THE STRATIGRAPHY OF CRETACEOUS MUDSTONES IN THE EASTERN FUEGIAN ANDES: NEW DATA FROM BODY AND TRACE FOSSILS

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ABSTRACT

The stratigraphy of Cretaceous marine mudstones in the Fuegian Andes, roughly equivalent to Charles Darwin's clay-slate formation, remains a still unsolved problem. Previous records of Albian, Turonian-Coniacian, and Santonian-Campanian bivalves are combined with new findings of the Late Albian inoceramid *Inoceramus anglicus* Woods, and the Maastrichtian ammonites *Diplomoceras* sp., *Anagaudryceras* sp., *Maorites densicostatus* (Kilian and Reboul), *Maorites* sp., and *Pachydiscus* (*Neodesmoceras*) sp. to further constrain the Cretaceous stratigraphy of the eastern Fuegian Andes. In addition, new records of distinctive trace fossils and ichnofabric are meaningful for stratigraphic division and delineation of paleoenvironmental settings in these Cretaceous mudstones. The Lower Cretaceous ichnoassemblage of *Chondrites targioni* (Brongniart) and *Zoophycos* isp. is consistent with the inferred slope-volcaniclastic apron settings of the Yahgan Formation; *Nereites missouriensis* (Weller) reflects distal basin plain depositional settings for the Beauvoir Formation. In the Upper Cretaceous, the "Estratos de Buen Suceso" record the earliest extensively bioturbated horizons, reflecting prolonged well-oxygenated bottom conditions. In the Bahía Thetis Formation, organic-rich, channel margin or distal basin slaty mudstones record the last occurrence of inoceramid bivalves in the Austral Basin; the generalized absence of trace fossils is consistent with dysoxic bottom conditions. The thoroughly bioturbated Policarpo Formation, records a marked change in paleoceanographic conditions. The strong contrast in the intensity of bioturbation between the Upper Campanian-Maastrichtian Bahía Thetis Formation, almost devoid of trace fossils, and the highly bioturbated Maastrichtian-Danian Policarpo Formation reflects a change from dysoxic-anoxic to well ventilated conditions, probably associated with a cooling trend of bottom waters in the austral deep oceans.

Keywords: *Clay-slate formation, Inoceramid, Ammonites, Cretaceous, Trace fossils, Fuegian Andes.*

RESUMEN: *Estratigrafía de las fangolitas del Cretácico en los Andes Fueguinos orientales: Nuevos datos de cuerpos y trazas fósiles.* En los Andes Fueguinos la estratigrafía de las fangolitas del Cretácico marino (*clay-slate formation* de Charles Darwin), constituye un problema no enteramente resuelto. Datos previos de bivalvos del Albiano, Turoniano-Coniaciano, y Santoniano-Campaniano, junto con nuevos hallazgos de inoceramidos del Albiano tardío, *Inoceramus anglicus* Woods, y amonites maastrichianos, *Diplomoceras* sp., *Anagaudryceras* sp., *Maorites densicostatus* (Kilian y Reboul), *Maorites* sp., y *Pachydiscus* (*Neodesmoceras*) sp. se utilizan para obtener una mejor resolución estratigráfica. Además, nuevas asociaciones distintivas de trazas fósiles permiten ajustar la interpretación paleoambiental. La asociación de *Chondrites targioni* (Brongniart) y *Zoophycos* isp. del Cretácico inferior es consistente con el modelo inferido de rampa volcaniclástica para la Formación Yahgan. En la Formación Beauvoir la presencia de *Nereites missouriensis* (Weller) refleja condiciones de depositación en planicies distales de la cuenca. En el Cretácico superior, los "Estratos de Buen Suceso" registran los primeros horizontes bioturbados asociados a fondos con prolongados periodos de condiciones de buena oxigenación. En la Formación Bahía Thetis, fangolitas pizarreñas ricas en materia orgánica depositadas en márgenes de canales o en planicies distales, registran la última aparición de bivalvos inocerámidos en la Cuenca Austral. La ausencia generalizada de trazas fósiles es consistente con condiciones de fondos anóxicos. La Formación Policarpo, densamente bioturbada, marca un profundo cambio en las condiciones paleoceanográficas. El fuerte contraste en la intensidad de la bioturbación entre las Formaciones Bahia Thetis, Campaniano-Maastrichtiano, con escasa presencia de trazas fósiles y Policarpo, Maastrichiano-Daniano, altamente bioturbada, refleja el cambio de condiciones de fondo disóxico-anóxico a óxico, probablemente asociado al comienzo del enfriamiento de las aguas profundas del océano austral.

Palabras clave: *Clay-slate formation, Inoceramidos, Amonites, Trazas fósiles, Cretácico, Andes Fueguinos.*

INTRODUCTION

The stratigraphic division of Cretaceous marine mudstones in the Fuegian Andes (Fig. 1) is a major and still unsolved problem. These mudstones correspond roughly to the clay-slate formation of Charles Darwin (1846); a very extensive formation of folded, low-grade metamorphic rocks with scarce marine fossils. In the course of the voyage of HMS Beagle Darwin noted that "*The great clay-slate formation of Tierra del Fuego being Cretaceous, is certainly a very interesting fact,--whether we consider the appearance of the country, which, without the evidence afforded by the fossils, would form the analogy of most known districts, probably have been considered as belonging to the Palaeozoic series,…*"(Darwin 1846, p. 152).

The evidence mentioned by Darwin included a few fossils from Mount Tarn, on the western side of the Strait of Magellan, Brunswick Peninsula in Chile (Fig. 2d), particularly the ammonites described by Forbes (in Darwin 1846) as "*Ancyloceras simplex*" d'Orbigny, from Mount Tarn (Fig. 2f), and "*Hamites elatior*" Sowerby, from the coastal area nearby Port Famine. We now know that these fossils are not Albian hamitids; the "*A. simplex*" is a Maastrichtian kossmaticeratid, probably a deformed fragment of *Maorites*, and "*H. elatior*" is a *Diplomoceras*, also of Maastrichtian age (Spath 1953, Lahsen and Charrier 1972). However, the correction in the age of these ammonite-bearing strata does not change the fact that in the Fuegian Andes, Albian to Maastrichtian fine-grained rocks have quite similar lithological and structural features and consequently they are very difficult to distinguish in the field (Fig. 2).

