11’ on Nordenskjöld’s map (Figure 3), is situated about 50 m above sea level between the northeast shore and the 190 m high plateau occupying a major part of the northeast of the island. The area forms a smoothly undulating expanse covering some 100 m in length and width (see Wiman, 1905a, p. 2; 1905b, p. 248). This locality has been revisited by earth scientists many times since the 1980s, and it is one of the most productive paleontological sites in Antarctica.

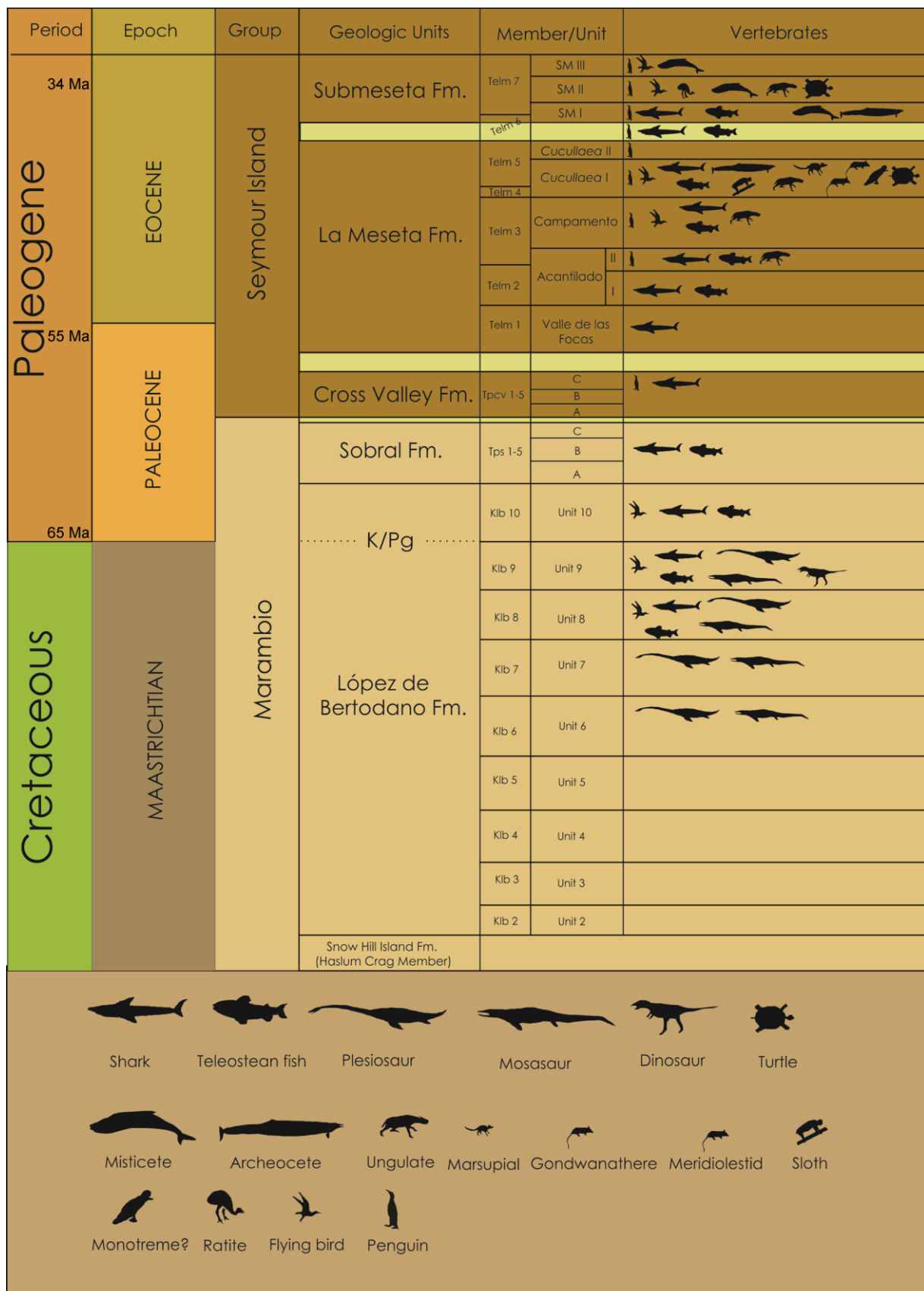


Figure 2 Time scale, stratigraphy and vertebrate fossil record for the Late Cretaceous–Paleogene rocks in Seymour Island, Antarctic Peninsula, West Antarctica. Temporal and sedimentary units not to scale.

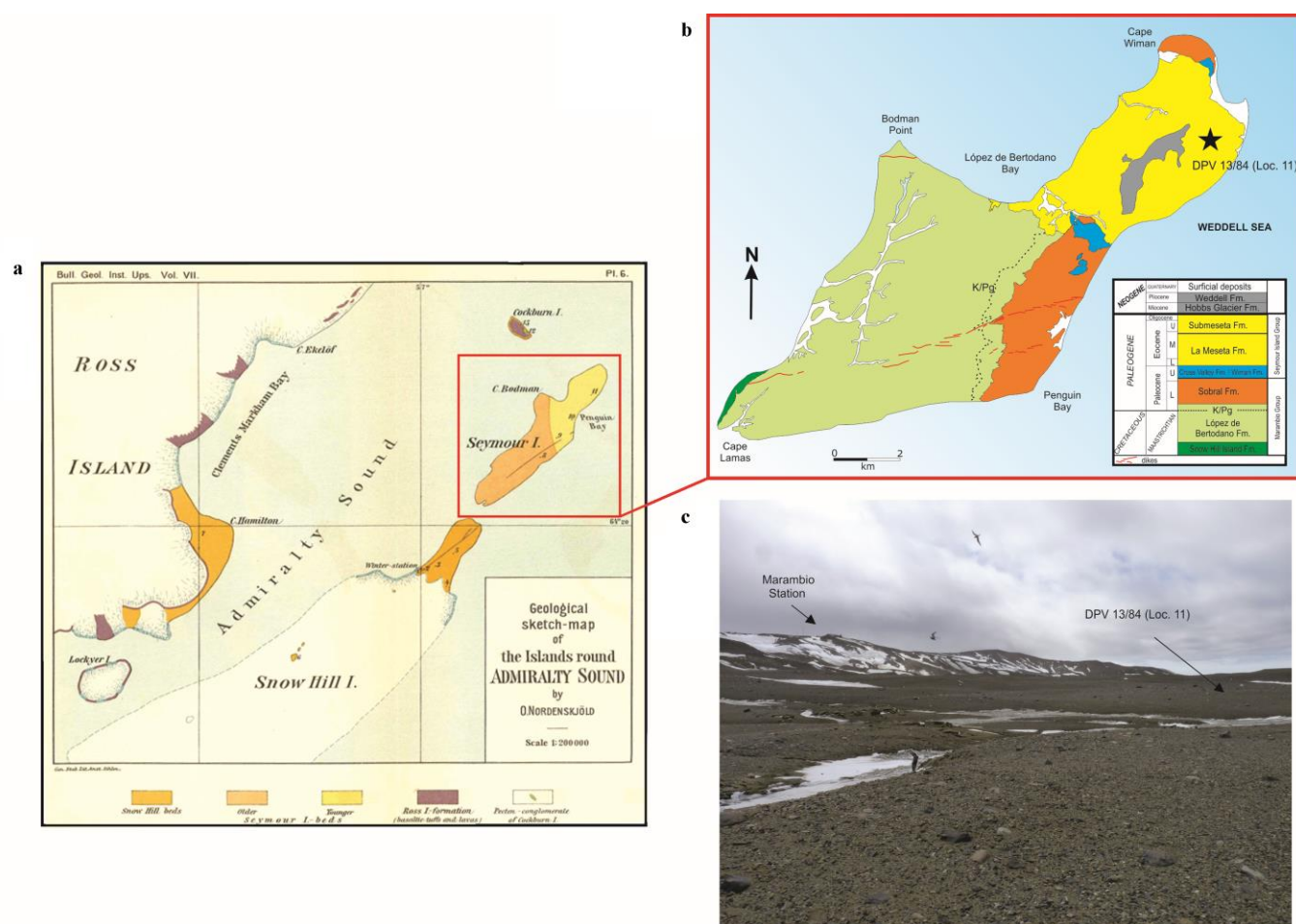


Figure 3 **a**, “Geological sketch-map of the Islands round Admiralty Sound” drawn by Otto Nordenskjöld (Wiman, 1905b) showing the location of the Locality 11 on Seymour Island; **b**, Geological map of Seymour (Marambio) Island, Antarctic Peninsula showing locality DPV 13/84 (black star); **c**, Landscape of the northeastern end of Seymour Island, Antarctic Peninsula showing the continuous and undulating surface exposure of the locality DPV 13/84 of the Submeseta Formation (looking east).

The Swedish South Polar Expedition was one of the most scientifically successful expeditions in the history of Antarctic exploration (Nordenskjöld, 1905; Wiman, 1905a; Dusén, 1908; Gothan, 1908; Woodward, 1908; Wilckens, 1911; Halle, 1913). The first fossil vertebrate collection from Antarctica was made on Seymour Island by this expedition. Wiman (1905a) was the first scientist who described and figured the fossil vertebrate collection collected by the Swedish South Polar Expedition (Figures 4 and 5).

One of the puzzling aspects of the history of exploration of the James Ross Basin and particularly Seymour Island is the failure by the paleontological community to fully recognize the scientific potential of this basin for nearly 70 years. After the Swedish South Polar Expedition (1901–1903), more than 40 years passed before the basin was scientifically visited again, this time by members of the Falkland Islands Dependencies Survey (now the British Antarctic Survey).

The establishment of the Argentinian Marambio Station on Seymour Island in 1969 initiated the modern

phase of geological and paleontological studies in the James Ross Basin. The recovery of a moderately varied Eocene land vertebrate fauna from the northern portion of the island rekindled interest in this area after the discovery of the first land mammal in Antarctica (Woodburne and Zinsmeister, 1982, 1984).

3 General geology, stratigraphy and geo-heritage attributes of fossil vertebrates from Seymour Island

The Late Cretaceous–Paleogene strata of the James Ross Basin comprise a thick sequence of marine sedimentary rocks divided into three lithostratigraphic groups: the basal Gustav Group (Aptian–Coniacian), the intermediate Marambio Group (Santonian–Danian), and the upper Seymour Island Group (Paleogene; e.g., Rinaldi, 1982; Crame et al., 1991; Riding and Crame, 2002). The sedimentary sequence exposed in the James Ross Basin comprises a 6–7 km thick section from Late Cretaceous to

latest Eocene and probably earliest Oligocene (MacDonald et al., 1988). The high-latitude biota in both the Cretaceous and Paleogene beds are unusually rich and comparable to those from New Zealand and southeastern

Australia (Reguero et al., 2013). Among fossil marine vertebrate remains, chondrichthyans seemingly were dominant elements in the Eocene Antarctic fish fauna (Figure 6).

