



Review paper

Sedimentary cycles, ammonite diversity and palaeoenvironmental changes in the Upper Cretaceous Marambio Group, Antarctica

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ABSTRACT

Cretaceous sedimentary rocks of the James Ross Basin offer a unique Austral record of the transition from mild mid-Turonian–early Campanian to relatively cold Maastrichtian palaeoclimatic conditions. After deposition of deep-marine Lower to Upper Cretaceous sediments and tectonic inversion of the basin, the Upper Cretaceous–Danian Marambio Group reflects the development of a shelf extended for more than 100 km into the Weddell Sea. The expansion of the shelf area was punctuated by three major transgressive–regressive cycles: the N (Santonian–early Campanian); NG (late Campanian–early Maastrichtian); and MG (early Maastrichtian–Danian) sequences. Faunal groups sensitive to changing water-mass conditions, such as ammonites and inoceramids, exhibit unusual patterns of diversity changes and/or early extinctions. In the N Sequence ammonite generic richness is minimum in the Santonian, then it increases gradually to an early Campanian maximum and decreases in the latest early Campanian. This pattern is typical for transgressive–regressive cycles, where broadening of the shelf during peak transgression controls maximum diversity. The molluscs Scaphitidae, Nostoceratidae, Inoceramidae, and most Trigonidae disappeared from Antarctica during the early Campanian. By the early–late Campanian boundary, the last Antarctic inoceramids show a distinctive shell structure that probably reflects thermal stress. In the nearby Tierra del Fuego region, deep-marine inoceramids disappeared by the early Maastrichtian, concomitant with a marked change from anoxic–dysoxic to well-oxygenated bottom conditions. The ammonites of the NG and MG sequences are dominated by kossmaticeratids, both in generic richness (which is much lower than in the N Sequence) and specimen abundance, but their diversity pattern do not reflect the expansion of the shelf during peak transgression. Dominance of the Kossmaticeratidae, concomitant with a known Austral temperature decline in the seawater, supports the idea that kossmaticeratids were stenothermal ammonites that flourished in Antarctica when the water masses had attained their preferred temperature and were displaced towards lower latitudes when a certain minimum threshold temperature was reached in the late Maastrichtian. These diversity changes and local extinctions closely match published temperature-cooling trends in the southern ocean and the oxygenation event at the inoceramid extinction level in Tierra del Fuego probably reflects cooling and enhanced bottom ventilation, promoted by circulation of deep Antarctic waters.

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1. Introduction

At the northeast tip of the Antarctic Peninsula, the James Ross Basin (Fig. 1) comprises one of the most complete and highly fossiliferous Upper Cretaceous marine sedimentary sections in the Southern Hemisphere (see Zinsmeister, 1988 for a colourful history of the early scientific discovery of the area). During the last decades, stratigraphical and palaeontological research conducted by the British Antarctic Survey, Instituto Antártico Argentino and American geologists, have firmly established that the James Ross archipelago

includes a Santonian–Danian composite section in excess of 3000 m in thickness (Olivero et al., 1986, 2008; Macellari, 1988; Pirrie, 1989; Crame et al., 1991, 1996, 2004; Pirrie et al., 1991, 1997; Scasso et al., 1991; Marenssi et al., 1992; Zinsmeister and Feldmann, 1996, and the bibliography therein; Olivero and Medina, 2000).

The relatively complete and expanded succession containing the Maastrichtian/Paleogene boundary (K/Pg) at the top of this section in Seymour Island has been the focus of considerable research interest, particularly for its implications on the problem of the extinction pattern of many fossil groups, including ammonites (Macellari, 1986), bivalves (Zinsmeister and Macellari, 1988), foraminifera (Huber, 1988), palynomorphs (Askin, 1988) and diatoms and silicoflagellates (Harwood, 1988). The emerging pattern from

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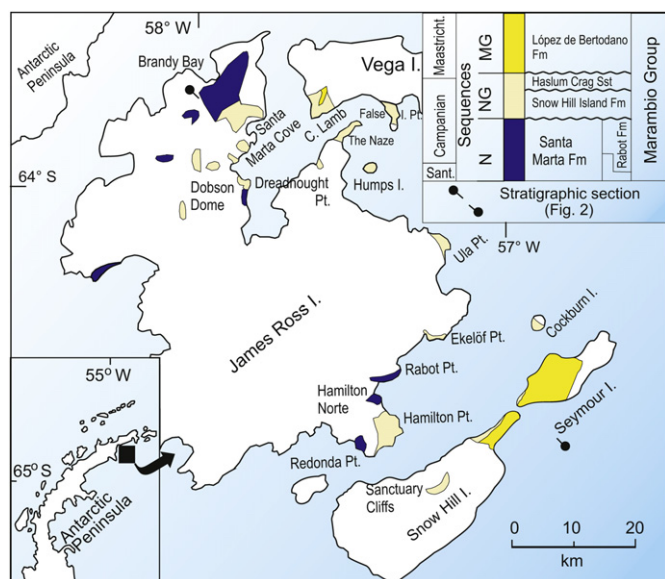


Fig. 1. Situation of the study area, geological scheme of the James Ross Basin and stratigraphy of the Marambio Group.

these studies is that the K/Pg extinction event in Antarctica may be gradational in nature. In addition, the Antarctic Santonian–Danian succession records an unusual pattern of early disappearance of cosmopolitan groups that extend their record well into the Maastrichtian elsewhere in the world. Among them are the early last record in Antarctica of the ammonite families Scaphitidae and Nostoceratidae, the inoceramid and most trigoniid bivalves in the latest early–earliest late Campanian; the Baculitidae in the latest Campanian; the Phylloceratina in the early Maastrichtian; and the belemnites in the early Maastrichtian. These early extinction patterns were interpreted as reflecting mainly a pronounced phase of Campanian–Maastrichtian cooling of the seawater in Antarctica (Crame et al., 1996; Zinsmeister and Feldmann, 1996; Olivero and Medina, 2000). The connection between cooling and extinction patterns in Antarctica is indeed attractive, particularly considering that Late Cretaceous cooling in southern high-latitude areas is confirmed by isotopic evidence (Ditchfield et al., 1994; Huber et al., 1995; Barrera and Sabin, 1999). However, studies on the precise timing of radiation and extinction events, and in general of diversity changes and their relationships to sedimentary facies and transgressions are lacking in the James Ross Basin: these subjects are addressed in this study.

Three stratigraphic sequences have been proposed for the Santonian–Danian succession of the James Ross Basin; the N, Santonian–early Campanian; the NG, late Campanian–early Maastrichtian; and the MG, early Maastrichtian–Danian, sequences. The names of these sequences were derived from the most common kossmaticeratid ammonites that characterize each of them: N for *Natalites*; NG for *Neograhamites* and *Gunnarites*; and MG for *Maorites* and *Grossouvrites* (Olivero and Medina, 2000). The main objectives of this study are twofold. The first is to present a combined analysis of sedimentary facies, depositional systems, and ammonite diversity trends for each of these sequences. Additionally, a palaeoenvironmental comparison is made between the levels of extinction of the inoceramids in Antarctica and Tierra del Fuego. The second objective is to contrast these diversity trends with known patterns of diversity changes associated with transgressions and regressions (e.g., Newell, 1967; Kauffman, 1977; Hallam, 1987; House, 1993; Hallam and Wignall, 1999). Combined with published isotopic-derived temperature trends in the

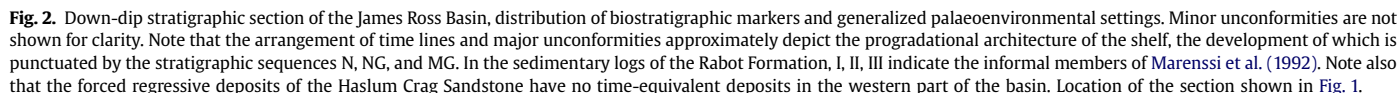
southern ocean the results of the integrated stratigraphical, sedimentological and diversity analysis show contrasting patterns of radiations and extinctions, particularly for the environmentally sensitive ammonites. Thus, in the N Sequence the radiation and extinction of relatively cosmopolitan ammonite groups appear to accompany the proposed diversity–area effect (e.g., Hallam, 1987), whereas in the NG and MG sequences, which are dominated by the relatively endemic kossmaticeratids, the radiation and extinction patterns do not reflect the enlargement and reduction of the shelf during transgressions and regressions. Possible explanations for these contrasting patterns of radiations and extinctions are developed in this paper.