In this study, previous records of Albian, Turonian-Coniacian, and Santonian-Campanian bivalves, mostly inoceramids (Olivero and Martinioni 1996a, Olivero and Medina 2001) are combined with new findings of latest Albian inoceramids and Maastrichtian ammonites to further constrain the Cretaceous stratigraphy of the eastern Fuegian Andes. In addition, new records of characteristic trace fossil assemblages with distinctive ichnofabrics, restricted to particular sedimentary successions of the Yahgan Formation, Beauvoir Formation, Bahía Thetis Formation, Policarpo Formation, and "Estratos de Buen Suceso", constitute meaningful data for the stratigraphic division of the relatively homogeneous, mudstone-rich Cretaceous deposits.

STRATIGRAPHIC FRAMEWORK

The stratigraphy of southernmost South America has been controlled since the Mesozoic by a series of contrasting tectonic regimes, represented by Late Jurassic-Early Cretaceous extension, Late Cretaceous-Paleogene compression, and latest Paleogene-Neogene and present day strike-parallel transcurrent motion (Katz 1972, Dalziel *et al.* 1974, Suárez *et al.*1985, Kohn *et al.* 1995, To-rres Carbonell *et al.* 2008). Accordingly, Cretaceous rocks in the Fuegian Andes are distributed in three tectonostratigraphic domains: 1) the magmatic arc, located along the axis of the southern archipelago, includes Lower Cretaceous andesitic (Hardy Formation) and Upper Cretaceous plutonic rocks (Beagle Channel Plutonic Group); 2) the Rocas Verdes Marginal Basin includes Lower Cretaceous, low-grade metamorphic rocks, mostly slates and sandstones of the Yahgan and Beauvoir formations, and Upper Jurassic-Lower Cretaceous ophiolitic rocks; and 3) the Austral and Malvinas foreland basins, separated in the northern area by the Dungeness or Rio Chico Arch, include Upper Cretaceous rocks dominated by slaty mudstones (Fig. 1).

According to a recent review (see Olivero and Malumián 2008, and the bibliography cited therein), the Yahgan Formation represents a volcaniclastic apron of mudstones and deep-marine andesite-rich turbidites and the Beauvoir Formation records basin plain and slope mudstones. Both formations reflect Late Jurassic-Early Cretaceous extension and the consequent origination of the Rocas Verdes Marginal Basin. The earliest Late Cretaceous ductile deformation, isoclinal folding, and low-grade regional metamorphism of these rocks indicate a compressional tectonic regime that resulted in the closure of the marginal basin. The Fuegian Andes were uplifted by the Late Campanian; subsequent propagation of the compressional deformation and subsidence by tectonic loading along the northern orogenic margin resulted in the formation of the Austral and Malvinas foreland basins. The Turonian-Lower Campanian "Estratos de Buen Suceso" represent the final stages of the closure of the marginal basin and/or the beginning of the foreland basins. Conglomerate beds in the Bahía Thetis Formation bear foliated clasts of Andean-derived rocks and thus they record uplifting and subaerial erosion of the Fuegian Andes. The youngest Cretaceous rocks are included in the Policarpo Formation, which includes the Maastrichtian/Danian boundary at its top (Olivero *et al.* 2003).

Figure 3 summarizes the paleontological information, including partly new body and trace fossil data, used in this study to differentiate particular horizons within these lithologically homogeneous stratigraphic units. The stratigraphic implications of these data are described for each formation in the next section.

LOWER CRETACEOUS

On the main island of Tierra del Fuego, Darwin (1846) recorded only Cenozoic fossils in the vicinity of Cape San Sebastian, including *Nothofagus* leaves and mollusks. The first fossils from the region, which are now accepted as uppermost Jurassic or Cretaceous in age, were recorded in 1839 near Nassau Bay (Navarino Island) by James Dwight Dana, a geologist of Charles Wilkes` United States Exploring Expedition (cf. Andersson 1906, Kranck 1932). The first Cretaceous fossils from the main island of Tierra del Fuego were found in 1882 nearby Ushuaia by Lovisato. They include trace