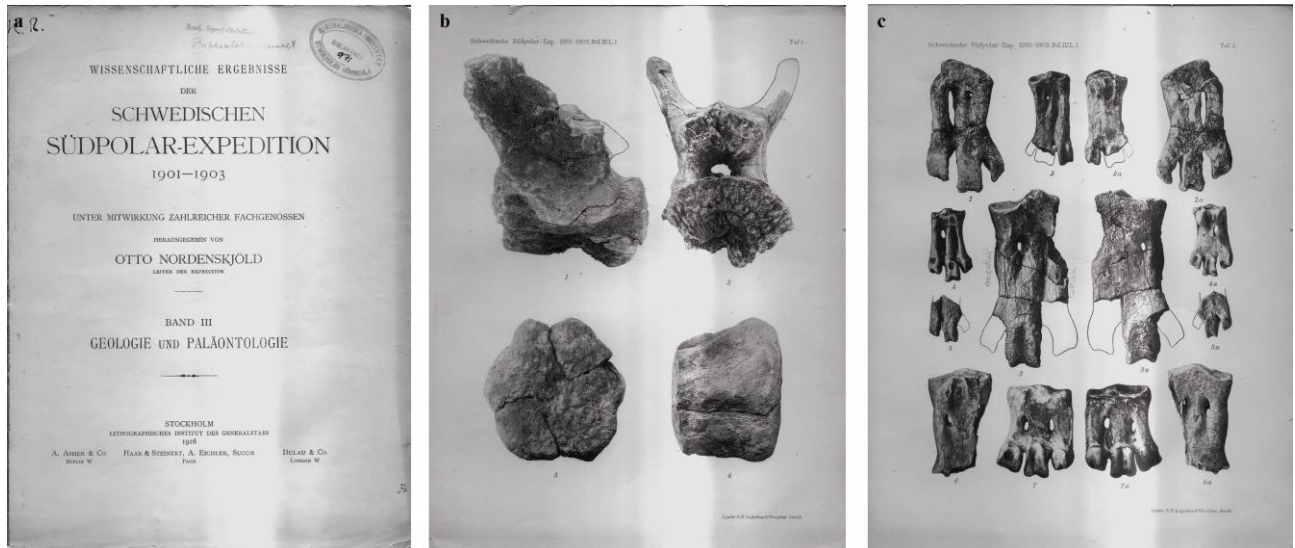


Figure 4 Wiman's publication (1905a): Über die alttertiären Vertebraten der Seymourinsel. Wissenschaftliche Ergebnisse der Schwedischen Südpolar Expedition 1901–1903. **a**, Original cover page of the contribution; **b**, Plate 1 (TAF. I.) two vertebrae of *Zeuglodon* sp. (1 to 4); **c**, Plate 2 (TAF. II.) tarsometatarsi of “*Eospheniscus gunnari*” (1, 1a), *Delphinornis larsenii* (2, 2a), *Anthropornis nordenskjöldi* (3, 3a), *Spheniscus* sp. (4, 4a), *Ichtyopteryx gracilis* (5, 5a).



Figure 5 Seymour Island fossil penguins collected by the Swedish South Polar Expedition (1901–1903) and described by Wiman (1905a). **a**, *Palaeudyptes gunnari*, NRM A.7, holotype, incomplete tarsometatarsus; **b**, *Delphinornis larseni*, NRM A.21, holotype, incomplete tarsometatarsus; **c**, *Ichtyopteryx gracilis*, NRM A.20, incomplete tarsometatarsus; **d**, *Anthropornis nordenskjöldi*, NRM A.45, holotype, incomplete tarsometatarsus. NRM (Naturhistoriska Riksmuseet of Stockholm). Scale bar = 5 cm.

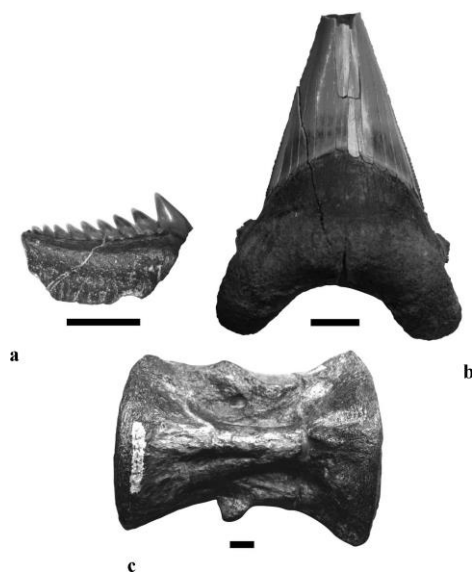


Figure 6 Paleogene Elamosbranchii and Teleostei from Seymour Island. **a**, *Hexanchus* sp., lateral lower tooth, La Meseta Formation, *Cucullaea* Allomember at IAA 1/95 locality; **b**, Lower tooth of *Carcharocles auriculatus*, La Meseta Formation, *Cucullaea* Allomember at DPV 2/84 locality; **c**, cf. *Xiphiorhynchus*, caudal vertebrae, La Meseta Formation, Acantilados II Allomember (TELM 3), at IAA 2/93 locality. Scale bar = 1 cm.

Paleogene beds of the James Ross Basin are exclusively marine, and only exposed on Seymour and the nearby Cockburn islands (Figure 1). They are comprised of shallow marine shelf deposits of the uppermost López de Bertodano and Sobral formations (early Paleocene) and the incised valley systems of the Cross Valley (late Paleocene), La Meseta (middle Eocene) and Submeseta (Late Eocene/?earliest Oligocene) formations.

The fossil vertebrates forming the basis of this study were derived from Late Cretaceous to Paleogene deposits on Seymour Island. Fossiliferous sediments on Seymour Island belong to two groups that span the Late Cretaceous to the Late Eocene/?earliest Oligocene. These include the lower Marambio Group, composed of the López de Bertodano and Sobral formations and the overlying Seymour Island Group consisting of the Cross Valley, La Meseta, and Submeseta formations (e.g., Zinsmeister, 1982; Grande and Chatterjee, 1987; Crame et al., 1991). Locations of key Cretaceous and Paleogene fossil vertebrate sites on Seymour Island can be seen in Figure 7, and the locations of Late Cretaceous/Paleogene vertebrate type localities are listed in Appendix Table 1.

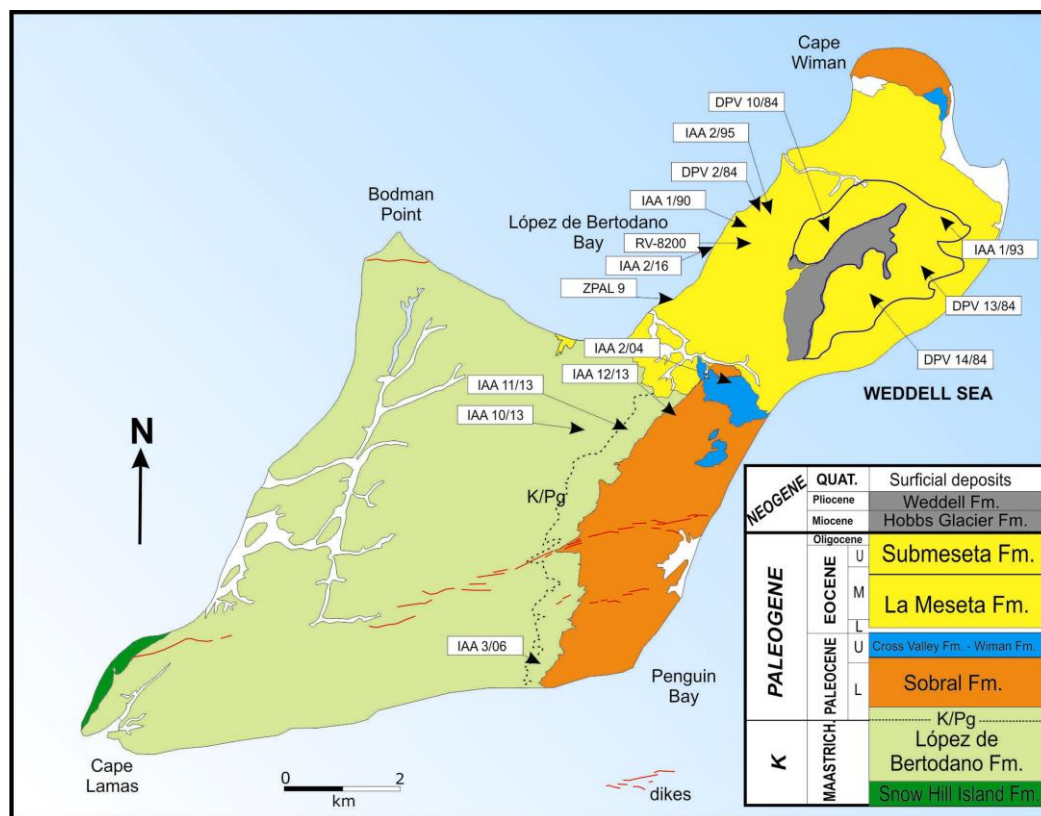


Figure 7 Schematic geological maps (after Montes et al., 2013) of key fossil vertebrate sites in Seymour Island, north-eastern Antarctic Peninsula. Position of the Cretaceous–Paleogene boundary (K/Pg) is indicated.

3.1 López de Bertodano Formation

The López de Bertodano Formation (LBF) contains a fully marine fauna (e.g., Macellari, 1988; Crame et al., 2004; Witts et al., 2016) indicative of open marine conditions. In addition, global changes in temperature and other paleoceanographic events can be recognized in the basin (e.g., Tobin et al., 2012; Bowman et al., 2013). Age based on macrofossil and dinoflagellate biostratigraphy, strontium isotope chemostratigraphy, and magnetostratigraphy (McArthur et al., 1998; Crame et al., 2004; Tobin et al.,

2012; Bowman et al., 2013; Witts et al., 2016), as well as the presence of an iridium anomaly at the K/Pg boundary (Elliot et al., 1994), dates this unit as Maastrichtian–Danian.

The LBF has been the subject of extensive paleontological and stratigraphic studies over the last 30 years (Feldmann and Woodburne, 1988 and authors therein; Crame et al., 2004; Bowman et al., 2012; Olivero, 2012), and contains the best shallow-marine record in the Southern Hemisphere of the K/Pg mass extinction event (Zinsmeister, 1998; Witts et al., 2016). The locality IAA 10/13 (Figures 7, 8) is very productive and has a significant high geo-heritage value (see Appendix Table 2).



Figure 8 General view of the uppermost horizons of the López de Bertodano Formation at Seymour Island showing the K/Pg boundary between units 9 (Late Maastrichtian) and 10 (Danian). Localities IAA 10/13 and 11/13 are indicated.

Mesozoic marine reptiles, mosasaurs and elasmosaurid plesiosaurs (Figure 9) are important components of the Cretaceous marine deposits of Unit 9 of the López de Bertodano Formation. Terrestrial vertebrates are less common, including dinosaurs (Figure 10f) and unpublished

flying birds. Exceptional preservation is seen in the holotype (an almost complete skeleton) of the bird *Conflicto antarcticus* (Figure 10d) from Unit 10 at IAA 3/06 locality (Figures 7, 8). Species and locality types of the López de Bertodano Formation are listed in Appendix Table 1.