2. Material and methods

The sedimentological and stratigraphical data used to prepare the composite down-dip section across the James Ross Basin depicted in Fig. 2 is mainly based on field work conducted by myself and colleagues during several Antarctic field seasons between 1986 and 2011 (see Olivero et al., 1986, 1991, 1992, 2004, 2007, 2008; Olivero, in press, 2007; Scasso et al., 1991; Strelin et al., 1992; Olivero and Medina, 2000; Olivero and López Cabrera, 2010). Additional sedimentological and stratigraphical data are from Macellari (1988), Pirrie (1989), Crame et al. (1991, 1996, 2004), Pirrie et al. (1991, 1997), Marensi et al. (1992) and Martinioni (1992). The stratigraphic subdivision of the Marambio Group used herein is based on these studies with slight modifications. The Santa Marta Formation is subdivided into the Alpha and Beta members following the original subdivision established in Olivero et al. (1986) and Scasso et al. (1991). These members are approximately equivalent to the Lachman Crag Member of Crame et al. (1991) and Pirrie et al. (1997). The Gamma Member (Olivero et al., 1986) and the Hamilton Point Member (Pirrie et al., 1997) are retained, but they are incorporated into the Snow Hill Island Formation instead of the Santa Marta Formation as originally defined (see Olivero and Medina, 2000; Olivero et al., 2008). The Gamma Member is approximately equivalent to the Herbert Sound Member of Crame et al. (1991). The Haslum Crag Member of the Snow Hill Island Formation (Pirrie et al., 1997) is elevated to formation status and differentiated as the Haslum Crag Sandstone (see Olivero et al., 2008).

Across basin correlation of 12 localities (Figs. 1 and 2) is based on ammonite stratigraphy established by Olivero (1984, 1988, 1992, in press), Macellari (1986), Olivero and Zinsmeister (1989), Olivero and Medina (2000) and an assessment of previous palaeontological work by Kilian and Reboul (1909), Spath (1953) and Howarth (1966). The lower boundary of most of the defined ammonite assemblages, e.g., ammonite assemblages 2–11, is based on the first appearance datum (FAD) of a particular kossmaticeratid genus or the co-occurrence of several genera (Olivero, 1992, in press; Olivero and Medina, 2000; Fig. 2).

The ammonite diversity analysis is based on the author's taxonomic evaluation of more than 7000 specimens collected or observed in the field in 12 key localities shown in Figs. 1 and 2. Three parameters are used for evaluation of the ammonite faunal changes in each of the stratigraphic intervals defined by the Santonian–Maastrichtian ammonite assemblages 1–14: (1) the total number of specimens; (2) the percentage composition of the fauna, including three categories (kossmaticeratids, heteromorphs, and the rest of the fauna); and (3) the diversity, expressed as generic richness. These three parameters are plotted at the midpoint of every stratigraphical interval defined by a particular ammonite assemblage, except for ammonite assemblages 8 and 11, which include thicker stratigraphical intervals and these parameters are plotted at two points in the lower and upper third of the ammonite



assemblage. The collected specimens are housed in the Geological Department of the University of Buenos Aires, Museo Argentino de Ciencias Naturales Bernardino Rivadavia, Buenos Aires, and the Laboratorio de Geología Andina, Centro Austral de Investigaciones Científicas (CADIC-CONICET), Ushuaia. The illustrated specimens that bear the label CIRGEO are presently housed at the Museo Argentino de Ciencias Naturales Bernardino Rivadavia, Buenos Aires, maintaining the original repository number.

3. Stratigraphy and palaeoenvironmental settings

The James Ross Basin is a back-arc basin developed to the east of an active magmatic arc located along the Antarctic Peninsula (Fig. 1). Cretaceous strata in the James Ross archipelago include two major stratigraphic units: the Aptian–Coniacian Gustav Group and the Santonian–Danian Marambio Group. The basal coarse-grained Gustav Group is 2100 m thick and consists of deep-water conglomerates and sandstones, representing the base of the slope and slope depositional settings. Overlying the basal Gustav Group are fan-delta deposits of the Hidden Lake Formation that originated during the partial tectonic inversion of the basin (Ineson, 1989; Buatois and López-Angrián, 1992; Whitham et al., 2006). The overlying finer-grained Marambio Group, about 3000 m thick, is dominated by highly fossiliferous fine-grained sandstones and mudstones, with subordinate conglomerates and coquinas deposited on the mid-outer to inner shelf (Rinaldi et al., 1978; Olivero et al., 1986; Pirrie, 1989; Crame et al., 1991, 1996, 2004; Pirrie et al., 1997; Olivero and Medina, 2000).

Overall the Marambio Group represents the construction of a prograding shelf extending for more than 100 km into the Weddell Sea (Fig. 3). The expansion of the shelf area was punctuated by three major sedimentary cycles: the N (Santonian–early Campanian); NG (late Campanian–early Maastrichtian); and MG (early Maastrichtian–Danian) sequences (Figs. 1 and 2). The boundary of the basal N Sequence is defined by the abrupt facies change at the contact between the sandstone-dominated upper Hidden Lake Formation and the mudstone-dominated lower part of the Santa Marta Formation. The base of the overlying NG and MG sequences are marked by prominent, basin-wide unconformities associated with erosional surfaces that eliminate several tens of metres of stratigraphical thickness of the underlying units. The sequences include a variety of shelf deposits, comprising deep-water deltaic successions, estuarine deposits, shallow-marine coquinas, storm-influenced deposits, and distal tempestites and offshore mudstones

(Fig. 2). These deposits are correlated across the basin by means of 15 ammonite assemblages (Figs. 4–6) distributed in 12 key localities.

Based on this stratigraphic framework a preliminary linkage of depositional systems is interpreted across the basin, together with the evaluation of sea-level changes and patterns of radiations and extinctions of the ammonite fauna for each sequence.

3.1. The N Sequence (Santonian–early to basal late Campanian)

3.1.1. Lithology and palaeoenvironmental settings

The N sequence is superbly exposed at two localities on James Ross Island, to the northwest in Brandy Bay–Santa Marta Cove and to the southeast in Rabot, Hamilton and Redonda points. Minor outcrops are present in Dreadnought Point and in the vicinity of the Dobson Dome (Fig. 1). In Brandy Bay the N Sequence comprises the ca. 1000-m-thick Santa Marta Formation that includes the Alpha and Beta members (Fig. 2). In southeastern James Ross Island, the ca. 300-m-thick Rabot Formation (Marenssi et al., 1992) is a lateral equivalent of the upper Beta Member (Fig. 2).

At Brandy Bay, the Alpha and Beta members of the Santa Marta Formation consist of four vertically stacked intergrading facies associations (Fig. 2) that form a regressive sequence (Scasso et al., 1991; Olivero, 2007). In the lower part of the Alpha Member, the basal facies association consists of friable, massive or laminated muddy tuffaceous, very fine-grained sandstones with minor intercalation of hard, tuffaceous, graded coarse- to fine-grained sandstones capped by bioturbated siltstones. Small fragments of carbonized plant material as well as large tree trunks are abundant locally. Invertebrate fossils are scarce in the lowest 100 m of the section (Fig. 2), which may be of latest Coniacian age according to the ammonite fauna (Kennedy et al., 2007). Stratigraphically above this level, articulated inoceramid bivalves are dominant in the friable muddy sandstones. The accompanying ammonites are dominated by heteromorphs and several graded sandstone beds contain abundant specimens of *Baculites* cf. *kirki* Matsumoto.