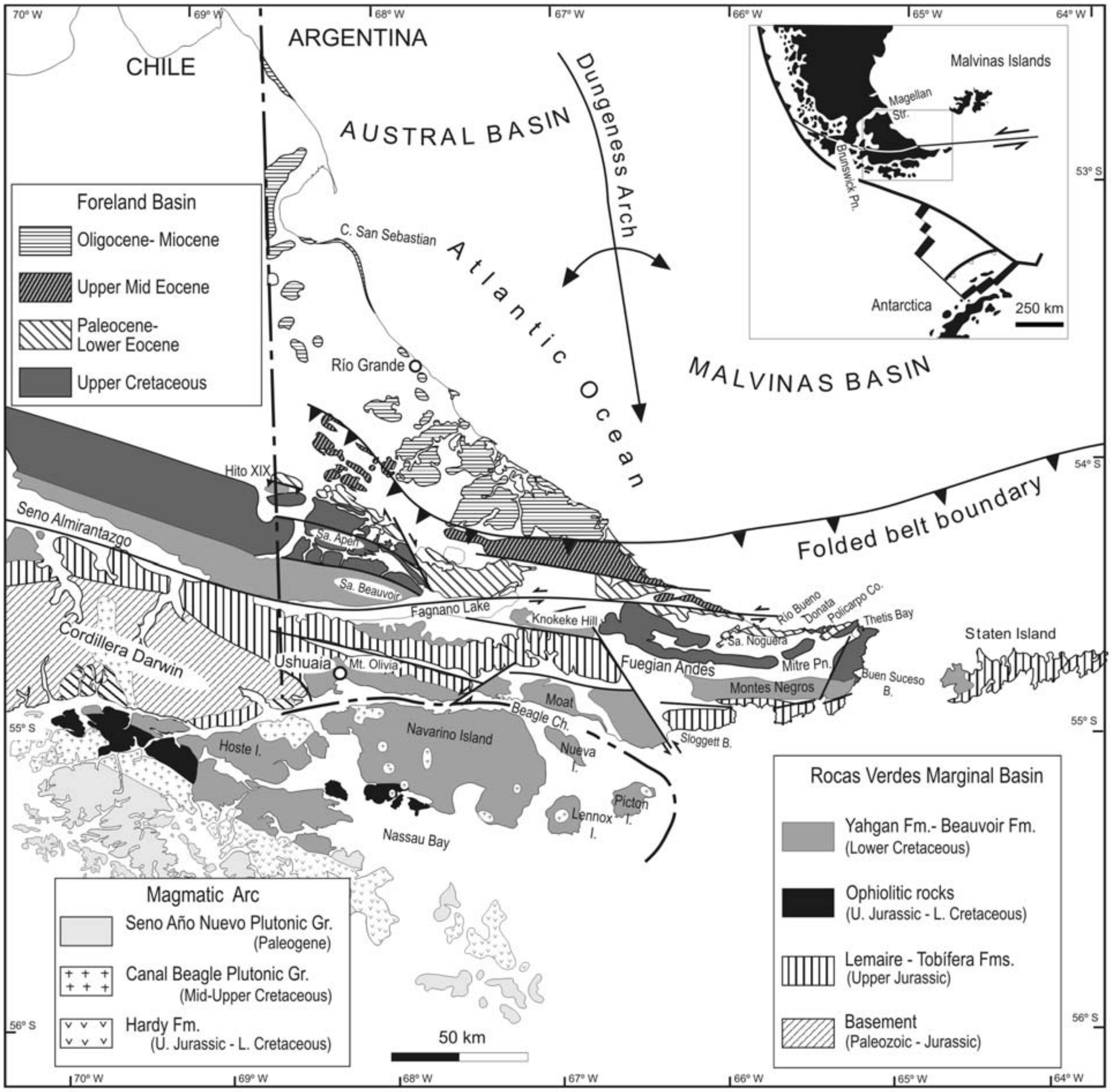

Figure 1: Locality map, tectonic settings, and distribution of Lower and Upper Cretaceous rocks in the Rocas Verdes Marginal basin and Austral/Malvinas Foreland basins.

fossils (and calcareous algae?) described by Richter (1925), together with Cretaceous radiolaria from the Staten and New Year islands (also collected by Lovisato) and several fossils, including belemnites from the Hito XIX area, collected by the Expedition of University of Buenos Aires to Tierra del Fuego (Doello Jurado 1922).

Yahgan Formation

The Yahgan Formation was established by Kranck (1932) for the slates, slaty mudstones, and andesite-rich greywackes exposed in Mount Olivia and Ushuaia. The Formation is well exposed along the northern margin of the Beagle Channel, from Ushuaia to Bahía Sloggett (Fig. 1); and in Hoste, Navarino, Nueva, Lennox, and Picton islands (Katz and Watters 1966, Dott *et al.* 1977, Winn 1978, Suárez *et al.* 1985). Dominant sedimentary facies are: a) black mudstones, fine-grained, thin-bedded turbidites (Fig. 2a) and tuff; b) classical turbidites; and c) massive to graded sandstones. Petrographic composition of the sandstones is uniform and dominated by lithic andesitic fragments and plagioclase, suggesting derivation from the volcanic arc, located to the South in the Fuegian Archipelago (Winn 1978, Suárez *et al.* 1985, Olivero and Martinioni 1996b). This is well documented with paleocurrent data on the island of South Georgia, now displaced along the North Scotia Ridge to the east (Dalziel *et al.* 1974, Macdonald 1986).

Body and trace fossils are very scarce in the Yahgan Formation (Fig. 3). On Navarino Island Tithonian-Neocomian ammonites and belemnites (Aguirre-Urreta