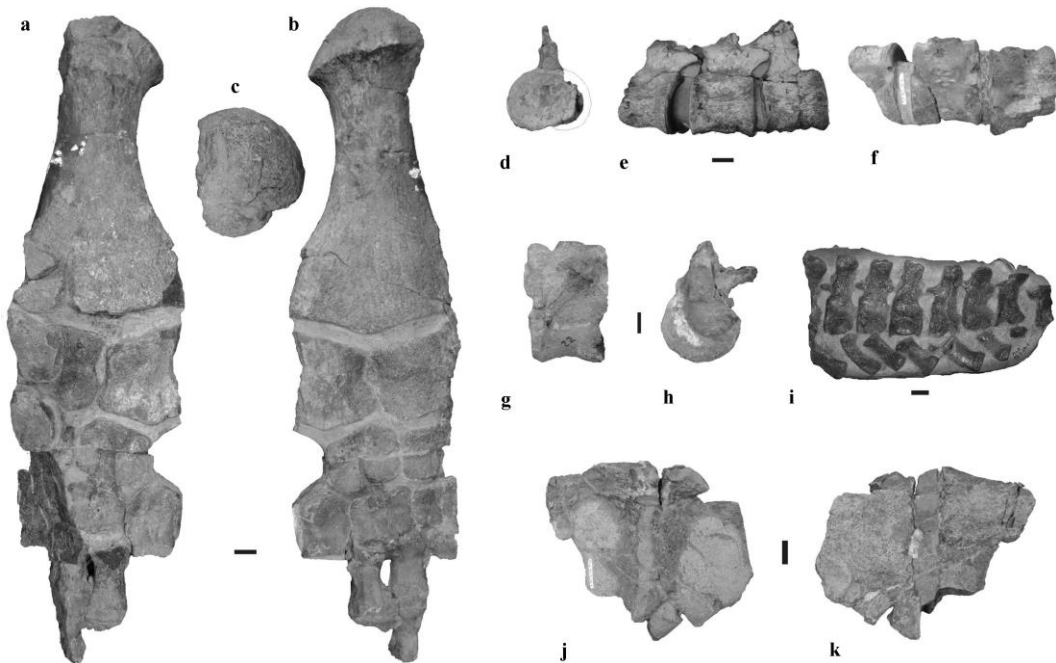


Figure 9 Marine reptiles from Seymour Island. Elasmosauridae indet., MLP 82-I-28-1, partial skeleton, López de Bertodano Formation, Unit 9 at IAA 10/13 locality. **a–c**, Femur and phalanxes; **d**, cervical vertebrae (anterior view); **e**, right lateral view; **f**, ventral view; **g**, dorsal vertebrae (left lateral view); **h**, dorsal vertebrae (anterior view); **i**, caudal vertebrae (left lateral view); **j** and **k**, coracoid (dorsal and ventral view). Scale bar = 20 mm.

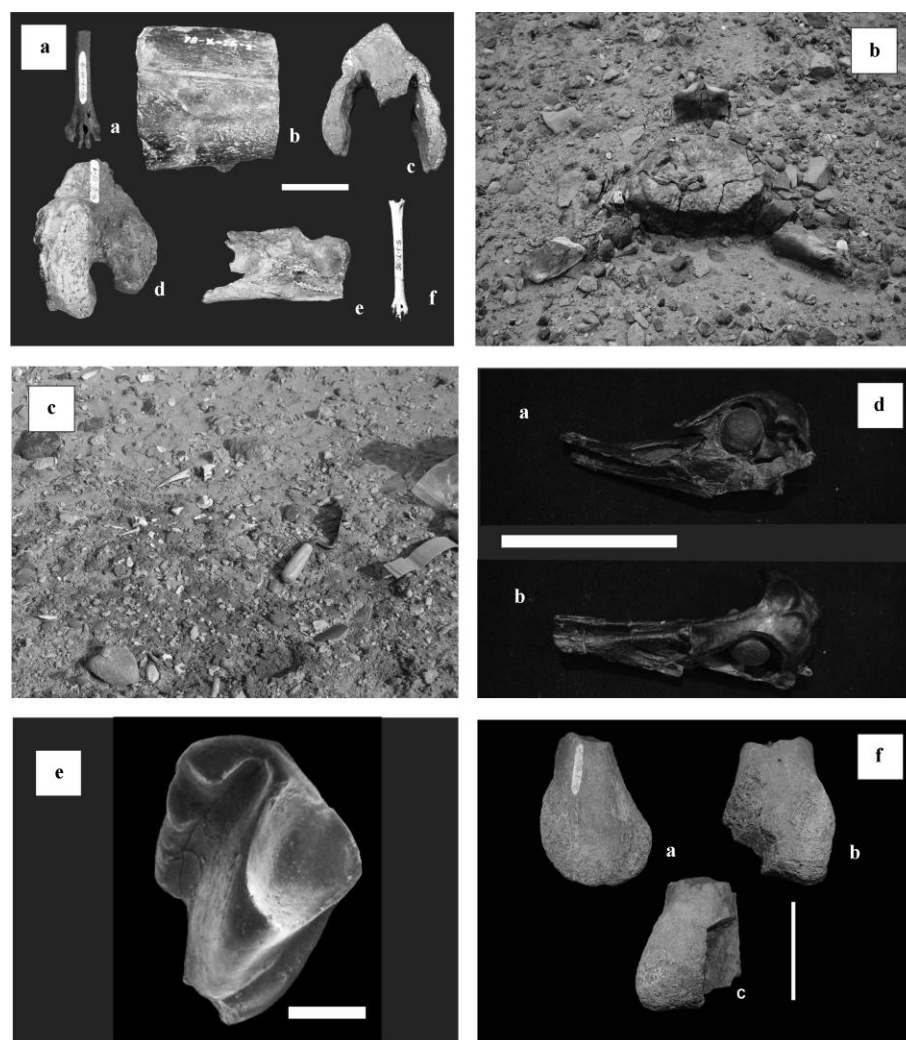


Figure 10 Seymour Island vertebrate Paleontological Heritage. **a**, Eocene birds from La Meseta Formation: *a*. *Antarctobaenus carlinii*, holotype, MLP 95-I-10-8, distal fragment of left tarsometatarsus; **b** and **c**. Pelagornithidae, gen et sp. indet., MLP 78-X-26-1, fragment of the rostrum: lateral and transversal views; **d**. Ratitae, gen. et sp. indet., MLP 94-III-15-1, distal end of right tarsometatarsus; **e**. Pelagornithidae, gen et sp. indet., MLP 83-V-30-1, posterior fragment of the right mandible, lingual view; **f**. Diomedidae, gen. et sp. indet., MLP 86-I-1-5, left tarsometatarsus. Scale bar = 2 cm. **b**, *Llanocetus* sp., vertebrae weathered in poorly consolidated pebbly at locality DPV 14/84, Submeseta Formation, Submeseta II Allomember. **c**, Fossil penguin skeleton weathered in poorly consolidated pebbly at locality DPV 13/84, Submeseta Formation, Submeseta II Allomember. **d**, *Conflicto antarcticus*, holotype, MLP 07-III-1-1, skull with **a**-left and **b**-dorsal views, López de Bertodano Formation, Unit 10 at locality IAA 3/06. **e**, Seymour Island meridiolestid, gen. et sp. nov., MLP 91-II-4-3, right? upper molar (M3?) in mesio occlusal view. La Meseta Formation, *Cucullaea* I Allomember at locality IAA 1/90. Scale bar = 1 mm. **f**, Hadrosauriidae? dinosaur, MLP 96-I-6-2, distal end of metatarsal (**a**) lateral, (**b**) dorsal, (**c**) ventral views. Scale bar = 50 mm. López de Bertodano Formation, Unit 9, at locality IAA 10/13.

3.2 Sobral Formation

The Sobral Formation is a 218 m thick sedimentary unit and unconformably overlies the López de Bertodano Formation. The contact is an erosional surface that records marine regression (Macellari, 1988; Sadler, 1988; Marensi et al., 2012). The formation outcrops on the south-eastern tip of Seymour Island (Figure 7) and represents a shallowing sequence from a mid-shelf setting to a proximal delta front depositional environment (Macellari, 1988; Sadler, 1988; Marensi et al., 2012). The top of the unit is a high-relief unconformity below

the Late Paleocene Cross Valley Formation (Santillana et al., 2007). The Sobral Formation represents silicoclastic sedimentation on a marine shelf during at least two transgressive-regressive cycles. Relative sea-level low-stands produced down cutting and incision while most accumulation took place during following sea-level rises. In this way internal unconformity bounded units present a coarsening-upward arrangement from muddy to sandy dominated lithofacies (Marensi et al., 2012). Few vertebrate fossils were recovered from this unit (chondrichthyes and teleostean fishes) (Appendix Table 2). The geo-heritage value of this unit is low.

3.3 Cross Valley Formation

The Cross Valley Formation is a 195-m-thick lenticular unit, 1.5 km long and c. 600 m wide. Its strata dip towards the SE, and the main outcrop is located in the central part of the island. Three discontinuity bounded allomembers were recognized within the formation: Cross Valley A, B and C (Marensi et al., 2012).

The base of the unit, Allomember Cross Valley A, corresponds to a 0.30–1 m thick medium-grained massive sandstone bed rich in glaucony. The bulk of the allomember is composed of coarse- to fine-grained cross-bedded sandstones with a high percentage of volcanic material arranged into three fining upward cycles 30–40 m thick.

Charcoalified wood is frequently found in the sandstones. This Allomember A is interpreted as deposited in subtidal channels with the upper section made up of interbedded medium-grained sandstones and mudstones (Pujana et al., 2015).

The skeleton of the oldest Antarctic penguin, *Crossvallia unienwillia* (Tambussi et al., 2005, see Appendix Table 1) was recovered from site IAA 2/04 (Figures 7, 11c), Cross Valley C Allomember (Bahía Pingüino Member in previous works). The Middle Eocene/?earliest Oligocene La Meseta and Submeseta formations fill an incised valley and comprises sediments representing deltaic, estuarine and very shallow marine environments (Figure 12).