At approximately the 300 m level (Fig. 2) the upper part of the Alpha Member grades to a regular alternation of coarsening and thickening upward, friable, graded tuffaceous sandy turbidites capped by laminated, carbonized plant fragments. At regular intervals of 4–6 m in thickness, highly bioturbated and fossiliferous, well-cemented beds of tuffaceous turbidites are intercalated within the succession (Fig. 7). The latter beds preserve an abundant and diverse ammonite fauna, with many specimens in vertical position, either dispersed in the bed or concentrated within and

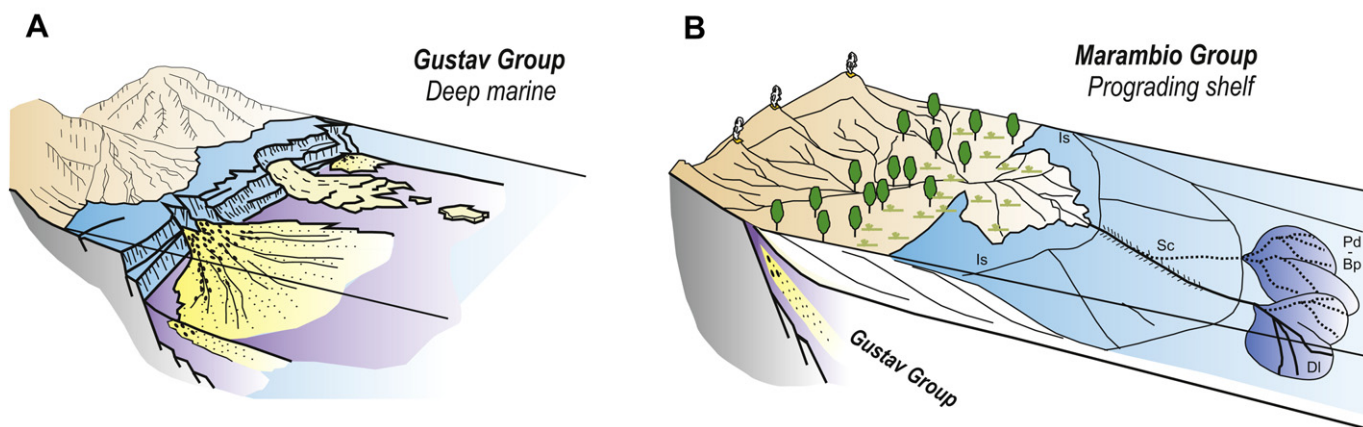


Fig. 3. Palaeoenvironmental settings. Cartoons depicting idealized palaeoenvironmental settings of A, the deep-marine Gustav Group and B, the prograding shelf deposits of the Marambio Group. A, based on Buatois and López-Angrián (1992) and Whitham et al. (2006). B, based on Scasso et al. (1991), correspond to the deep-water deltaic system of the Santa Marta Formation. Pd-Bp, prodelta-basin plain settings; DI, depositional lobes; Sc, slope–channel complex; Is, Inner shelf settings.

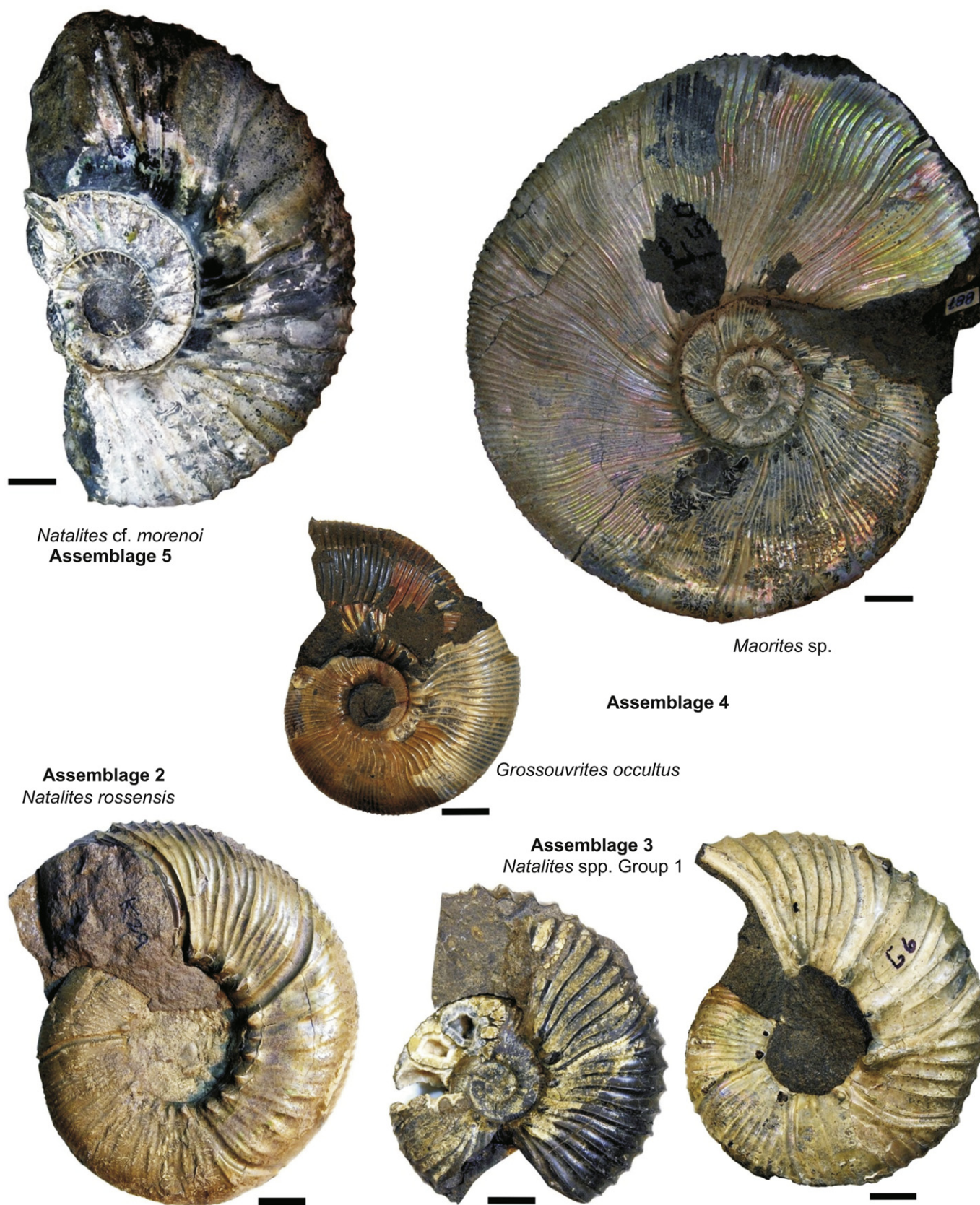


Fig. 4. Kossmaticeratidae marker fossils of ammonite assemblages 2–5, N Sequence, Santa Marta Formation, James Ross Basin. *Natalites cf. morenoi*, CIRGEO 930, Beta Member; *Maorites sp.*, CIRGEO 887, Beta Member; *Grossouvrites occultus*, CADIC PI 165, Beta Member; *Natalites rossensis*, CADIC PI 166, Alpha Member; *Natalites* spp. Group 1, left CIRGEO 1311, right CIRGEO 1308, Alpha Member. Scale bar represents 1 cm in all figures.