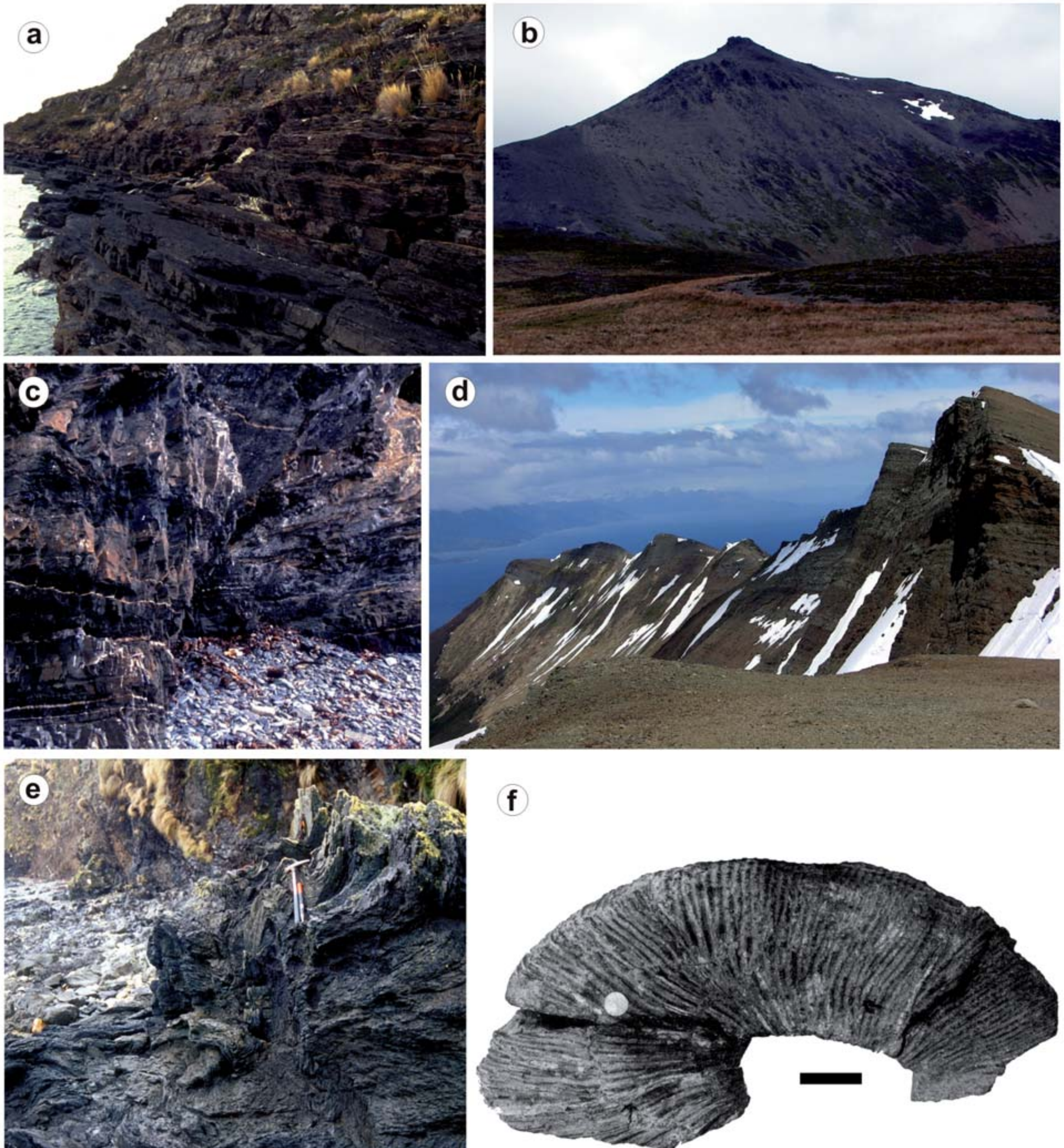

Figure 2: Structure, lithology, and paleontology of Cretaceous rocks. a) Thin-bedded turbidites, Yahgan Formation, Lower Cretaceous, Beagle Channel close to Ushuaia. b) Black mudstones, Beauvoir Formation, Lower Cretaceous (Albian), Knokeke Hill area. c) Black mudstones and interbedded light-gray tuffs, Estratos de Buen Suceso, Upper Cretaceous (Santonian-Lower Campanian). d) Upper Cretaceous (Maastrichtian) interbedded siltstones and fine-grained sandstones, Mount Tarn, Brunswick Peninsula, Chile. e) Highly folded, black mudstones and fine-grained sandstones, Bahía Thetis Formation, Thetis Bay. f) Crushed ?*Maorites* sp. from Mount Tarn. This is the original specimen, housed at the Natural History Museum, London (B.M. No. 2612), collected by Darwin and described by Forbes as "*Ancyloceras simplex*" d´Orbigny. Scale bar: 1 cm.

and Suárez 1985); Aptian-Albian corals, gastropods, and bivalves (Dott *et al.* 1977); and indeterminate inoceramids (Katz and Watters 1966) were reported. Microfossils, particularly radiolaria, are apparently common, but not well preserved due to the strong tectonic deformation of the rocks (Kranck 1932, Olivero and Martinioni 1996b). The trace fossil *Chondrites targioni* (Brongniart) and the presumed fossil calcareous algae "*Lithocaulon antarcticum*" Bornemann were described by Richter (1925) from the vicinity of Ushuaia. Biostratigraphically diagnostic Late Albian fossils are known from Moat, where *Actinoceramus concentricus* (Parkinson) and *Inoceramus carsoni* Mc Coy were recorded (Olivero and Martinioni

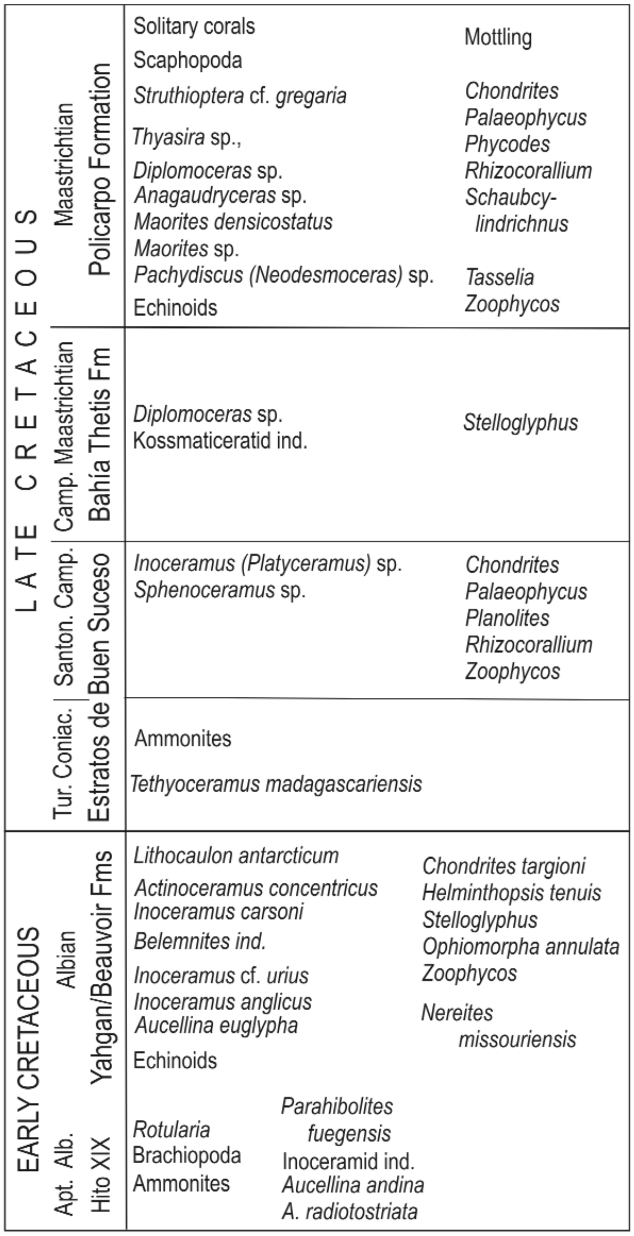

Figure 3: Stratigraphic distribution of characteristic body and trace fossils in the Cretaceous of the Fuegian Andes (explanation in the text).

1996a). Fine-grained turbidites and mudstones nearby Ushuaia and adjoining Mount Martial bear scarce and ill-preserved belemnites.

Trace fossils are rare and restricted to a few horizons; *Chondrites targioni* (Fig. 4b) and *Zoophycos* isp. are the most common trace fossils and are locally abundant in particular beds. A few localities, e.g. on the coast of the Beagle Channel just east from Ushuaia, bear a more diversified ichnoassemblage, including *Chondrites targioni*, *Helminthopsis tenuis*, *Stelloglyphus* isp., *Ophiomorpha* cf. *annulata*, and *Zoophycos* isp. (Fig. 3). A similar trace fossil assemblage, with the addition of *Phycosiphon incertum*, was recorded in the Yahgan Formation by Winn (1978).