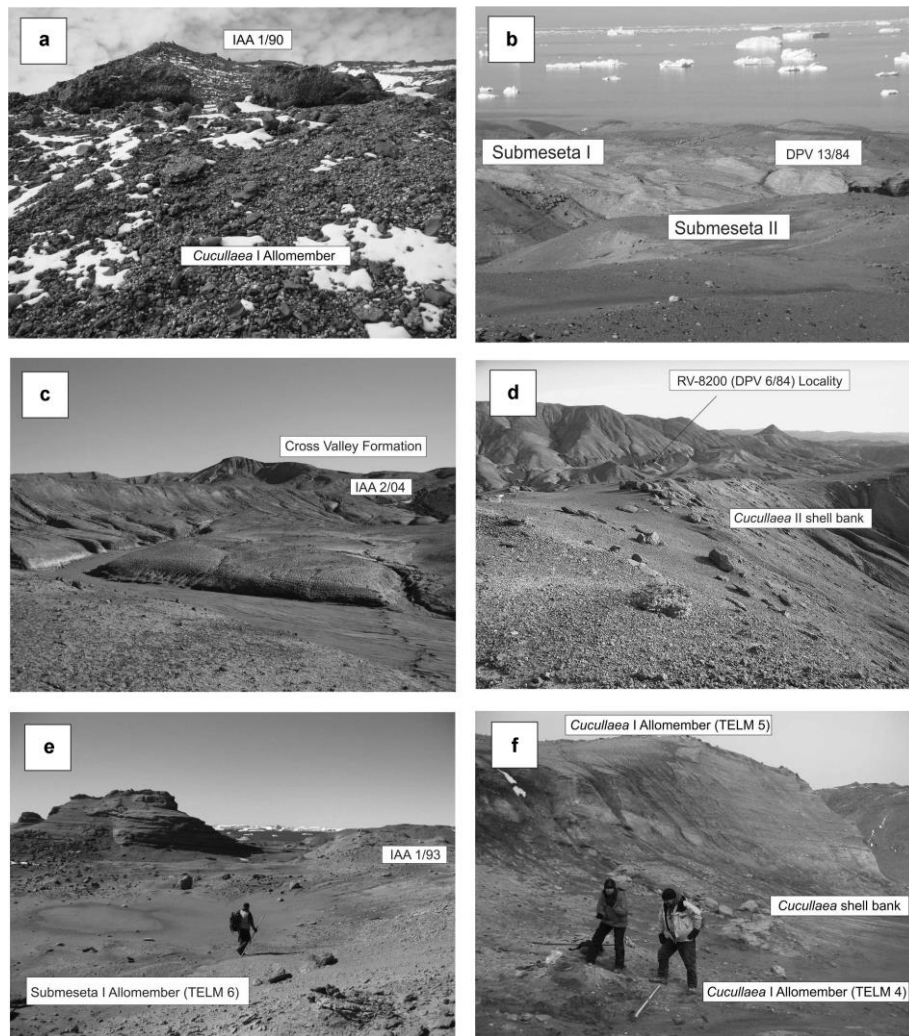


Figure 11 Seymour Island vertebrate Paleontological Heritage: Most important Paleogene vertebrate fossil-containing sites: **a**, Site IAA 1/90, Naticids bed, La Meseta Formation, *Cucullaea* I Allomember (TELM 5); **b**, Site DPV 13/84, Submeseta Formation, Submeseta II Allomember (TELM 7); **c**, Site IAA 2/04, Cross Valley Formation, Cross Valley C Allomember (Bahía Pingüino Member in previous works, e.g., Tambussi et al., (2005)); **d**, Site RV-8200 (DPV 6/84), La Meseta Formation, *Cucullaea* I Allomember (TELM 5); **e**, Site IAA 1/93, Submeseta Formation, Submeseta I Allomember (TELM 6); **f**, Site DPV 2/84, *Cucullaea* shell bank, La Meseta Formation, *Cucullaea* I Allomember (TELM 4). Locality with very abundant specimens of the bivalve *Cucullaea raea* and gastropod darwinellids, west side of plateau at north end of Seymour Island.

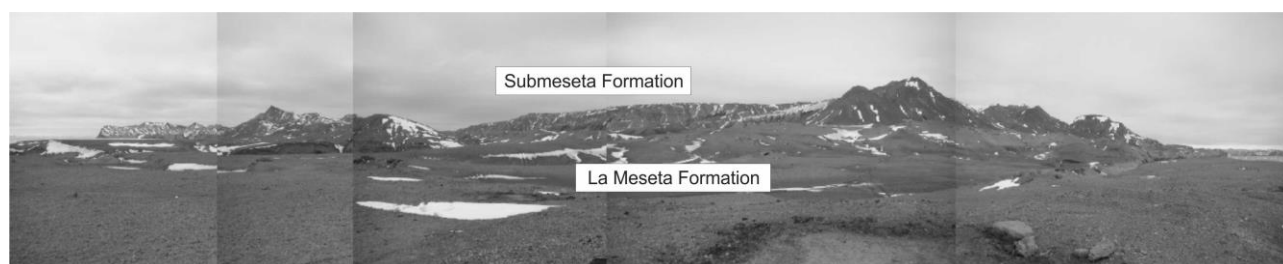


Figure 12 Landscape of the northern end of Seymour Island, Antarctic Peninsula showing the continuous surface exposure of La Meseta Formation and Submeseta Formation (looking west, to the Cockburn Island).

3.4 La Meseta Formation

These approximately 560 m thick fossiliferous sediments were originally considered a single formation, the La Meseta Fm., which was named and subdivided by Elliot and Trautman (1982). This formation crops out on the northern third of Seymour Island and it consists of poorly unconsolidated mudstones and sandstones with interbedded shell-rich conglomerate filling a 7 km wide incised valley system (Marensi, 1995; Marensi et al., 1998a, 1998b). Sediments were deposited in deltaic, estuarine and shallow marine settings.

The *Cucullaea* I Allomember crops out all around the foothills of the meseta (Plateau) in the northern part of Seymour Island and has a maximum thickness of 90 m (Figure 12). It is composed of shelly channel fills, sand-mud alternations, and cross-bedded fine sands. The unit was deposited in estuarine to shallow marine estuary settings (Marensi et al., 1998a, 1998b, 2002).

The vertebrate fossils of the La Meseta Formation are mainly represented by cartilaginous fishes, which seemingly represents the major faunal component of the pre-Oligocene Antarctic fish faunas (Kriwet et al., 2016). Fossil chondrichthyans include more than 35 species within 22 families of selachians, batoids, and chimaeroids, which have been reported from different levels within the La Meseta Formation and at different localities on Seymour Island (see Welton and Zinsmeister, 1980; Jerzmanska, 1988, 1991; Eastman and Grande, 1989, 1991; Long, 1992a, 1992b, 1994; Balushkin, 1994; Cione and Reguero, 1995, 1998; Doktor et al., 1996; Kriwet, 2005; Kriwet et al., 2016; Engelbrecht et al., 2016, 2017) (Appendix Table 3).

Localities IAA 1/90 (Figures 7, 11a) and IAA 2/95 (Figure 7) are located in thin shell lenses on the north side of Seymour Island that are dominated by naticid gastropods and informally referred to as a 'Natica horizon' (Bomfleur et al., 2015). This conglomeratic lens is less than 1 m thick and was interpreted as a nearshore, shallow-marine environment by Stilwell and Zinsmeister (1992). These localities, besides diversified marine invertebrates (see Stilwell and Zinsmeister, 1992), contain remains of diverse

fossil terrestrial mammals with small- and medium-size mammals (Figures 10e, 13, 14) (Goin et al., 1991; Marensi et al., 1994; Reguero et al., 2013). Marine vertebrates are also present, among them penguin remains as well as ichthyofauna represented by numerous isolated shark teeth (Long, 1992a, 1992b; Cione and Reguero, 1994; Reguero et al., 2013; Appendix Table 3). Species and locality types of the La Meseta Formation are listed in Appendix Table 1.

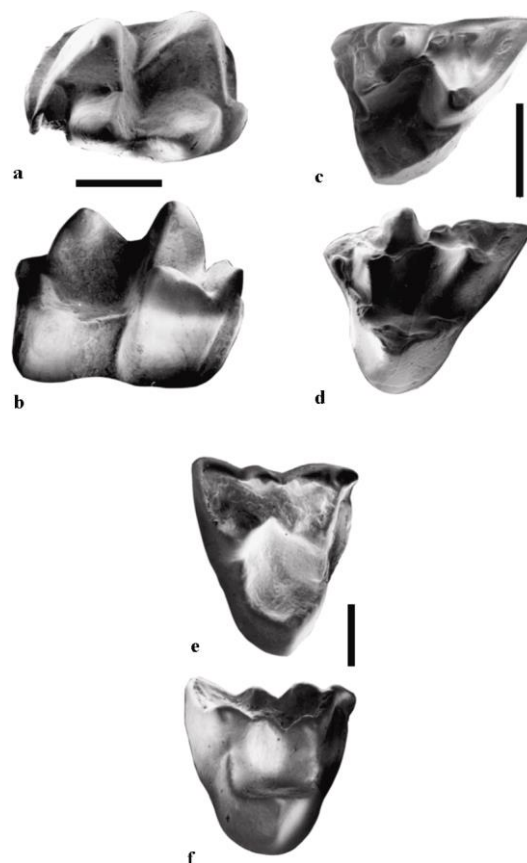


Figure 13 Antarctic metatherians from the La Meseta Formation. **a** and **b**, *Pauladelphys juanjoi*, MLP 95-I-10-2, right lower molar (m?3); occlusal and labial views; **c** and **d**, *Pauladelphys juanjoi*, MLP 96-I-5-45, left upper molar, occlusal and lingual views; **e**, *Xenostylus peninsularis*, MLP 94-III-15-10, right upper molar, occlusal and lingual views. Scale bar = 1 mm.

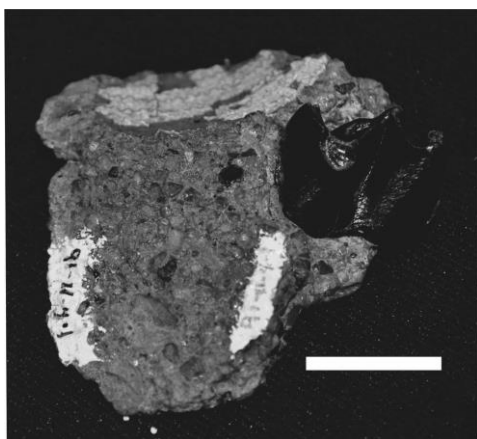


Figure 14 Litoptern *Notiolofos arquinotiensis*, MLP 91-II-4-1, right lower molar embedded in a consolidated sand matrix close to a fragment of *Cucullaea*, *Cucullaea* shell bank, La Meseta Formation, *Cucullaea* I Allomember (TELM 4). Scale bar = 10 mm.

3.5 Submeseta Formation

The new middle Eocene–earliest Oligocene Submeseta Formation (Montes et al., 2013) was previously considered as the Submeseta Allomember of La Meseta Formation (Marensi et al., 1998a). This unit is about 160 m thick and crops out continuously around the uppermost flanks of the “meseta”. The depositional and lithological environments are similar to the *Cucullaea* I and *Cucullaea* II allomembers, with the uppermost part of the sedimentary sequence being thicker and including very fine sandstones, mudstones, and gravel sheets (Marensi, 2006). These lens-shaped units represent different stages related to sea level fluctuations as described by Marensi et al. (2002) that were deposited in deltaic, estuarine, and shallow marine environments (Porebski, 1995; Marensi et al., 1998b). The Submeseta Formation is divided into three members named from base to top: Submeseta I (TELM 6), Submeseta II (TELM 7 in partem), and Submeseta III (TELM 7 in partem). Magnetostratigraphically calibrated dinocyst biostratigraphy suggests a latest Eocene age (Priabonian) for middle and upper TELM 7, consistent with a mollusc-based $^{87}\text{Sr}/^{86}\text{Sr}$ date of 34.2 ± 0.87 Ma for the top of the same unit (Dingle and Lavelle, 1998).

The highest diversity of Weddellian penguins is documented in the *Anthropornis nordenskjoeldi* Biozone (Tambussi et al., 2006) within the Submeseta II Allomember at DPV 13/84 locality (Figures 7, 11b). Sphenisciforms of the *Anthropornis nordenskjoeldi* Biozone provide the major taxonomic and body size diversity with 10–14 species co-occurring sympatrically (Reguero et al., 2013). Remains of fossil penguins and whales, articulated and disarticulated, are very common in the Submeseta II Allomember (Figure 10c). The fossil vertebrate content of the Submeseta Formation is listed in Appendix Table 4. Species and locality types of the Submeseta Formation are listed in

Appendix Table 1.