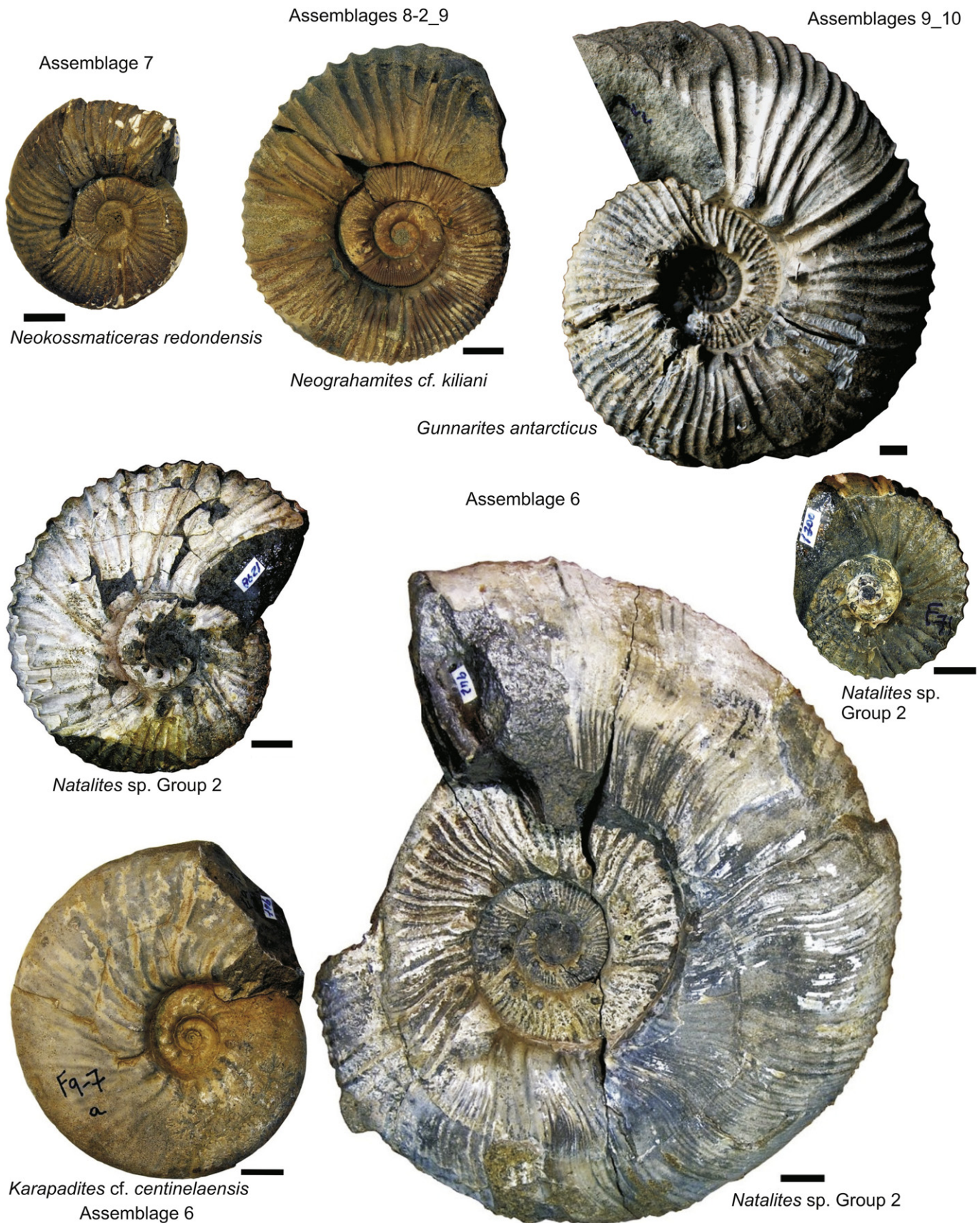


Fig. 5. Kossmaticeratidae marker fossils of ammonite assemblages 6 and 7, N Sequence, and ammonite assemblages 8-2, 9, and 10, NG Sequence, James Ross Basin. *Neokossmaticeras redondensis* CIRGEO 1555, Rabot Formation; *Neograhamites cf. kiliani*, CIRGEO 1789, Sanctuary Cliffs Member, Snow Hill Island Formation; *Gunnarites antarcticus*, Cape Lamb Member, Snow Hill Island Formation, Vega Island; *Natalites* spp. Group 2, left CIRGEO 1298, centre CIRGEO 942, right CIRGEO 1300, Beta Member, Santa Marta Formation; *Karapadites cf. centinelaensis*, CIRGEO 948, Beta Member, Santa Marta Formation. Scale bar represents 1 cm in all figures.

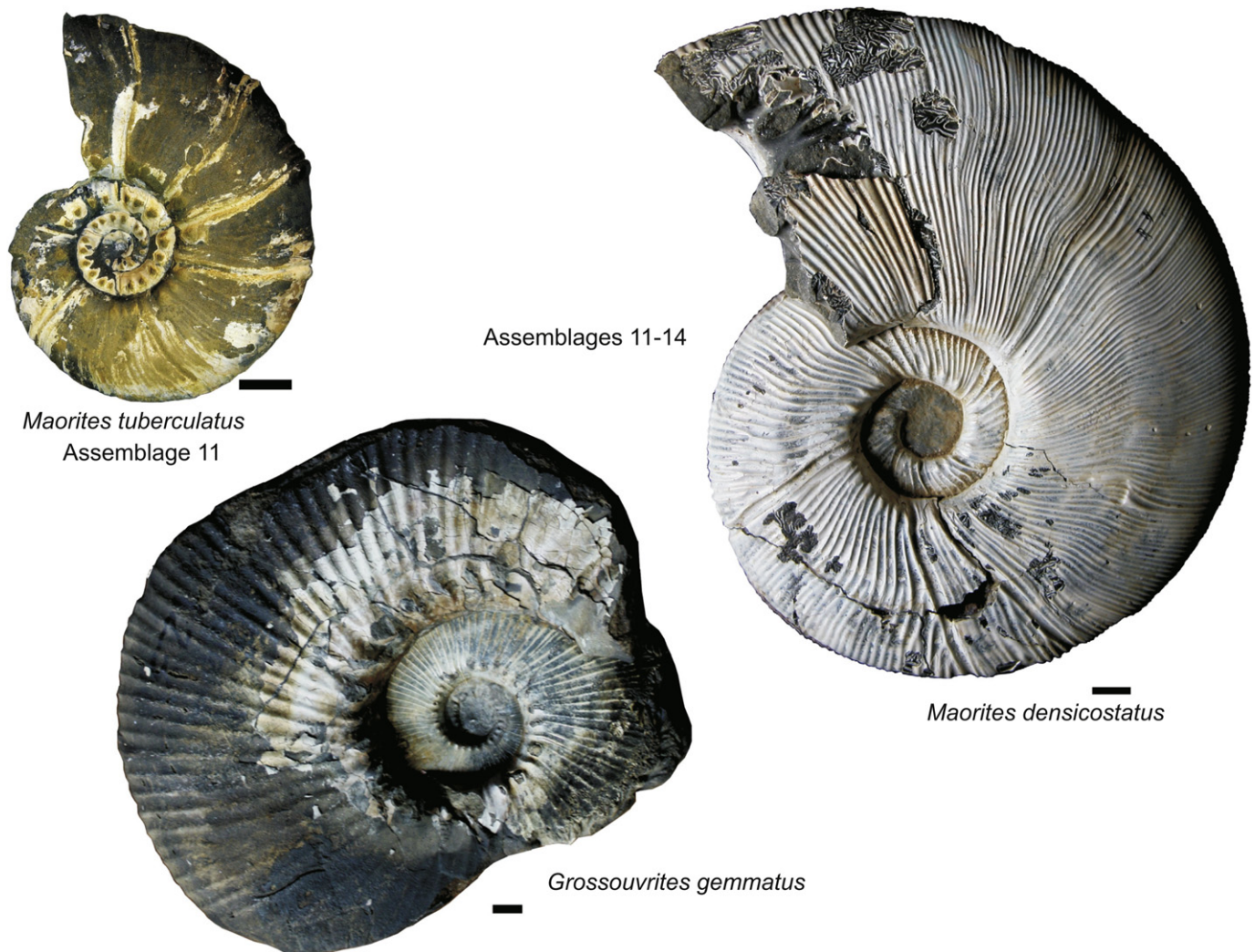


Fig. 6. Kossmaticeratidae of ammonite assemblages 11 and 11–14, MG Sequence, López de Bertodano Formation, James Ross Basin. *Maorites tuberculatus*, CADIC PI 168; *Maorites densicostatus*, CADIC PI 169; *Grossouvrites gemmatus*, CADIC PI 170. Scale bar represents 1 cm in all figures.

around the body chamber of large pachydiscids (Olivero, 2007). The topmost part of these beds contains abundant specimens of the serpulid *Rotularia* and the gastropod *Cerithium* sp.; less abundant is the bivalve *Pinna* sp. in life position, solitary corals, crinoids, and brachiopods. These fossiliferous beds are located at the top of coarsening and thickening-upward turbidites.