Beauvoir Formation

The Beauvoir Formation (Camacho 1967) consists predominantly of homogeneous black or bluish, massive to faintly laminated dark slates and gray tuffs mainly exposed in Sierra de Beauvoir, in the belt stretching from the eastern part of Lake Fagnano to the Montes Negros, just west of Good Success (Buen Suceso) Bay (Figs. 1 and 2b). Locally, the black slates are rhythmically interbedded with thin, fine-grained sandstones. Stratification is only visible in the latter beds, whereas in the massive slates the bedding is defined only by the presence of thin tuff beds. The fossiliferous marlstones cropping out near Hito XIX in the Argentinean-Chilean border are provisionally included in the Beauvoir Formation. These marlstones contain abundant specimens of the Aptian-Albian bivalves *Aucellina* "*radiotostriata*" Bonarelli, A. "*andina*" Feruglio (Macellari 1979), and *A. striata* Richter (Richter 1925). Additional fossils include serpulids, brachiopods, inoceramids, probably *Inoceramus anglicus* Woods or *I. sutherlandi* MacCoy (cf. Medina 2007) and abundant rostra of the belemnite *Parahibolites fuegensis* (Stolley) in interbedded sandstone beds (Richter 1925) and large, poorly preserved ammonites.

The massive, dark slates of the Beauvoir Formation near Knokeke Hill and Buen Suceso Bay contain several horizons with abundant but ill-preserved inoceramids, which normally are concentrated in very thin beds. Part of this material includes the Albian *Mytiloides* cf. *ipuanus* (Wellman), of which the nominal species "*Inoceramus*" *urius* Wellman and "*I. kapuus*" Wellman are now considered as synonyms (see Crampton 2004). Associated, very thin beds include abundant well-preserved, articulate shells of the Late Albian *Aucellina euglypha* Woods (Fig. 5b) covered by a thin pyrite coating (Olivero and Medina 2001). Rare, complete but badly deformed echinoids are associated with the latter bivalves. Near the locality of Knokeke Hill, black slates record relatively well preserved and articulated shells of *Inoceramus anglicus* (Fig. 5a) and delicate back-filled burrows of *Nereites missouriensis* (Weller) (Fig. 4a).

In the subsurface, the stratigraphically equivalent mudstone-dominated rocks of the Nueva Argentina Formation and Arroyo Alfa Formation contain Early-Mid Albian and Late Albian foraminiferal assemblages, respectively (Flores *et al.* 1973).