4 Concluding remarks

Fossil occurrences across the world are endangered by development, construction, collecting, and vandalism, even though many outstanding examples have been protected by World Heritage Sites, national parks, monuments and reserves, state and provincial parks, and local government and non-profit organizations, as well as some private individuals. The basic necessities of paleontological site conservation are the ongoing identification and scientific assessment of sites with the help of geoscientists and producing the correct responses to threatening developments to the sites.

In Antarctica, Seymour Island fossil vertebrates represent valuable paleontological resources which serve as important keys for learning about the ancient environment, determining the age of strata and studying the past history of West Antarctica. On Seymour Island, although vertebrate fossils can be considered as part of geological heritage, they are facing some threats. As explained above, fossil occurrences on this island are endangered by some threats i.e., development, collecting (oversampling) and neglect. To protect these fossils and fossil sites, and to increase awareness of the importance of them, the SCAR Action Group on Geological Heritage and Geo-conservation with the collaboration of the Geoscience Group of SCAR will initiate a proper way to conserve these fossils and fossil sites. Important areas of this island contain numerous and various vertebrate fossils, mainly from the Cretaceous and Paleogene. Paleontologists, geologists and researchers have been coming to Seymour Island since the beginning of the 20th century to study the fossils and geological data of the island. The geo-conservation of selected fossiliferous sites with high value of geo-heritage within Seymour Island includes Mesozoic: López de Bertodano Formation, Unit 9, and the Cretaceous–Paleogene (K/Pg) boundary; and Paleogene: La Meseta Formation, *Cucullaea* I Allomember, and Submeseta Formation, Submeseta II Allomember) with well-exposed marine stratigraphy.

Different areas of Seymour Island display a large number of potential geosites based on the fossil vertebrates with significant paleontological heritage values. All these vertebrate fossils and sites are unique in Antarctica and form part of the history of life on earth, and they have played a significant role in reconstructing this history. All data are made available to enhance focus on the ultimate goal of the study, which is to demonstrate the findings as justifications for the conservation of the area.

Abbreviations

DPV–División Paleontología de Vertebrados, Museo de La Plata, La Plata, Argentina

IAA-PV–Repositorio Antártico de Colecciones Paleontológicas y Geológicas, Instituto Antártico Argentino (IAA), Buenos Aires, Argentina

MLP–Museo de La Plata, La Plata, Argentina

NRM–Swedish Natural History Museum, Stockholm, Sweden

TTU–Museum of Texas Tech University, USA

ZPAL–Institute of Geological Sciences, Polish Academy of Sciences, Krakow, Poland

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Appendix Table 1 Late Cretaceous/Paleogene vertebrate type localities located in Seymour Island. Taxonomic list, stratigraphy, geographic locations, coordinates and references

Taxon		Formation	Allomember/ unit	Sadler (1988)	Age	Type locality	Coordinates	Collection	Holotype	Reference
Class	Species									
Osteichthyes	<i>Argentina antarctica</i>	La Meseta	<i>Cucullaea</i> I	TELM 5	Early–Middle Eocene	IAA 2/95	64°13'58"S; 56°39'06"W	NRM	NRM-PZ P.15964	Schwarzshans et al. (2016)
Osteichthyes	<i>Diaphus? marambionis</i>	La Meseta	<i>Cucullaea</i> I	TELM 5	Early–Middle Eocene	IAA 2/95	64°13'58"S; 56°39'06"W	NRM	NRM-PZ P.15966	Schwarzshans et al. (2016)
Osteichthyes	<i>Macrurodon eastmani</i>	La Meseta	<i>Cucullaea</i> I	TELM 5	Early–Middle Eocene	IAA 1/90	64°14'04.67"S; 53°39'56.38"W	NRM	NRM-PZ P.15970	Schwarzshans et al. (2016)
Osteichthyes	<i>Palimphemus seymourensis</i>	La Meseta	<i>Cucullaea</i> I	TELM 5	Early–Middle Eocene	IAA 2/95	64°13'58"S; 56°39'06"W	NRM	NRM-PZ P.15973	Schwarzshans et al. (2016)
Osteichthyes	<i>Coelorinchus balushkini</i>	La Meseta	<i>Cucullaea</i> I	TELM 5	Early–Middle Eocene	IAA 1/90	64°14'04.67"S; 53°39'56.38"W	NRM	NRM-PZ P.15976	Schwarzshans et al. (2016)
Osteichthyes	<i>Coelorinchus nordenskjöldi</i>	La Meseta	<i>Cucullaea</i> I	TELM 5	Early–Middle Eocene	IAA 1/90	64°14'04.67"S; 53°39'56.38"W	NRM	NRM-PZ P.15978	Schwarzshans et al. (2016)
Osteichthyes	<i>Hoplobrotula? antipoda</i>	La Meseta	<i>Cucullaea</i> I	TELM 5	Early–Middle Eocene	IAA 1/90	64°14'04.67"S; 53°39'56.38"W	NRM	NRM-PZ P.15984	Schwarzshans et al. (2016)
Osteichthyes	<i>Notoberyx cionei</i>	La Meseta	<i>Cucullaea</i> I	TELM 5	Early–Middle Eocene	IAA 2/95	64°13'58"S; 56°39'06"W	NRM	NRM-PZ P.15987	Schwarzshans et al. (2016)
Osteichthyes	<i>Cepola anderssoni</i>	La Meseta	<i>Cucullaea</i> I	TELM 5	Early–Middle Eocene	IAA 2/95	64°13'58"S; 56°39'06"W	NRM	NRM-PZ P.15996	Schwarzshans et al. (2016)
Osteichthyes	<i>Proeleginops grandeastmanorum</i>	Submeseta	Submeseta II	TELM 7	Late Eocene	Unknown	no data			Balushkin (1994)
Osteichthyes	<i>Marambionella andreae</i>	La Meseta	Acantilados II	TELM 2	Early–Middle Eocene	ZPAL 9	64°14'53.2"S; 56°41'39.57"W	ZPAL	ZPAL P.III/1B	Jerzemska (1991)
Holocephali	<i>Chimaera seymourensis</i>	La Meseta	Acantilados II	TELM 2	Early–Middle Eocene	Unknown	no data	FMNH	FMNH PF.10649	Ward and Grande (1991)
Holocephali	<i>Callorhynchus stahli</i>	La Meseta	Acantilados II	TELM 2	Early–Middle Eocene	ZPAL 8	64°15'31.06"S; 56°41'05.8"W	ZPAL	ZPAL P.9/1	Kriwet and Gazdzicki (2003)
Holocephali	<i>Callorhynchus torresi</i>	López de Bertodano	Unit 9	KLB 9	Late Maastrichtian	IAA 10/13	64°15'54.23"S; 56°42'28.03"W	SGO	SGO.PV.22011	Rodrigo et al. (2013)
Chondrichthyes	<i>Squalus woodburnei</i>	La Meseta	<i>Cucullaea</i> I	TELM 5	Early–Middle Eocene	RV-8200 (DPV 6/84)	64°14'21.78"S; 56°39'44.84"W	UCR	UCR 22105	Long (1992a)
Chondrichthyes	<i>Squalus weltoni</i>	La Meseta	<i>Cucullaea</i> I	TELM 5	Early–Middle Eocene	RV-8200 (DPV 6/84)	64°14'21.78"S; 56°39'44.84"W	UCR	UCR 22088	Long (1992a)
Chondrichthyes	<i>Pristiophorus laevis</i>	La Meseta	<i>Cucullaea</i> I	TELM 5	Early–Middle Eocene	IAA 2/95	64°13'58"S; 56°39'06"W	NRM	NRM-PZ P.16055	Engelbrecht et al. (2016)

Continued Appendix

Taxon		Formation	Allomember/ unit	Sadler (1988)	Age	Type locality	Coordinates	Collection	Holotype	Reference
Class	Species									
Chondrichthyes	<i>Anomotodon multidenticulata</i>	La Meseta	<i>Cucullaea</i> I	TELM 5	Early–Middle Eocene	RV-8266	no data	UCR	UCR 21177	Long (1992a)
Chondrichthyes	<i>Notorampnoscyllium woodwardi</i>	La Meseta	<i>Cucullaea</i> I	TELM 5	Early–Middle Eocene	IAA 1/90	64°14'04.67"S; 53°39'56.38"W	NRM	NRM-PZ P.16015	Engelbrecht et al. (2017a)
Chondrichthyes	<i>Coelometalouia pannucea</i>	La Meseta	<i>Cucullaea</i> I	TELM 5	Early–Middle Eocene	IAA 2/95	64°13'58"S; 56°39'06"W	NRM	NRM-PZ P.16046	Engelbrecht et al. (2017b)
Chondrichthyes	<i>Abdounia mesetae</i>	La Meseta	<i>Cucullaea</i> I	TELM 5	Early–Middle Eocene	IAA 1/95	64°14'28.55"S; 56°40'18.9"W	NRM	NRM-PZ P.15808	Engelbrecht et al. (2017b)
Chondrichthyes	<i>Abdounia richteri</i>	La Meseta	<i>Cucullaea</i> I	TELM 5	Early–Middle Eocene	IAA 1/90	64°14'04.67"S; 53°39'56.38"W	NRM	NRM-PZ P.16209	Engelbrecht et al. (2017b)
Chondrichthyes	<i>Kallodontis rhytistemma</i>	La Meseta	<i>Cucullaea</i> I	TELM 5	Early–Middle Eocene	IAA 1/90	64°14'04.67"S; 53°39'56.38"W	NRM	NRM-PZ P.16143	Engelbrecht et al. (2017b)
Chondrichthyes	<i>Meridiogaleus cristatus</i>	La Meseta	<i>Cucullaea</i> I	TELM 5	Early–Middle Eocene	IAA 1/90	64°14'04.67"S; 53°39'56.38"W	NRM	NRM-PZ P.16243	Engelbrecht et al. (2017b)
Chondrichthyes	<i>Raja manitaria</i>	La Meseta	<i>Cucullaea</i> I	TELM 5	Early–Middle Eocene	IAA 2/95	64°13'58"S; 56°39'06"W	NRM	NRM-PZ P.16271	Engelbrecht et al. (2018)
Chondrichthyes	<i>Raja amphitrita</i>	La Meseta	Submeseta I	TELM 6	Middle Eocene	IAA 1/93	64°13'51.8"S; 56°35'53.14"W	NRM	NRM-PZ P.16264	Engelbrecht et al. (2018)
Chondrichthyes	<i>Marambitoraja leiostemma</i>	La Meseta	<i>Cucullaea</i> I	TELM 5	Early–Middle Eocene	IAA 2/95	64°13'58"S; 56°39'06"W	NRM	NRM-PZ P.16257	Engelbrecht et al. (2018)
Chondrichthyes	<i>Mesetataraja maleficapelli</i>	La Meseta	<i>Cucullaea</i> I	TELM 5	Early–Middle Eocene	IAA 2/95	64°13'58"S; 56°39'06"W	NRM	NRM-PZ P.16250	Engelbrecht et al. (2018)
Mosasauria	<i>Kaikaifilu hervei</i>	López de Bertodano	Unit 9	KLB 9	Late Maastrichtian	IAA 10/13	64°15'54.23"S; 56°42'28.03"W	SGO	SGO.PV.6509	Otero et al. (2017)
Plesiosauria	<i>Mortumerta seymourensis</i>	López de Bertodano	Unit 9	KLB 9	Late Maastrichtian	IAA 10/13	64°15'54.23"S; 56°42'28.03"W	TTU	TTU	Chatterjee and Small (1989)
Aves	<i>Anthropornis nordenskjoeldi</i>	Submeseta	Submeseta II	TELM 7	Late Eocene	Loc. 11 (DPV 13/84)	64°14'47.37"S; 56°36'11.68"W	NRM	NRM A.45	Wiman (1905)
Aves	<i>Anthropornis grandis</i>	Submeseta	Submeseta II	TELM 7	Late Eocene	Loc. 11 (DPV 13/84)	64°14'47.37"S; 56°36'11.68"W	NRM	NRM	Wiman (1905)
Aves	<i>Palaeudyptes gunnari</i>	Submeseta	Submeseta II	TELM 7	Late Eocene	Loc. 11 (DPV 13/84)	64°14'47.37"S; 56°36'11.68"W	NRM	NRM A.7	Wiman (1905)
Aves	<i>Palaeudyptes klekowskii</i>	Submeseta	Submeseta II	TELM 7	Late Eocene	ZPAL 4	64°14' 22.85"S; 56°38'46.9"W	ZPAL	IB/P/B-0065	Myrcha et al. (2002)