In the lower part of the Beta Member, the next facies association consists of graded tuffaceous, pebbly or coarse-grained sandy turbidites cut erosively by large channels filled with re-sedimented conglomerates and debris flows (Fig. 8A, B). Slumped beds, with syndimentary folds are relatively common (Fig. 8C). Re-sedimented fossils, including ammonites, belemnites and bivalves are abundant locally. In the upper part of the Beta Member, the facies association consists of an alternation of thick, bioturbated packages of fine-grained, well-sorted, micaceous sandstones, silty very fine-grained sandstones, and mudstones, with abundant plant fragments, leaves, and large tree trunks. Small ammonites are associated generally with plant fragments. Bivalves, dominated by *Pterotrignia* sp. and *Cucul-laea* sp., are preserved with commonly articulated valves in their presumed life position. Aporrhaid gastropods are also abundant. Bioturbated beds are cut erosively by lenticular packages (e.g., channels) that consist of basal, clast-supported conglomerate and coquina, overlain by parallel-laminated or cross-bedded sandstones

(Fig. 9). Relatively thicker coquina beds are more common in the upper part of the Beta Member where they bear relatively abundant belemnite rostra, scaphopods, and trigoniid bivalves. A distinctive feature of these four facies association is that the clastic composition of the sandstone beds is dominated by volcanoclastic grains, mainly glass shards, pumice lapilli, and lithic (andesitic) components produced by the coeval volcanic activity in the magmatic arc (Fig. 3B; Pirrie, 1989; Scasso et al., 1991; Olivero, 2007).

The intergrading vertical stacking of these four facies associations in the Santa Marta Cove and Brandy Bay section of the Santa Marta Formation suggests the evolution of a progradational deep-water delta system (Scasso et al., 1991), which includes the following sub-environments arranged in a distal-to-proximal position: prodelta-basin plain; base-of-slope depositional lobes; slope-channel complex and inner-shelf-delta plain (Fig. 2). Pirrie (1989) presented a similar palaeoenvironmental interpretation for the Santa Marta Formation.

At Dreadnought Point, the basal part of the section consists of ca. 70 m of poorly exposed silty, fine-grained sandstones with abundant large specimens of *Antarcticeramus rabotensis* Crame and Luther and *Natalites* spp. Group 2 (Strelin et al., 1992; Olivero, in press). At Rabot Point (Fig. 2) the outcrops of the N Sequence include a lower package, between 0 and about the 85 m level (i.e.,



Fig. 7. Prodelta lobe deposits of the Alpha Member, Santa Marta Formation, N Sequence. A, coarsening and thickening upward turbidite package interpreted as prograding lobe deposits; thickness is about 5 m. B, detailed view of a turbidite: es, basal erosive surface; gs, graded, coarse-grained sandstone division; ss, silty sandstone division; cd, laminated, carbonaceous claystone division.

the informal member I of the Rabot Formation; Marensi et al., 1992; Pirrie et al., 1997) of sandstone and re-sedimented conglomerate beds, analogous to those of the Beta Member of the Santa Marta Formation but of slightly younger age (Fig. 2). This package contains the ammonites *Baculites bailyi* Woods, *Maorites* sp., *Grossouvrites occultus* Olivero and Medina, *Opiophyllites* sp., and *Natalites* cf. *morenoi* (Riccardi), together with dimitobelid belemnites. This lower part of the section is interpreted as reflecting progradation of the envisaged deltaic slope, which prograded from the Brandy Bay area to Rabot Point during the time interval of ammonite assemblages 4 and 5 (see “Biostratigraphy” below and Fig. 2).

The mid-part of the Rabot Formation at Rabot Point, between the 85 and ca. 270 m level (informal member II of Marensi et al., 1992) and the lower part of the sections at Hamilton Norte and Redonda Point (Fig. 2), consist of variable proportions of sandstones with hummocky cross-stratification, interpreted as storm-influenced deposits (cf. Martinioni, 1992), and interbedded bioturbated mudstones and tuffs (Fig. 10A). Some sandstone beds are normally graded, have sharp bases with flutes, and record a transition of sedimentary structures from structureless or crudely laminated lower parts that grade to hummocky cross-stratification and then to wave or combined flow ripples (Fig. 10C). These sandstones are probably best interpreted as wave-modified turbidites (cf. Lamb et al., 2008).

The informal member II of the Rabot Formation at Rabot, Hamilton Norte and Redonda points records a dense concentration of very abundant specimens of large *A. rabotensis* (Fig. 10D) and brachiopods, forming a mid-outer shelf inoceramid-brachiopod-rich biofacies that is a lateral equivalent of the mollusc biofacies dominated by robust shells of *Cucullaea*, *Pterotrigonia* and gastropods in the inner shelf settings of the upper Beta Member of the Santa Marta Formation (Fig. 2).

At the Redonda Point, Hamilton Norte and Rabot Point sections, the uppermost part of the Rabot Formation is dominated by sandstones (Fig. 2) where ammonites are scarce or virtually absent (the informal member III of Marensi et al., 1992). The sandstone beds have sharp bases with flute casts and sole marks, followed by structureless divisions capped by parallel-laminated or hummocky

cross-stratified divisions. Interestingly, the basal flute casts preserve graphoglyptid trace fossils, including *Paleodictyon italicum* (Fig. 10B), *Megagraption submontanum*, *Desmograption* isp. and *Urohelminthoidea* isp. Graphoglyptids are well known, particularly in the Mesozoic–Cenozoic, as diagnostic trace fossils of the deep-marine *Nereites* ichnofacies (Seilacher, 1967); however, a few occurrences of these trace fossils are also known in outer shelf facies (see Olivero et al., 2010, and the bibliography therein). Given the geological context in Antarctica, these graphoglyptid trace fossils are interpreted as representing outer shelf settings.

3.1.2. Biostratigraphy

In northwest James Ross Island six successive ammonite assemblages (Fig. 2) were recognized in the Alpha and Beta members of the Santa Marta Formation (Olivero, 1992). The lowest Ammonite Assemblage 1: *Baculites* cf. *kirki*, lacks kossmaticeratids and was referred to the Santonian. The base of Ammonite Assemblage 1 is marked by the first appearance datum (FAD) of *B. cf. kirki*, approximately at the 100 m level, Alpha Member. This species is associated with undetermined Phylloceratina, *Neophylloceras* sp., undetermined Lytoceratidae, *Tetragonites* sp., *Gaudryceras* sp., *Anagaudryceras* sp., *Scaphites* sp., *Hoploscaphtes?* sp., *Yezoites* spp., *Eubosttrychoceras* cf. *elongatum* (Whiteaves), *Scalarites* sp., *Polyptychoceras* cf. *obstrictum* (Jimbo), and *Anapachydiscus* sp. (Olivero, 1992; Fig. 2, Ammonite Assemblage 1).