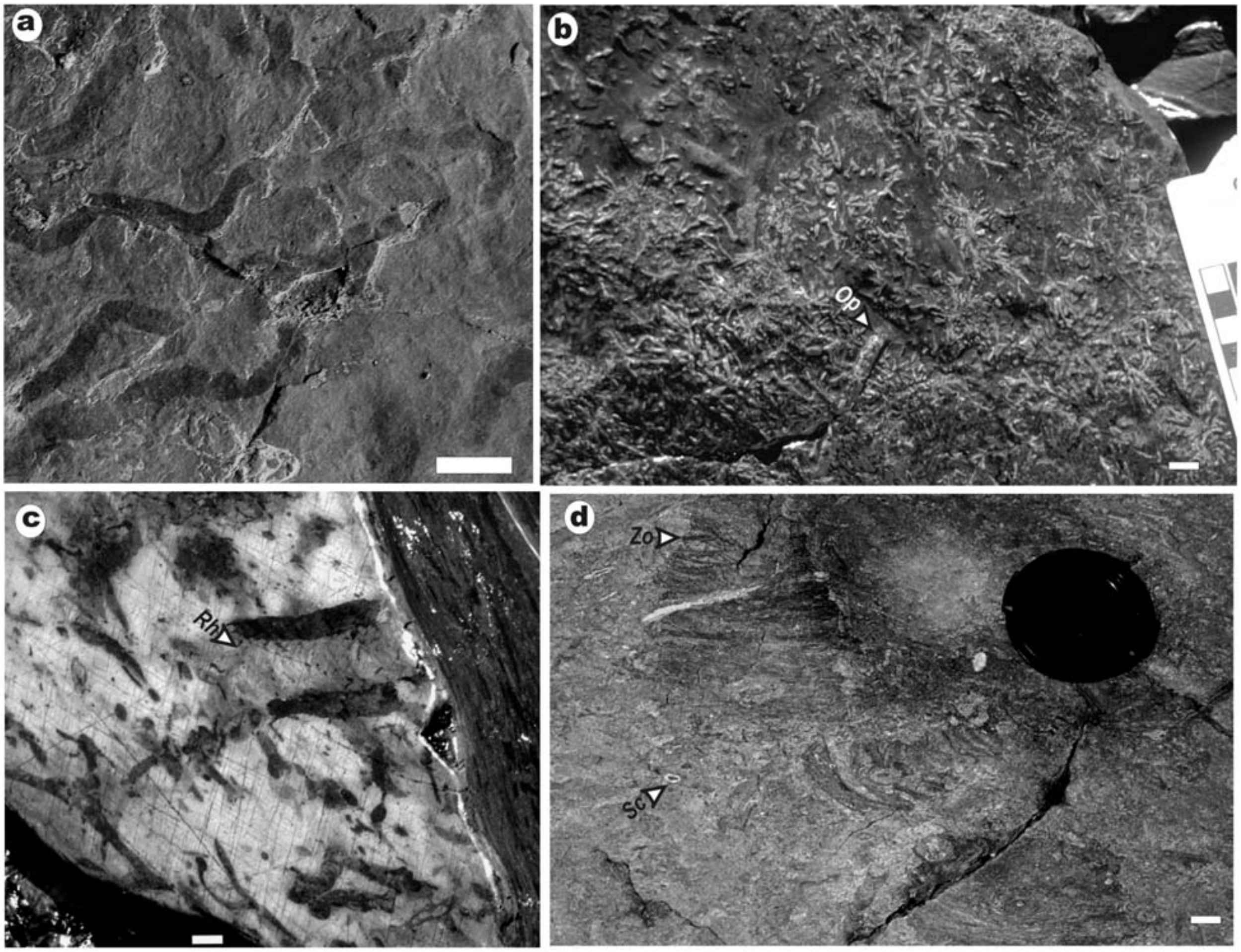

Figure 4: Typical trace fossils and ichnofabrics of Cretaceous rocks in the Fuegian Andes. a) *Nereites missouriensis* (Weller) from Albian beds of the Beauvoir Formation near Knokeke Hill, CADIC PI 88. b) Dense ichnofabric of *Chondrites targioni* (Brongniart) and associated *Ophiomorpha* cf. *annulata* (Op), Lower Cretaceous Yahgan Formation, Beagle Channel near Ushuaia, field specimens. c) Localized horizons with a relatively dense ichnofabric in mudstones and isolated specimens of *Rhizocorallium* isp. (Rh), Estratos de Buen Suceso, Santonian-Lower Campanian, Buen Suceso Bay, field specimens. d) Typical ichnofabric affecting thick packages in the Maastrichtian Policarpo Formation, *Zoophycos* isp. (Zo) and *Schaubcylindrichnus* ("*Terebellina*") isp. (Sc) are the only recognizable structures in the intensely mottled background, field specimens. Scale bar: 1 cm.

UPPER CRETACEOUS

"Estratos de Buen Suceso"

These beds include a thick sedimentary succession of folded dark gray and black, slaty mudstones, marlstones, and sandy siltstones with common quartz veins. The lower part of the succession, exposed in the southern part of the bay, is dominated by marlstones, impure limestones, and fine-grained silty sandstones. The slaty micritic limestones and marly mudstone record well-preserved, articulated shells of *Tethyoceramus madagascariensis* (Heinz). This species has been referred to the Middle Coniacian in Madagascar and New Zealand, and to the Upper Turonian-Lower Coniacian in Antarctica (cf. Olivero and Medina 2001). The exact age and identity of inoceramids assigned to "*Inoceramus*" (=*Tethyoceramus*) *madagascariensis* is now debated. Walaszczyk *et.al* (2004) argue that the New Zealand material is not true "*I.*" *madagascariensis* and should be referred to "*I.*" *nukeus* Wellman. However, Crampton (writ. comm. 2008) believes that some New Zealand material is indistinguishable from topotype *T. madagascariensis* (e.g., compare Crampton 1996 pl. 16M and pl. 17E, with Walaszczyk *et al.* 2004, Fig. 13B and fig. 14E, respectively). The Tierra del Fuego material is indistinguishable from the Antarctic specimens, and appears to differ from "*I.*"? *nukeus*, which is almost equivalve and much less inflated than *T. madagascariensis.*

The upper part of the succession, exposed along the northern margin of the bay, is dominated by dark slaty mudstones and silty sandstones, with some interbedded light gray, thin tuff beds (Fig. 2c). The slaty mudstones contain occasional, large specimens (up to 50 cm high) of complete shells of *Inoceramus* (*Platyceramus*) sp. and relatively small, well-preserved specimens of *Sphenoceramus* sp. The association described by Olivero and Medina (2001) was referred to the Santonian-Lower Campanian.