Taxon		Species	Formation	Allomember/ unit	Sadler (1988)	Age	Type locality	Coordinates	Collection	Holotype	Reference
Class											
Aves	<i>Ichthyopteryx</i>	<i>gracilis</i>	Submeseta	Submeseta II	TELM 7	Late Eocene	Loc. 11 (DPV 13/84)	64°14'47.37"S; 56°36'11.68"W	NRM	NRM A.20	Wiman (1905)
Aves	<i>Archaeospheniscus</i>	<i>wimani</i>	Submeseta	Submeseta II	TELM 7	Late Eocene	Unknown	no data	BM	BM A.3331	Marples (1953)
Aves	<i>Delphinornis</i>	<i>larseni</i>	Submeseta	Submeseta II	TELM 7	Late Eocene	Loc. 11 (DPV 13/84)	64°14'47.37"S; 56°36'11.68"W	NRM	NRM A.21	Wiman (1905)
Aves	<i>Delphinornis</i>	<i>gracilis</i>	Submeseta	Submeseta II	TELM 7	Late Eocene	ZPAL 4	64°14' 22.85"S; 56°38'46.9"W	ZPAL	IB/P/B-0279a	Myrcha et al. (1990)
Aves	<i>Delphinornis</i>	<i>arctowskii</i>	Submeseta	Submeseta II	TELM 7	Late Eocene	ZPAL 4	64°14' 22.85"S; 56°38'46.9"W	ZPAL	IB/P/B-0484	Myrcha et al. (1990)
Aves	<i>Mesetaornis</i>	<i>polaris</i>	Submeseta	Submeseta II	TELM 7	Late Eocene	ZPAL 4	64°14' 22.85"S; 56°38'46.9"W	ZPAL	IB/P/B-0278	Myrcha et al. (1990)
Aves	<i>Marambiornis</i>	<i>exilis</i>	Submeseta	Submeseta II	TELM 7	Late Eocene	ZPAL 4	64°14' 22.85"S; 56°38'46.9"W	ZPAL	IB/P/B-0490	Myrcha et al. (1990)
Aves	<i>Tonniornis</i>	<i>mesetaensis</i>	Submeseta	Submeseta II	TELM 7	Late Eocene	DPV 10/84	64°14' 22.85"S; 56°38'46.9"W	MLP	MLP 93-X-1-145	Tambussi et al. (2006)
Aves	<i>Tonniornis</i>	<i>minimum</i>	Submeseta	Submeseta II	TELM 7	Late Eocene	DPV 10/84	64°14' 22.85"S; 56°38'46.9"W	MLP	MLP 93-I-6-3	Tambussi et al. (2006)
Aves	<i>Crossvallia</i>	<i>unienwillia</i>	Cross Valley	Cross Valley C		Late Paleocene	IAA 2/04	64°15'50"S; 56°40'0"W	MLP	MLP 00-I-10-1	Tambussi et al. (2005)
Aves	<i>Apros dokitos</i>	<i>mikrotero</i>	Submeseta	Submeseta III	TELM 7	Late Eocene	DPV 16/84	64°13'30.50"S; 56°38'44.57"W	MLP	MLP 00-I-1-19	Acosta Hospitaleche et al. (2017)
Aves	<i>Notoleptos</i>	<i>giglii</i>	Submeseta	Submeseta II	TELM 7	Late Eocene	DPV 16/84	64°13'30.50"S; 56°38'44.57"W	MLP	MLP 12-I-20-305	Acosta Hospitaleche and Gelfo (2016)
Aves	<i>Conflicto</i>	<i>antarcticus</i>	López de Bertodano	Unit 10	KLB 10	Early Paleocene	IAA 3/06	64°18'3.6"S; 56°44'19.2"W	MLP	MLP 07-III-1-1	Tambussi et al. (2019)
Aves	<i>Polarornis</i>	<i>gregorii</i>	López de Bertodano	Unit 9	KLB 9	Late Maastrichtian	IAA 10/13	64°15'54.23S; 56°42'28,03"W	TTU	TTU P9265	Chatterjee (2006)
Aves	<i>Antarctoboenus</i>	<i>carlinii</i>	La Meseta	<i>Cucullaea</i> I	TELM 5	Early–Middle Eocene	IAA 2/95	64°13'58"S; 56°39'06"W	MLP	MLP 95-I-10-8	Cenizo et al. (2016)
Mammalia	<i>Llanocetus</i>	<i>denticrenatus</i>	Submeseta	Submeseta II	TELM 7	Late Eocene	Loc. 11 (DPV 13/84)	64°14'47.37"S; 56°36'11.68"W	USNM	USNM 183022	Mitchell (1989)
Mammalia	<i>Derorhynchus</i>	<i>minutus</i>	La Meseta	<i>Cucullaea</i> I	TELM 5	Early–Middle Eocene	IAA 1/90	64°14'04.67"S; 53°39'56.38"W	MLP	MLP 96-I-5-44	Goin et al. (1999)

Taxon		Continued Appendix								
Class	Species	Formation	Allomember/ unit	Sadler (1988)	Age	Type locality	Coordinates	Collection	Holotype	Reference
Mammalia	<i>Pauladelphys juanjoi</i>	La Meseta	<i>Cucullaea</i> I	TELM 5	Early–Middle Eocene	IAA 1/90	64°14'04.67"S; 53°39'56.38"W	MLP	MLP 96-I-5-45	Goin et al. (1999)
Mammalia	<i>Xenostylos peninsularis</i>	La Meseta	<i>Cucullaea</i> I	TELM 5	Early–Middle Eocene	IAA 1/90	64°14'04.67"S; 53°39'56.38"W	MLP	MLP 94-III-15-10	Goin et al. (1999)
Mammalia	<i>Perrodelyphys coquinense</i>	La Meseta	<i>Cucullaea</i> I	TELM 5	Early–Middle Eocene	IAA 1/90	64°14'04.67"S; 53°39'56.38"W	MLP	MLP 96-I-5-11	Goin et al. (1999)
Mammalia	<i>Marambiotherium glaciaris</i>	La Meseta	<i>Cucullaea</i> I	TELM 5	Early–Middle Eocene	IAA 1/90	64°14'04.67"S; 53°39'56.38"W	MLP	MLP 95-I-10-1	Goin et al. (1999)
Mammalia	<i>Woodburnodon casei</i>	La Meseta	<i>Cucullaea</i> I	TELM 5	Early–Middle Eocene	IAA 1/95	64°14'28.55"S; 56°40'18.9"W	MLP	MLP 04-III-1-2	Goin et al. (2007)
Mammalia	<i>Antarctodolops dailyi</i>	La Meseta	<i>Cucullaea</i> I	TELM 5	Early–Middle Eocene	RV-8200 (DPV 6/84)	64°14'21.78"S; 56°39'44.84W	UCR	UCR 20910	Woodburne and Zinsmeister (1984)
Mammalia	<i>Antarctodolops mesetaense</i>	La Meseta	<i>Cucullaea</i> I	TELM 5	Early–Middle Eocene	RV-8200 (DPV 6/84)	64°14'21.78"S; 56°39'44.84W	MLP	MLP 96-I-5-12	Chornogubsky et al. (2009)
Mammalia	<i>Eurydolops seymourensis</i>	La Meseta	<i>Cucullaea</i> I	TELM 5	Early–Middle Eocene	RV-8200 (DPV 6/84)	64°14'21.78"S; 56°39'44.84W	UCR	UCR 22355	Case et al. (1988)
Mammalia	<i>Pujatodon ektopos</i>	La Meseta	<i>Cucullaea</i> I	TELM 5	Early–Middle Eocene	IAA 1/90	64°14'04.67"S; 53°39'56.38"W	MLP	MLP 14-I-10-20	Goin et al. (2018)
Mammalia	<i>Meridiolestida</i> gen et sp. nov	La Meseta	<i>Cucullaea</i> I	TELM 5	Early–Middle Eocene	IAA 1/90	64°14'04.67"S; 53°39'56.38"W	MLP	MLP 91-II-4-3	Martinelli et al. (2014)
Mammalia	<i>Notiolofo arquiniotensis</i>	Submeseta	Submeseta II	TELM 7	Late Eocene	DPV 16/84	64°13'30.50"S; 56°38'44.57"W	MLP	MLP 95-I-10-6	Bond et al. (2006)
Mammalia	<i>Notiolofo requeroi</i>	La Meseta	<i>Cucullaea</i> I	TELM 4	Early–Middle Eocene	IAA 2/16	64°13'56.89"S; 56°39'60"W	MLP	IAA-PV 173	Gelfo et al. (2017)
Mammalia	<i>Antarctodon sobrali</i>	La Meseta	<i>Cucullaea</i> I	TELM 4	Early–Middle Eocene	DPV 2/84	64°13'53.58"S; 56°39'13.74"W	MLP	MLP 08-XI-30-1	Bond et al. (2011)

Appendix Table 2 Vertebrate Paleontological Geoheritage: Taxonomic list, stratigraphy, geographic locations and references for fossil vertebrates from the Early Maastrichtian Snow Hill Island (SHIF), Late Maastrichtian/Danian López de Bertodano (LBF), and Paleocene Sobral (SF) and Cross Valley (CVF) formations of Seymour Island, Antarctic Peninsula