The bases of the following early Campanian ammonite assemblages 2–6 were defined at the first occurrence of a particular kossmaticeratid genus and/or species (Olivero, 1992). At the 250 m level, Alpha Member, the base of Ammonite Assemblage 2 is defined by the FAD of the kossmaticeratid *Natalites rossensis* Olivero (Fig. 4). This relatively abundant species is associated with undetermined Phylloceratina, *Neophylloceras* sp., *Tetragonites* sp., *Gaudryceras* sp., *Anagaudryceras* sp., *Vertebrites* sp., *Hoploscaphtes?* sp., *Yezoites* spp., *B. cf. kirki*, *Ainoceras zinsmeisteri* Olivero, *Eubosttrychoceras medinae* Olivero, undetermined Nostoceratidae, *Polyptychoceras* sp., *Ryugasella antarctica* Olivero, *Damesites* cf. *hetonaiensis* Matsumoto, *Anapachydiscus constrictus* Olivero, *Anapachydiscus* sp., and *Placentoceras* sp. (Olivero, 1984, 1988, 1992; Fig. 2, Ammonite Assemblage 2).

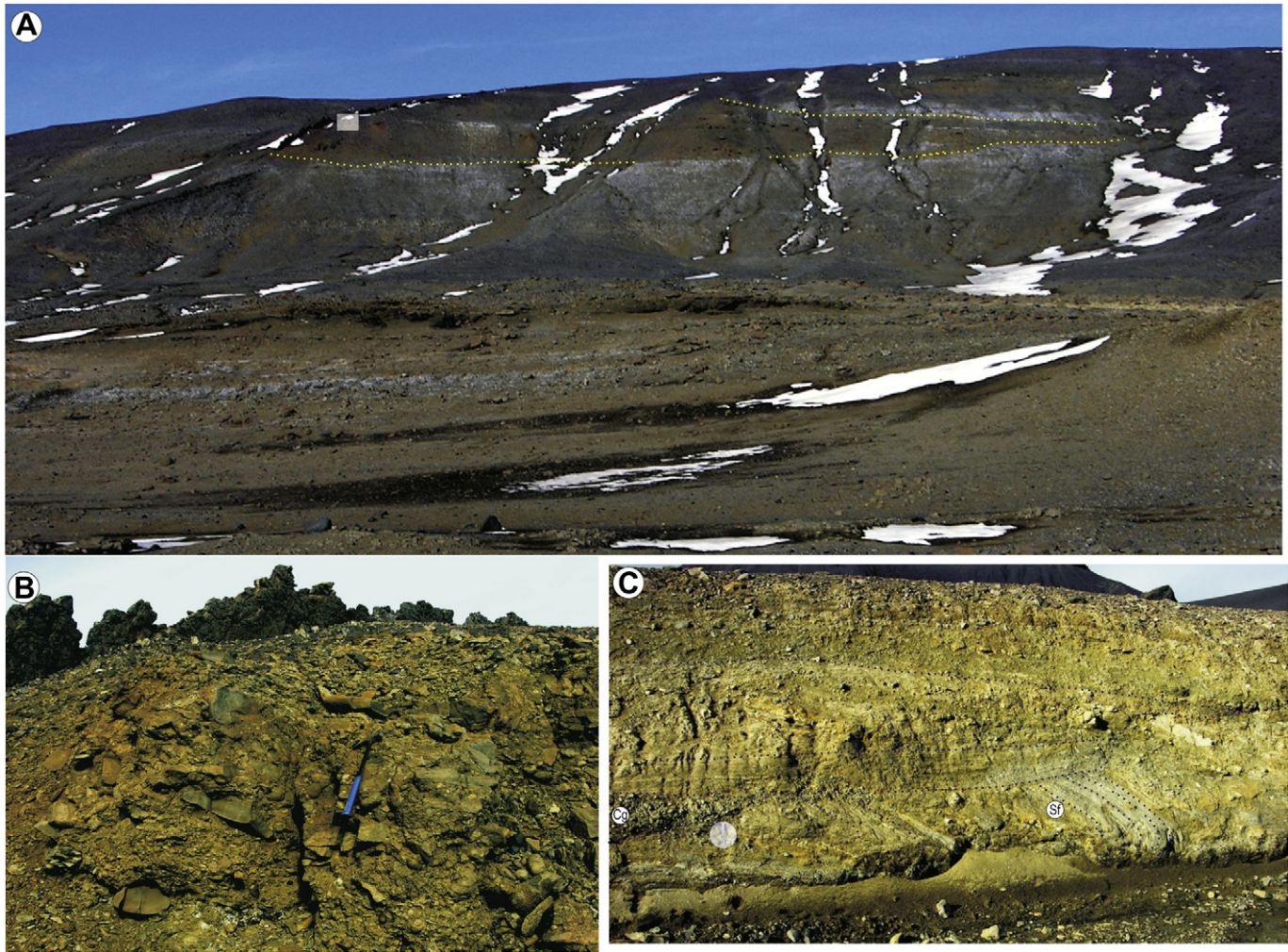


Fig. 8. Delta slope channel complex of the lower Beta Member, Santa Marta Formation, N Sequence. A, large channel filled with re-sedimented conglomerates and debris flow; half-channel width (dots) is about 100 m; location of B indicated by a square. B, detailed picture of a debris flow deposit having large, re-sedimented concretions; hammer for scale is about 40 cm in length. C, chaotic, delta-slope deposits, including lenticular conglomerates (Cg) and folded slump deposits (Sf); hammer, encircled, is about 40 cm in length.

The FAD of *Natalites* spp. Group 1 (Fig. 4) defines the base of Ammonite Assemblage 3, which is located at approximately the 300 m level of the Alpha Member. The associated ammonite fauna includes undetermined *Phylloceratina*, *Neophylloceras* sp., *Tetragonites* sp., *Gaudryceras* sp., *Anagaudryceras* sp., *Vertebrites* sp., *Hoploscaphtes*? sp., *Yezoites* spp., *A. zinsmeisteri*, *E. medinai*, undetermined *Nostoceratidae*, *Parasolenoceras* sp., *R. antarctica*, *D. cf. hetonaiensis*, *Hauericeras* (*Gardeniceras*) sp., *Kitchinites* sp., *Caledonites validus* Olivero, *Caledonites* sp., *A. constrictus*, *Anapachydiscus* sp., and *Eupachydiscus paucituberculatus* Olivero (Olivero, 1984, 1988, 1992; Fig. 2, Ammonite Assemblage 3).

The base of Ammonite Assemblage 4 is defined by the FAD of the kossmaticeratids *Grossouvrites occultus* Olivero and Medina and *Maorites* sp. (Fig. 4), located at approximately the 500 m level within the Beta Member. The associated ammonites include undetermined *Phylloceratina*, *Gaudryceras* sp., *Baculites bailyi* Woods, *Baculites rectus* Marshall, *Baculites* sp., *Parasolenoceras* spp., *Hauericeras* (G.) sp., *Kitchinites* (K.) cf. *angolaensis* Howarth, *Oio-phylites decipiens* Spath, *Caledonites* sp., and *E. paucituberculatus* (Olivero, 1984, 1988, 1992; Fig. 2, Ammonite Assemblage 4).

At approximately the 670 m level, Beta Member, the FAD of the kossmaticeratids *Natalites* cf. *morenoi* (Riccardi) (Fig. 4) and *Natalites taylori* (Spath) marks the base of Ammonite Assemblage 5. The associated ammonite fauna includes *Pseudophyllites* sp., *Gaudryceras*

sp., *Anagaudryceras* sp., *B. rectus*, *Baculites* sp., *Polyptychoceras* sp., *Parasolenoceras* spp., *Ryugasella* sp., *O. decipiens*, *Hauericeras* sp., *G. occultus*, and *Maorites* sp. (Olivero, 1992; Fig. 2, Ammonite Assemblage 5).



Fig. 9. Inner shelf coquina (Co) capped by cross-bedded sandstones (Ss), upper Beta Member, Santa Marta Formation, N Sequence.