The silty sandstones within the Santonian-Lower Campanian beds record se-

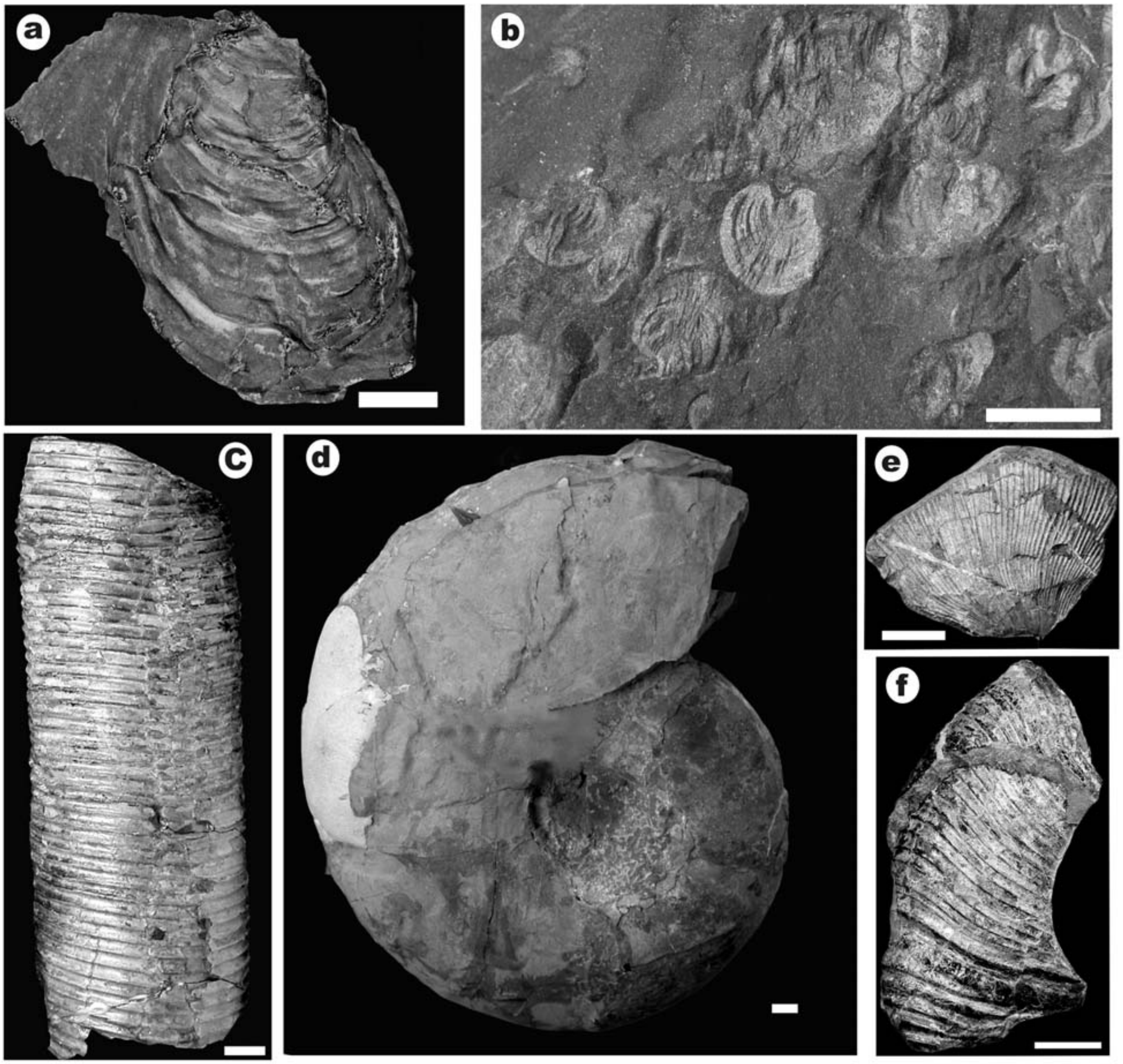

Figure 5: Cretaceous ammonites and bivalves from the Fuegian Andes. a) *Inoceramus anglicus* Woods, Upper Albian, Beauvoir Formation, right valve, CADIC PI 87; b) Black mudstones with pyritized shells of *Aucellina euglypha* Woods, Upper Albian, Beauvoir Formation, CADIC PI6 a; c) Fragment of the body chamber of *Diplomoceras* sp., Maastrichtian, Policarpo Formation, CADIC PI 85; d) *Pachydiscus* (*Neodesmoceras*) sp., Maastrichtian, Policarpo Formation, CADIC PI 84; e) and f) Fragments of the body chamber of crushed *Maorites* spp., Maastrichtian, Policarpo Formation; e) *Maorites densicostatus* (Kilian and Reboul) CADIC PI 86; f) *Maorites* sp. CADIC PI 89. Scale bar: 1 cm.

veral fully bioturbated horizons. The trace fossils *Chondrites, Palaeophycus, Planolites*, *Rhizocorallium* (Fig. 4c), and *Zoophycos* are recognized within a heavily bioturbated background.

Bahía Thetis Formation

The dominant slaty mudstones and sandstones cropping out in the Thetis Bay area were first recognized by Furque and Camacho (1949). Olivero *et.al* (2003) studied the Bahía Thetis Formation and recognized three packages, more than 250 m thick, of hard, highly deformed rocks including: 1) dark, organic-rich, laminated mudstones and tuffs with incipient cleavage; 2) resedimented conglomerates and pebbly mudstones; and 3) turbidite sandstones and slaty mudstones.

The lowest organic-rich package bears abundant radiolaria and more restricted foraminifera. The latter comprise a low diversity, agglutinated assemblage typical of dysoxic environments and are characterized by *Rzehakina epigona* (Rzehak), *R. lata* Cushman and Jarvis and *R. fissistomata* (Grzybowski) (Caramés and Malumián 2006). In the second package, the conglomerates include large clasts of radiolarian-bearing slates and foliated rhyolites, derived from the Beauvoir-Yahgan Formations and Jurassic volcanics, respectively. In the third package, the turbidites (Fig. 2e) bear scarce, ill-preserved ammonites, including flattened fragments of

Diplomoceras sp. and kossmaticeratids. Trace fossils are very rare, and only a few specimens of *Stelloglyphus* were recovered. The absence of trace fossils is consistent with the high organic matter content and the preservation of delicate sedimentary banding in the slaty mudstones. Based on the recorded foraminifera and ammonites the Bahía Thetis Formation was assigned to the Late Campanian-?Early Maastrichtian (Olivero *et al.* 2003, Caramés and Malumián 2006).

Policarpo Formation

The Policarpo Formation is very well exposed along the Atlantic shore of Península Mitre, between Policarpo Cove and San Vicente Cape (Furque and Camacho 1949, Olivero *et al.* 2002, 2003). The extensive, but less well-exposed rocks forming the NW belt of strata in the Sierra de Noguera and Sierra de Apen are also included in the Policarpo Formation (Fig. 1).

In the type area of Península Mitre the Policarpo Formation includes a minimum thickness of 350 m, and probably more than 700 m, of bioturbated, tuffaceous, monotonous organic-rich, dark gray, very hard sandy mudstones and silty sandstones. Fresh-pyroclastic material is relatively abundant, and some fine-grained tuffaceous sandstones are almost exclusively composed of zoned, euhedral plagioclase crystals and volcanic glass.

Most part of the Policarpo Formation consists of a crude alternation of tuffaceous mudstones and silty sandstones but the stratification is not always apparent due to the intense bioturbation. Totally bioturbated thick packages occur repeatedly, and they are commonly characterized by a high abundance of sandy, agglutinated tubes of *Schaubcylindrichnus* (previously assigned to "*Terebellina*"). In addition to a dense background mottling, the trace fossils *Tasselia, Rhizocorallium, Phycodes, Teichichnus* and small *Chondrites* are occasionally recorded (Fig. 4d). Some horizons bear a dense concentration of large *Zoophycos* burrows.

Relatively abundant invertebrate body fossils are common in certain concretionary horizons, but they are very difficult to recover due to the extreme hardness of the rocks. Irregular echinoids are very common near the faulted contact with the Bahía Thetis Formation near Cabo San Vicente. Solitary corals, scaphopods, gastropods, bivalves, and ammonites are less abundant. One horizon at the contact with the Río Bueno Formation near Puesto Río Bueno, bears relatively well-preserved specimens of *Diplomoceras* sp., *Anagaudryceras* sp., *Maorites densicostatus* (Kilian and Reboul), *Maorites* sp. and large *Pachydiscus* (*Neodesmoceras*) sp. (Fig. 5c-f). Near Puesto Donata, very well-preserved specimens of the gastropod *Stru-thioptera* cf. *gregaria* Wilckens were recovered.

The foraminifera are dominated by agglutinated cosmopolitan forms that include the oldest record in the Austral Basin of *Spiroplectammina spectabilis* (Olivero *et al.* 2002, 2003, Olivero and Malumián 2008). Dinocysts are scarce and not well-preserved, but two assemblages of Maastrichtian and Danian age were tentatively recognized (Olivero *et al.* 2003).