Taxon	Stratigraphy	Reference
ELAMOSBRANCHII		
Lamniformes indet.	SF	Cione et al. (2018)
ODONTASPIDIDAE		
Odontaspidae indet.	LBF–Unit 9	Otero et al. (2014)
<i>Odontaspis</i> sp.	LBF–Unit 9	Martin and Crame (2006)
cf. <i>Odontaspis</i>	LBF–Unit 9	Martin and Crame (2006)
<i>Carcharias</i> sp.	LBF–Unit 9	Cione et al. (2018)
SQUALIDAE		
<i>Centrophoroides</i> sp.	LBF–Unit 9	Otero et al. (2014)
<i>Protosqualus</i> sp.	LBF–Unit 9	Cione et al. (2018)
PRISTIOPHORIDAE		
<i>Pristiophorus</i> sp.		Otero et al. (2014)
aff. <i>Propristiophorus</i> sp.	LBF–Unit 9	Cione et al. (2018)
CHLAMYDOSELACHIDAE		
<i>Chlamydoselachus tatere</i>	LBF–Unit 9	Otero et al. (2014)
OTODONTIDAE		
<i>Cretalamna</i> sp.	LBF – Unit 9	Otero et al. (2014)
<i>Cretalamna appendiculata</i>	LBF–Units 9/10	Cione et al. (2018)
HEXANCHIDAE		
<i>Notidanodon dentatus</i>	LBF–Unit 9	Martin and Crame (2006)
ORTHACODONTIDAE		
<i>Paraorthacodus</i> sp.	LBF–Unit 9	Cione et al. (2018)
<i>Sphenodus</i> sp.	LBF–Unit 9	Grande and Eastman (1986)
SELACHII indet.		
" <i>Ptychodus</i> "	LBF–Units 8/9	Woodward (1908)
HOLOCEPHALI		
CALLORHYNCHIDAE		
<i>Ischyodus dolloi</i>	LBF–Unit 9	Stahl and Chatterjee (2002)
<i>Callorhynchus torresi</i>	LBF–Unit 9	Otero et al. (2013)
<i>Callorhynchus</i> sp.	LBF–Unit 9	Martin and Crame (2006)
CHIMAERIDAE		
Gen. et sp. indet.	LBF–Unit 9	Stahl and Chatterjee (1999)
RHINOCHIMAERIDAE		
Rhinochimaeridae indet.	LBF–Unit 9	Otero et al. (2014)
ACTINOPTERYGII		
Ichthyodectiformes indet.	LBF–Unit 9	Cione et al. (2018)
PACHYCORMIDAE		
Pachycormidae indet.	LBF–Unit 9	Cione et al. (2018)

Continued Appendix

Taxon	Stratigraphy	Reference
BERYCIFORMES		
<i>Antarctiberyx seymouri</i>	LBF–Unit 9	Grande and Chatterjee (1987)
AULOPIFORMES		
ENCHODONTIDAE		
cf. <i>Enchodus</i>	LBF–Unit 9	Martin and Crame (2006)
PLESIOSAURIA		
ELASMOSAURIDAE		
Elasmosauridae indet.	LBF–Unit 9	del Valle et al. (1977)
<i>Mortimeria seymourensis</i>	LBF–Unit 9	Chatterjee and Small (1989)
cf. <i>Mauisaurus</i> sp.	LBF–Unit 9	Fostowicz and Gazdzicki (2001)
<i>Aristonectes parvidens</i>	LBF–Unit 9	Gasparini et al. (2003)
cf. <i>Aristonectes</i> sp.	LBF–Unit 9	O’Gorman et al. (2019)
MOSASAURIA		
MOSASAURIDAE		
Mosasauria gen. et sp. indet.	LBF–Unit 9	Gasparini and del Valle (1981)
<i>Kaikaifilu hervei</i>	LBF–Unit 9	Otero et al. (2017)
cf. <i>Moanasaurus</i>	LBF–Unit 9	Martin (2006)
<i>Mosasaurus</i> sp.	LBF–Unit 9	Martin and Crame (2006)
aff. <i>M. hoffmanni</i>	LBF–Unit 9	Martin (2006)
<i>Plioplatecarpus</i> sp.	LBF–Unit 9	Martin and Crame (2006)
cf. <i>Plioplatecarpus</i> sp.	LBF–Unit 9	Martin and Crame (2006)
<i>Leiodon</i> sp.	LBF–Unit 9	Martin and Crame (2006)
cf. <i>Hainosaurus</i> sp.	LBF–Unit 9	Martin et al. (2002)
Tylosaurinae indet.	SHIF	Martin and Crame (2006)
DINOSAURIA		
HADROSAURIDAE		
?Hadrosauridae indet.	LBF–Unit 9	Rich et al. (1999)
AVES		
SPHENISCIFORMES		
<i>Crossvallia unenwillia</i>	CVF	Tambussi et al. (2005)
ANSERIFORMES		
INCERTAE FAMILIAE		
<i>Conflictus antarcticus</i>	LBF–Unit 10	Tambussi et al. (2019)
GAVIIDAE		
<i>Neogaeornis</i> sp.	LBF–Unit 9	Chatterjee (1989)
<i>Polarornis gregorii?</i>	LBF–Unit 9	Reguero et al. (2013)

Appendix Table 3 Vertebrate Paleontological Geoheritage: taxonomic list, stratigraphy, and references for the fossil vertebrates content from the Late Eocene Submeseta Formation (SMF) of Seymour Island, Antarctic Peninsula

Taxon	Stratigraphy	Reference
ELAMOSBRANCHII		
HEXANCHIDAE		
<i>Heptanchias howelli</i>	<i>Cucullaea</i> I	Long (1992a)
<i>Hexanchus</i> sp.	<i>Cucullaea</i> I	Cione and Reguero (1994)
SQUALIDAE		
<i>Squalus woodburnei</i>	<i>Cucullaea</i> I	Long (1992a)
<i>Squalus weltoni</i>	<i>Cucullaea</i> I	Long (1992a)
<i>Centrophorus</i> sp.	<i>Cucullaea</i> I	Long (1992a)
<i>Dalatias licha</i>	<i>Cucullaea</i> I	Long (1992a)
<i>Deania</i> sp.	<i>Cucullaea</i> I	Long (1992a)
SQUATINIDAE		
<i>Squatina</i> sp.	<i>Cucullaea</i> I	Welton and Zinsmeister (1980)
PRISTIOPHORIDAE		
<i>Pristiophorus lanceolatus</i>	<i>Cucullaea</i> I	Long (1992a)
GINGLYMOSTOMATIDAE		
<i>Pseudoginglymostoma</i> cf. <i>P. brevicaudatum</i>	<i>Cucullaea</i> I	Long (1992a)
STEGOSTOMASTIDAE		
<i>Stegostoma</i> cf. <i>S. fasciatum</i>	<i>Cucullaea</i> I	Long (1992a)
ODONTASPIDIDAE		
<i>Odontaspis rutoti</i>	<i>Cucullaea</i> I	Long (1992a)
<i>Odontaspis winkleri</i>	<i>Cucullaea</i> I	Long (1992a)
<i>Carcharias macrotia</i>	<i>Cucullaea</i> I	Cione et al. (1977)
<i>Brachycarcharias lerichei</i>	<i>Cucullaea</i> I	Marrama et al. (2018)
CETORHINIDAE		
<i>Cetorhinus</i> sp.	<i>Cucullaea</i> I	Cione et al. (1998)
LAMNIDAE		
<i>Isurus praecursor</i>	<i>Cucullaea</i> I	Cione and Reguero (1994)
<i>Lamna</i> cf. <i>L. nasus</i>	<i>Cucullaea</i> I	Long (1992a)
<i>Carcharocles auriculatus</i>	<i>Cucullaea</i> I	Welton and Zinsmeister (1980)
PRISTIDAE		
<i>Pristis</i> sp.	<i>Cucullaea</i> I	Kriwet (2005)
MITSUKURINIDAE		
<i>Anomotodon multidenticulata</i>	<i>Cucullaea</i> I	Long (1992a)
CARCHARHINIDAE		
<i>Abdounia mesetae</i>	<i>Cucullaea</i> I	Engelbrecht et al. (2017)
<i>Abdounia richteri</i>	<i>Cucullaea</i> I	Engelbrecht et al. (2017)
<i>Scoliodon</i> sp.	<i>Cucullaea</i> I	Long (1992a)
<i>Galeorhinus</i> sp.	<i>Cucullaea</i> I	Engelbrecht et al. (2017)
HEMISCYLLIIDAE		
<i>Notorampnoscyllium woodwardi</i>	<i>Cucullaea</i> I	Engelbrecht et al. (2016)
ORECTOLOBIDAE		
<i>Oelometlaouia pannucea</i>	<i>Cucullaea</i> I	Engelbrecht et al. (2016)
TRIAKIDAE		
<i>Mustelus</i> sp.	<i>Cucullaea</i> I	Engelbrecht et al. (2017)

Continued Appendix

Taxon	Stratigraphy	Reference
<i>Meridiogaleus cristatus</i>	<i>Cucullaea</i> I	Engelbrecht et al. (2017)
<i>Kallodontis rhytistemma</i>	<i>Cucullaea</i> I	Engelbrecht et al. (2017)
DALATIIDAE		
<i>Eodalatias australis</i>	<i>Cucullaea</i> I	Engelbrecht et al. (2017)
MYLIOBATIDAE		
<i>Myliobatis</i> sp.	<i>Cucullaea</i> I	Cione et al. (1977)
<i>Myliobatiformes</i> gen. indet.	<i>Cucullaea</i> I	Engelbrecht et al. (2018)
RAJIDAE		
<i>Raja amphitrita</i>	<i>Cucullaea</i> I	Engelbrecht et al. (2018)
<i>Raja manitaria</i>	<i>Cucullaea</i> I	Engelbrecht et al. (2018)
<i>Marambioraja leiostemma</i>	<i>Cucullaea</i> I	Engelbrecht et al. (2018)
<i>Mesetaraja maleficapelli</i>	<i>Cucullaea</i> I	Engelbrecht et al. (2018)
MOBULIDAE		
gen. et sp. indet.	<i>Cucullaea</i> I	Bogan et al. (2016)
HOLOCEPHALI		
CALLORHYNCHIDAE		
<i>Ischyodus dolloi</i>	<i>Cucullaea</i> I	Grande & Eastman (1986)
CHIMAERIDAE		
<i>Chimaera seymouriensis</i>	<i>Cucullaea</i> I	Ward & Grande (1991)
OSTEICHTHYES		
PERCIFORMES		
CEPOLIDAE		
<i>Cepola anderssoni</i>	<i>Cucullaea</i> I	Schwarzahns et al. (2017)
ARGENTINIFORMES		
ARGENTINIDAE		
<i>Argentina antarctica</i>	<i>Cucullaea</i> I	Schwarzahns et al. (2017)
AULOPIFORMES		
PARAULOPIDAE		
<i>Paraulopus</i> sp.	<i>Cucullaea</i> I	Schwarzahns et al. (2017)
MYCTOPHIFORMES		
MYCTOPHIDAE		
<i>Diaphus? marambionis</i>	<i>Cucullaea</i> I	Schwarzahns et al. (2017)
GADIFORMES		
MORIDAE		
<i>Tripterophycis immutatus</i>	<i>Cucullaea</i> I	Schwarzahns et al. (2017)
MERLUCCIDAE		
<i>Macruronus eastmani</i>	<i>Cucullaea</i> I	Schwarzahns et al. (2017)
<i>"Mesetaichthys"</i>	<i>Cucullaea</i> I	Jerzemska & Swidnicki (1992)
GADIDAE		
<i>Palimphemus seymourensis</i>	<i>Cucullaea</i> I	Schwarzahns et al. (2017)
MACROURIDAE		
<i>Coelorinchus balushkini</i>	<i>Cucullaea</i> I	Schwarzahns et al. (2017)
<i>Coelorinchus nordenskjöldi</i>	<i>Cucullaea</i> I	Schwarzahns et al. (2017)
<i>Coelorinchus</i> sp.	<i>Cucullaea</i> I	Schwarzahns et al. (2017)