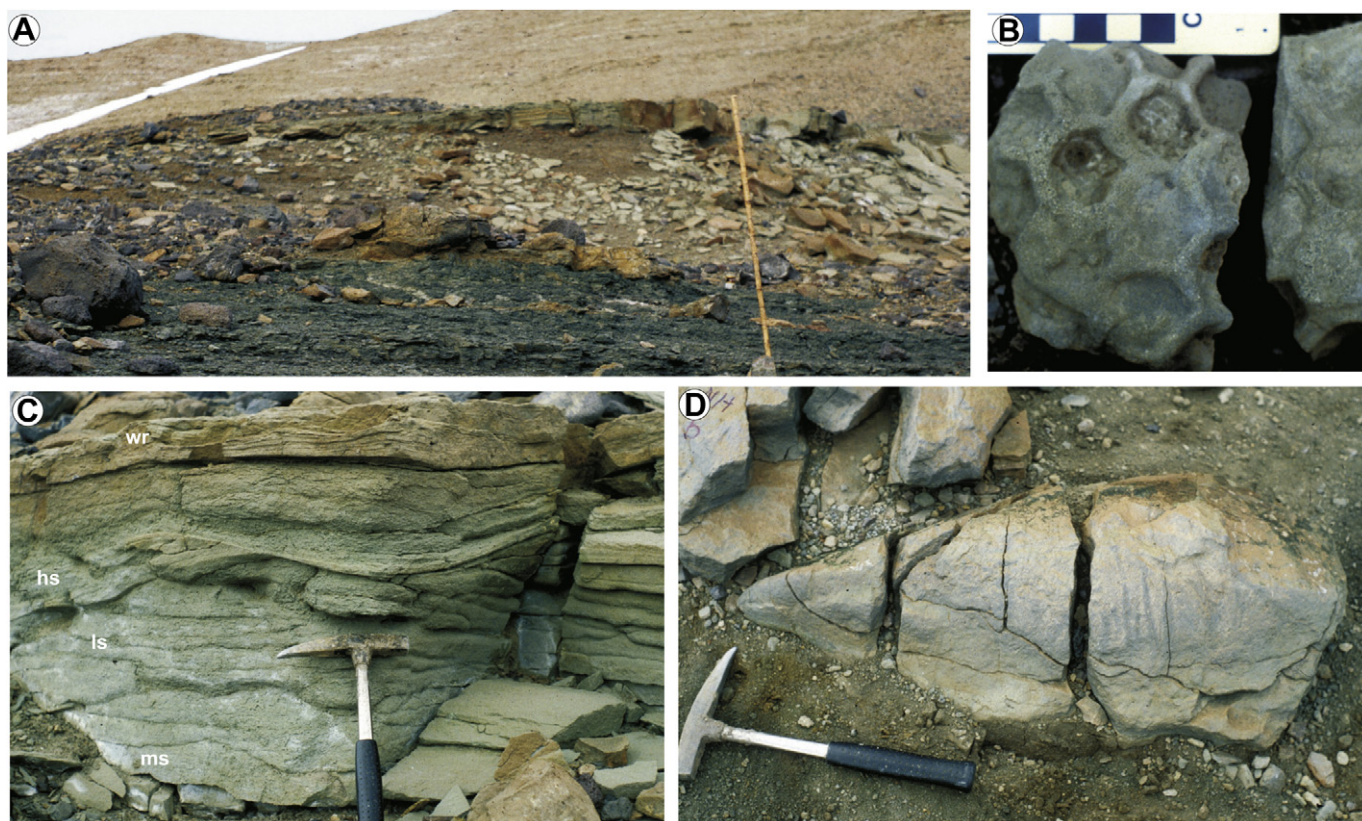


Fig. 10. Storm-influenced turbidites of the Rabot Formation, N Sequence. A, interbedded graded sandstone and bioturbated muds of the informal member II at the Hamilton Norte section; pole for scale is 1.5 m in length. B, the graphoglyptid *Paleodictyon italicum* recorded at the base of a graded sandstone, informal member III, Redonda Point; scale in cm. C, detailed view of a graded sandstone bed with a massive basal interval followed by hummocky cross-stratification and ending with wave ripple lamination; informal member II at the Hamilton Norte section. D, large *Antarcticeramus rabotensis* from the informal member II, Hamilton Norte Section. In C and D, the hammer for scale is about 40 cm in length.

At approximately the 800 m level, Beta Member, the base of Ammonite Assemblage 6 is marked by the first appearance of abundant specimens of *Karapadites* cf. *centinelaensis* (Blasco) followed slightly stratigraphically higher by the appearance of abundant specimens of *Natalites* spp. Group 2 (Fig. 5). The associated ammonite fauna includes *Neophylloceras* sp., *Tetragonites* sp., *Pseudophyllites* sp., *Gaudryceras* sp., *Zelandites* sp., *Parasolenoceras* spp., *Ryugasella* sp., *Oiophyllites* sp., undetermined Desmoceratidae, *G. occultus*, *Maorites* sp., *N. cf. morenoi*, *N. taylori*, and *Natalites* cf. *hauthali* (Paulcke) (Olivero, 1992, in press; Olivero and Medina, 2000; Fig. 2, Ammonite Assemblage 6). In the uppermost part of the Beta Member fine-grained silty sandstone beds interbedded with coquina lenses bear articulated specimens of the large *Antarcticeramus rabotensis* Crame and Luther associated with *Natalites* spp. Group 2.

The stratigraphic interval including ammonite assemblages 1–4 is only recorded at the Brandy Bay-Santa Marta Cove section, but the stratigraphic intervals corresponding to the upper part of Ammonite Assemblage 5 and the Ammonite Assemblage 6 also crop out partly at Dreadnought Point, Rabot Point, Hamilton Norte, and Redonda Point (Figs. 1 and 2). At Rabot Point, the sandstones and conglomerates of the lower part of the Rabot Formation, between 0 and approximately the 85 m level, contains the ammonites *B. bailyi*, *Maorites* sp., *G. occultus*, *Oiophyllites* sp., and *N. cf. morenoi*. This association corresponds to Ammonite Assemblage 5 (Fig. 2).

The succeeding strata, the informal member II, of the Rabot Formation contains ammonite assemblages 6 and 7 (Fig. 2). At Hamilton Norte and Redonda Point Ammonite Assemblage 6 is characterized by abundant *Natalites* cf. *hauthali*, which is a typical component of *Natalites* spp. Group 2, associated with *Parasolenoceras*

sp., gaudryceratids, tetragonitids and *Antarcticeramus rabotensis* (Olivero and Medina, 2000; Olivero, in press). The upper third of the member II of the Rabot Formation, 200 to approximately 270 m levels at the Redonda Point section, records a very different ammonite assemblage, characterized by abundant *Anagaudryceras* aff. *subsacaya* (Marshall) and other gaudryceratids and tetragonitids, *Polyptychoceras* sp., *Baculites* sp., and a new kossmaticeratid referred to *Neokossmaticeras redondensis* Olivero (Olivero, in press; Fig. 5). This particular ammonite fauna is differentiated as Ammonite Assemblage 7. Previous findings of *Metaplacenticerus* cf. *subtilistriatum* (Jimbo) and *Hoplitoplacenticerus* sp. from Punta Redonda (Marenssi et al., 1992; Medina et al., 1988) were probably recorded from the upper stratigraphical interval of Ammonite Assemblage 6 or the lower part of Ammonite Assemblage 7. Interestingly, the joint occurrence of *N. redondensis*, *M. cf. subtilistriatum* and *Hoplitoplacenticerus* sp., associated with *Baculites subanceps* Matsumoto and inoceramid shells (Olivero, 1992, in press; Olivero and Medina, 2000) is recorded in the Santa Marta Cove-Brandy Bay section in a single conglomerate bed at the base of the succeeding NG Sequence. This means that the stratigraphic interval encompassed by Ammonite Assemblage 7, and probably part of Ammonite Assemblage 6, in Punta Redonda and Hamilton Norte was eroded in the Santa Marta area, and their index ammonite species were concentrated in a single conglomerate at the base of the NG Sequence (Fig. 2).