CONCLUDING REMARKS

The first fossils to be discovered in the clay-slate formation were Cretaceous crinoids, gastropods, bivalves, and ammonites found by Darwin in 1834 on Mount Tarn (Darwin 1846). This discovery was followed soon by new records of Cretaceous invertebrates, notably among these were the findings of additional fossil mollusks in Mount Tarn by Hombron and Grange in 1837; belemnites in Nassau Bay by Dana in 1839; and bivalves and ammonites in 1887-1890 in the islands of Saint Peter and Saint Paul, Magellan Channel, reported by White (see Andersson 1906, Bonarelli 1917, Kranck 1932). Despite these discoveries of Cretaceous fossils in the clay-slate formation in distant localities, stretching more than 500 km between Navarino Island and Brunswick Peninsula south of Punta Arenas on the Strait of Magellan, a strong feeling of a Paleozoic age for most of the clay-slate formation still grew. This was based mainly on comparisons of the regional features of the low-grade metamorphic rocks with similar features in Paleozoic orogenic belts, particularly the basement in the British Isles and in Alpine areas, which at that time was thought to be of Paleozoic age (see Kranck 1932), and on the age interpretations of the dubious fossils found by Lovisato in 1881 in Staten Island (see Harrington 1943). However, the presumed Cambrian quartzites and schists from Staten Island turned out to be Jurassic acidic tuffs and volcaniclastic, foliated rocks, and the dubious Paleozoic fossils were probably part of the fibrous structure of Cretaceous inoceramid shells (Richter 1925) or belemnite rostra (Harrington 1943).

As has been confirmed by additional fossil discoveries in the clay-slate formation of the main island of Tierra del Fuego, including the first locality visited by Darwin on the island (Good Success Bay), we now know that all these rocks are of Cretaceous age (Olivero and Martinioni 1996a, Olivero and Medina 2001).

The relatively homogeneous lithology is a major obstacle to stratigraphic subdivision; nonetheless, particular combinations of fossil content, ichnofabric, and lithological features make it possible to recognize characteristic sedimentary successions in the Lower and Upper Cretaceous rocks.

In the Lower Cretaceous, only Aptian-Albian fossils have been recovered; however, the Yahgan Formation has thick horizons with massive sandstones and sandy turbidites, a lithological association that is not found in the homogenous, black slaty mudstones and tuffs of the Beauvoir Formation. The Yahgan Formation also has localized horizons dominated by the trace fossils *Chondrites* (Fig. 4b) and *Zoophycos*, an ichnoassemblage that is consistent with the inferred setting of a low-oxygenated slope (cf. Uchman 2007) in a volcaniclastic apron environment (Olivero and Martinioni

1996b, Olivero and Malumián 2008). The black, fine-grained rocks of the Beauvoir Formation contain localized horizons with *Nereites missouriensis* (Fig. 4a). This ichnofossil is a typical component of the *Nereites* ichnosubfacies, which is distributed in distal flysch facies and characterized by the dominance of deposit-feeding invertebrates, such as the tracemaker of *Nereites* (*cf.* Seilacher 1974, Uchman 2007). Accordingly, these fine-grained deposits probably reflect distal basin plain settings, occupying an intermediate position between the Pacific volcaniclastic apron of the Yahgan Formation and the typical, South-American cratonic slope settings of the Lower Cretaceous rocks in the Austral Basin (Wilson 1991). In the Upper Cretaceous, four distinctive successions are recognized: 1) the lower part (Turonian-Coniacian) of the "Estratos de Buen Suceso", 2) the upper part (Santonian-Lower Campanian) of the "Estratos de Buen Suceso"; 3) the Upper Campanian-?Lower Maastrichtian Bahía Thetis Formation; and 4) the Maastrichtian-Danian Policarpo Formation (Olivero and Medina 2001, Olivero *et al.* 2002, 2003, Olivero and Malumián 2008).

The lower part of the "Estratos de Buen Suceso" is characterized by marlstones, impure limestones, and fine-grained silty sandstones with *T. madagascariensis*, whereas the upper part is characterized by dark slaty mudstones, tuffs, and silty sandstones. The latter beds appear to record the earliest successions with extensively bioturbated horizons in the basin, probably reflecting for the first time prolonged periods with well-oxygenated bottom conditions (Fig. 4c). These beds alternate with those showing evidence for more oxygen-deficient bottom conditions, lacking trace fossils and populated locally by *Inoceramus* (*Platyceramus*) sp. and *Spheno-ceramus* sp. (Olivero and Medina 2001).

The resedimented conglomerates, pebbly mudstones, and sandy turbidites of the Bahía Thetis Formation record a very distinctive petrographic composition, with clear evidence that the source of clastic material was uplifted Andean rocks, including foliated, Jurassic acidic volcanics and radiolarian-rich Cretaceous slates. These coarse-grained clastic rocks probably reflect deposition in submarine fans, with a source area in the hinterland part of the growing Fuegian Andes. The associated dark, organic-rich slaty mudstones (Fig. 2e) are thought to have originated in channel margin or more distant basin settings. The foraminiferal content and the generalized absence of trace fossils are consistent with the interpreted dysoxic bottom conditions (Olivero *et al.* 2003, Caramés and Malumián 2006). The Bahía Thetis Formation probably records the last occurrence of inoceramid bivalves in the Austral Basin (Olivero *et al.* 2003, 2004).

The Maastrichtian-Danian Policarpo Formation records a marked, regional change of paleoceanographic conditions in the basin as is evidenced by the thoroughly bioturbated ichnofabric that characterizes thick sedimentary packages. This change in the ichnofabric occurs in the Maastrichtian Policarpo Formation just above the inoceramid extinction level in the Fuegian Andes. The inoceramids were apparently adapted to warm and poorly oxygenated waters and their global extinction pulses, during the mid-Maastrichtian, were related to cooling and enhanced bottom ventilation, promoted by circulation of deep Antarctic waters (MacLeod *et al.* 1996). The strong contrast in the intensity of bioturbation between the Upper Campanian-Lower Maastrichtian Bahía Thetis Formation, almost devoid of trace fossils, and the highly bioturbated Maastrichtian-Danian Policarpo Formation reflects a change from dysoxic-anoxic to well ventilated bottom conditions, probably associated with a cooling trend of bottom waters in the austral deep oceans (Olivero *et al.* 2003, 2004). In addition, the Policarpo Formation also records a distinctive petrographic composition, which is dominated by fresh volcaniclastic material implying a coeval volcanic pulse in the magmatic arc.

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