Continued Appendix

Taxon	Stratigraphy	Reference
OPHIDIIFORMES		
OPHIDIIDAE		
<i>Hoplobrotula? antipoda</i>	<i>Cucullaea</i> I	Schwarzahns et al. (2017)
CLUPEIFORMES		
CLUPEIDAE		
<i>Marambionella andreae</i>	Acantilados	Jerzmanska (1991)
OPLEGNATHIDAE		
<i>Oplegnathus</i> sp.	<i>Cucullaea</i> I	Cione et al. (1994)
XIPHIORHYNCHIDAE		
cf. <i>Xiphiorhynchus</i>	Acantilados	Cione et al. (2001)
TRICHIURIDAE		
<i>Trichiurus</i> sp.	<i>Cucullaea</i> I	Long (1991)
LABRIDAE		
gen. et sp. indet.	<i>Cucullaea</i> I	Long (1992b)
SILURIFORMES		
INCERTAE SEDIS		
Siluriformes indet.	<i>Cucullaea</i> I?	Grande and Eastman (1986)
BERYCIFORMES		
BERYCIDAE		
<i>Centroberyx</i> sp.	<i>Cucullaea</i> I	Schwarzahns et al. (2017)
Gen. et sp. indet..	Acantilados II	Doktor et al. (1996)
TRACHICHTHYIDAE		
<i>Notoberyx cionei</i>	<i>Cucullaea</i> I	Schwarzahns et al. (2017)
INDETERMINATE ACANTHOPTERYGII		
Acanthopterygii indet.	<i>Cucullaea</i> I	Schwarzahns et al. (2017)
Haemulidae? indet.	<i>Cucullaea</i> I	Schwarzahns et al. (2017)
Percoidei indet.	<i>Cucullaea</i> I	Schwarzahns et al. (2017)
Sparidae? indet.	<i>Cucullaea</i> I	Schwarzahns et al. (2017)
REPTILIA		
CRYPTODIRA		
DERMOCHELYIDAE		
<i>"Psephophorus" sp.</i>	<i>Cucullaea</i> I	de la Fuente et al. (1995)
TESTUDINES		
Testudines indet.	<i>Cucullaea</i> I	Bona et al. (2010)
AVES		
SPHENISCIFORMES		
<i>Anthropornis nordensjoeldi</i>	<i>Cucullaea</i> I, Campamento	Reguero et al. (2013)
<i>Anthropornis grandis</i>	<i>Cucullaea</i> I, Campamento	Reguero et al. (2013)
<i>Palaeudyptes klekowskii</i>	<i>Cucullaea</i> I	Reguero et al. (2013)
<i>Palaeudyptes gunnarii</i>	<i>Cucullaea</i> I, Acantilados II	Reguero et al. (2013)
<i>Delphinornis larsenii</i>	<i>Cucullaea</i> I	Reguero et al. (2013)
<i>Mesetaornis polaris</i>	<i>Cucullaea</i> I	Reguero et al. (2013)
<i>Marambiornis exilis</i>	<i>Cucullaea</i> I	Reguero et al. (2013)
<i>Archaeospheniscus wimani</i>	<i>Cucullaea</i> I	Reguero et al. (2013)

Continued Appendix

Taxon	Stratigraphy	Reference
ODONTOPTERYGIFORMES		
PELAGORNITHIDAE		
Pelagornithidae indet. morphotype 1	<i>Cucullaea</i> I	Cenizo et al. (2015)
PROCELLARIFORMES		
DIOMEDEIDAE		
?Diomedidae indet.	<i>Cucullaea</i> I	Acosta Hospitaleche and Gelfo (2016)
?Procellariidae indet.	<i>Cucullaea</i> I	Acosta Hospitaleche and Gelfo (2016)
GAVIIFORMES		
Gaviiformes indet.	<i>Cucullaea</i> I	Acosta Hospitaleche and Gelfo (2015)
cf. <i>Gaviiformes</i>	<i>Cucullaea</i> I	Acosta Hospitaleche and Gelfo (2015)
FALCONIFORMES		
INCERTAE SEDIS		
<i>Antarctoboenus carlinii</i>	<i>Cucullaea</i> I	Cenizo et al. (2016)
MAMMALIA		
MARSUPIALIA		
POLYDOLOPIDAE		
<i>Polydolops dailyi</i>	<i>Cucullaea</i> I	Woodburne and Zinsmeister (1982)
<i>Polydolops seymouriensis</i>	<i>Cucullaea</i> I	Case et al. (1988)
FAMILY INDET.		
<i>Pujatodon ektopos</i>	<i>Cucullaea</i> I	Goin et al. (2018)
MICROBIOTHERIIDAE		
Gen. et sp. indet.	<i>Cucullaea</i> I	Goin and Carlini (1995)
<i>Marambiotherium glacialis</i>	<i>Cucullaea</i> I	Goin et al. (1999)
<i>Woodburnodon casei</i>	<i>Cucullaea</i> I	Goin et al. (2007)
DERORHYNCHIDAE		
<i>Derorhynchus minutus</i>	<i>Cucullaea</i> I	Goin et al. (1999)
<i>Pauladelphys juanjoi</i>	<i>Cucullaea</i> I	Goin et al. (1999)
<i>Xenostylus peninsularis</i>	<i>Cucullaea</i> I	Goin et al. (1999)
Gen. et sp. indet.	<i>Cucullaea</i> I	Goin et al. (1999)
PREPIDOLOPIDAE		
<i>Perrodelys coquinense</i>	<i>Cucullaea</i> I	Goin et al. (1999)
MERIDIOLESTIDA		
cf. <i>Brandonia</i>	<i>Cucullaea</i> I	Martinelli et al. (2014)
GONDWANATHERIA		
SUDAMERICIDAE		
<i>Sudamerica?</i> sp.	<i>Cucullaea</i> I	Goin et al. (2006)
XENARTHRA		
Tardigrada indet.	<i>Cucullaea</i> I	Carlini et al. (1990)
LITOPTERNA		
SPARNOTHERIODONTIDAE		
<i>Notiolofo arquiniensis</i>	<i>Cucullaea</i> I, Campamento	Bond et al. (2006)
<i>Notiolofo regueroi</i>	<i>Cucullaea</i> I	Gelfo et al. (2017)
<i>Notiolofo</i> cf. <i>N. arquiniensis</i>	Acantilados II	Gelfo et al. (2014)
Sparnotheriodontidae indet.	Campamento	Marensi et al. (2002)

Continued Appendix		
Taxon	Stratigraphy	Reference
ASTRAPOTHERIA		
TRIGONOSTYLOPIDAE		
<i>Trigonostylops</i> sp.	<i>Cucullaea</i> I	Hooker (1992)
ASTRAPOTHERIIDAE		
<i>Antarctodon sobrali</i>	<i>Cucullaea</i> I	Bond et al. (2011)
MAMMALIA INCERTAE SAEDIS		
gen. et sp. indet.	Acantilados II	Vizcaíno et al. (1997)
<i>Eutheria incertae sedis</i>	Acantilados II	Gelfo et al. (2014)
CETACEA		
BASILOSAURIDAE		
gen. et sp. indet.	<i>Cucullaea</i> I	Buono et al. (2016)

Appendix Table 4 Vertebrate Paleontological Geoheritage: taxonomic list, stratigraphy, and references for the fossil vertebrates content from the Late Eocene Submeseta Formation (SMF) of Seymour Island, Antarctic Peninsula

Taxon	Stratigraphy	Reference
ELASMOBRANCHII		
SQUALIDAE		
<i>Squalus</i> sp.	Submeseta III	Kriwet et al. (2016)
<i>Squalus woodburnei</i>	Submeseta I	Engelbrecht et al. (2017)
<i>Squalus weltoni</i>	Submeseta I	Engelbrecht et al. (2017)
SQUATINIDAE		
<i>Squatina</i> sp.	Submeseta I, III	Kriwet et al. (2016)
PRISTIOPHORIDAE		
<i>Pristiophorus lanceolatus</i>	Submeseta III	Kriwet et al. (2016)
ODONTASPIDIDAE		
<i>Striatolamia</i> sp. cf. <i>S. macrotia</i>	Submeseta III	Kriwet et al. (2016)
<i>Palaeohypotodus</i> sp. cf. <i>P. rutoti</i>	Submeseta III	Kriwet et al. (2016)
<i>Carcharocles sokolovi</i>	Submeseta III	Kriwet et al. (2016)
TRIAKIDAE		
<i>Mustelus</i> sp.	Submeseta I	Engelbrecht et al. (2017)
HOLOCEPHALI		
CALLORHYNCHIDAE		
<i>Ischyodus dolloi</i>	Submeseta III	Kriwet et al. (2016)
AVES		
RATITAE		
gen. et sp. indet.	Submeseta II	Tambussi et al. (1994)
?Phorusrhacidae		
gen. et sp. indet.	Submeseta II	Case et al. (1987)
SPHENISCIFORMES		
<i>Anthropornis nordensjoeldi</i>	Submeseta I, II, III	Wiman (1905a)
<i>Anthropornis grandis</i>	Submeseta II, III	Wiman (1905a)
<i>Palaeedyptes klekowskii</i>	Submeseta II	Myrcha et al. (1990)
<i>Palaeedyptes gunnarii</i>	Submeseta II	Wiman (1905a)
<i>Palaeedyptes antarcticus</i>	Submeseta II	Wiman (1905a)

Continued Appendix

Taxon	Stratigraphy	Reference
<i>Delphinornis larsenii</i>	Submeseta II	Wiman (1905a)
<i>Delphinornis arctowskii</i>	Submeseta II	Myrcha et al. (2002)
<i>Delphinornis gracilis</i>	Submeseta II	Wiman (1905a)
<i>Mesetaornis polaris</i>	Submeseta II	Myrcha et al. (2002)
<i>Marambiornis exilis</i>	Submeseta II	Myrcha et al. (2002)
<i>Archaeospheniscus lopdelli</i>	Submeseta II	Myrcha et al. (2002)
<i>Archaeospheniscus wimani</i>	Submeseta II	Marples (1953)
<i>Tonniornis mesetaensis</i>	Submeseta II	Tambussi et al. (2006)
<i>Tonniornis minimum</i>	Submeseta II	Tambussi et al. (2006)
<i>Aprosdokitos mikrotero</i>	Submeseta II	Acosta Hospitaleche (2018)
ODONTOPTERYGIFORMES		
PELAGORNITHIDAE		
gen. et sp. Indet.	Submeseta II	Cenizo et al. (2015)
Pelagornithidae indet. morphotype 1	Submeseta III	Cenizo et al. (2015)
PROCELLARIFORMES		
DIOMEDEIDAE		
<i>Notoleptos giglii</i>	Submeseta III	Acosta Hospitaleche and Gelfo (2016)
MAMMALIA		
LITOPTERNA		
SPARNOTHERIODONTIDAE		
<i>Notiolofo arquiotianus</i>	Submeseta II	Bond et al. (2006)
CETACEA		
ARCHAEOCETI		
BASILOSAURIDAE		
<i>Zeuglodon</i> sp.	Submeseta II	Wiman (1905a)
<i>Zygorhiza</i> sp.	Submeseta II	Cozzuol (1988)
MYSTICETI		
CRENATICETI		
<i>Llanocetus denticrenatus</i>	Submeseta III	Mitchell (1989)
<i>Llanocetus</i> sp.	Submeseta II	Buono et al. (2016)
?Basilosauridae gen. et sp. indet.	Submeseta II	Buono et al. (2016)