3.1.3. Linkage of contemporaneous depositional systems: development of the shelf

The linkage of the envisaged depositional systems across the basin allows an estimation to be made of the extension of the shelf

area during deposition of the upper part of the N Sequence. As indicated by the interpreted inner shelf coquinas, with trigoniid-dominated biofacies, exposed between the Brandy Bay and Santa Marta Cove area (Figs. 1 and 2), the shoreline was probably located in this area during the time interval of Ammonite Assemblage 6. For this time slice these proximal facies grade laterally at Rabot and Redonda points into storm-influenced, relatively deep-marine graded sandstones and bioturbated mudstones. They record an inoceramid-brachiopod dominated biofacies that probably represents mid to outer shelf settings. The uppermost part of the N Sequence at Hamilton Norte and Redonda Point, including the time slice defined by Ammonite Assemblage 7 and the succeeding sandstone-dominated beds with graphoglyptid trace fossils, probably represents outer shelf settings. Consequently, the shelf area probably extended during the time slices of ammonite assemblages 6 and 7 from Brandy Bay-Santa Marta Cove to Redonda Point (Fig. 2).

3.2. The NG sequence (late Campanian–early Maastrichtian)

3.2.1. Lithology and palaeoenvironmental settings

Outcrops of the NG Sequence are widely exposed in the James Ross Basin, from Snow and Seymour islands to Santa Marta Cove area in James Ross Island (Fig. 1). The Sequence consists of ca. 1000 m of fine-grained sediments comprising the Hamilton Point, Sanctuary Cliffs, Karlsen Cliffs, Cape Lamb, and Gamma members of the Snow Hill Island Formation (Fig. 2; Olivero et al., 1986; Crame et al., 1991, 1996; Pirrie et al., 1997; Olivero and Medina, 2000) and the Haslum Crag Sandstone (Olivero et al., 2008). In the distal part of the basin, e.g., Hamilton Norte, the basal unconformity is defined at the abrupt facies change from outer shelf sandstone-dominated packages to offshore mud-dominated packages. In the proximal part of the basin, e.g., Brandy Bay-Santa Marta Cove, the basal unconformity is defined at the basal conglomerate including a mixing of reworked fossils from Ammonite Assemblage 7 of the N Sequence (Olivero, in press; Fig. 2).

In the distal part of the basin the basal part of the NG Sequence comprises the Hamilton Point Member of the Snow Hill Island Formation. This member consists of 500 m of mudstone with interbedded tuff beds; ammonites are scarce in these beds, but serpulids such as *Rotularia dorsolaevis* Ball and *R. fallax* (Wilckens) are relatively abundant (Marensi et al., 1992; Pirrie et al., 1997). Localized horizons also bear extremely abundant specimens of cirripeds and isselocrinid crinoids (Luther, 1999). Ostracods suggest

shelf settings for the Hamilton Point Member (Fauth et al., 2003). According to its stratigraphic position above outer shelf sandstones and mudstones with graphoglyptid trace fossils of the previous N Sequence, the Hamilton Point Member is interpreted as consisting of transgressive, offshore mudstone deposits. In the distal part of the basin, the Hamilton Point Member passes transitionally into the Sanctuary Cliffs Member of the Snow Hill Island Formation (Fig. 2). The Sanctuary Cliff Member (Fig. 11A) consists of 200 m of mudstones and sandstones with hummocky cross-stratification. The member contains abundant specimens of the kossmaticeratid ammonite *Neograhamites* cf. *kiliani* Spath.

In the proximal part of the basin the lower two thirds of the Gamma Member consist of inner shelf sandstones and coquinas. Fossils, particularly ammonites, are relatively scarce, but gastropods and bivalves could be locally common. In addition, the Gamma Member records dinosaur bones (Olivero et al., 1986, 1991), including a partial skeleton of the ankylosaurian dinosaur *Antarctopelta oliveroi* Salgado and Gasparini (2006). Ammonites are relatively abundant in the upper third of the Gamma Member, including the distinctive Ammonite Assemblage 9 (see “Biostratigraphy” below), which passes laterally into a sandstone-mudstone succession in Dreadnought Point (Strelin et al., 1992; Olivero, in press) and Humps Island (Pirrie and Riding, 1988), interpreted as tempestites deposited in offshore transition settings. The succeeding Cape Lamb and Karlsen Cliffs members (Crame et al., 1991; Pirrie et al., 1997) consist of a gradational coarsening- and thickening-upward succession of mudstones and sandstones. These members are very fossiliferous and particularly the ammonites are characterized by the dominance of the kossmaticeratid genus *Gunnarites* (Figs. 2 and 5).

At Vega Island, a basal transgressive conglomerate of the López de Bertodano Formation lies on an erosion surface cut into the Cape Lamb Member. In Snow Hill Island, a marked unconformity separates the Karlsen Cliffs Member from bioturbated glauconitic sandstones and mudstones with inclined heterolithic stratification of the Haslum Crag Sandstone (Fig. 12). The coarsening and thickening upward succession of the Karlsen Cliffs Member is interpreted as a prograding deltaic wedge. Above the unconformity, the Haslum Crag Sandstone records the incision, migration, and filling of relatively large and deep subtidal channels. Deeply incised into the Haslum Crag Sandstone, the base of the succeeding MG Sequence includes transgressive estuarine and shallow marine deposits of the López de Bertodano Formation that fill a previous fluvially and/or tidally scoured depression. The Haslum Crag Sandstone consists of

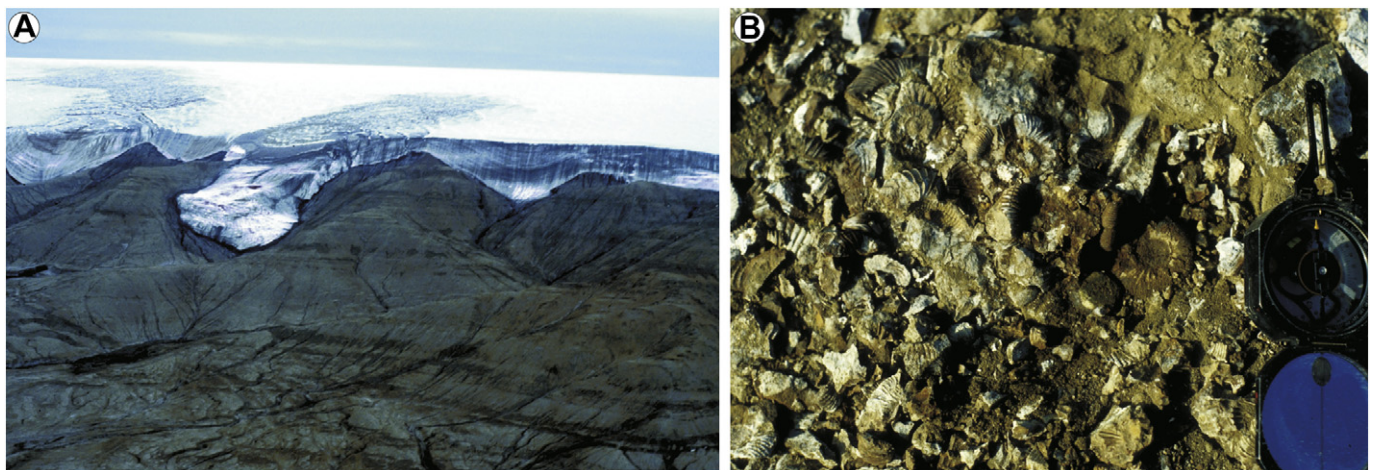


Fig. 11. Offshore mudstones and distal tempestites of the Sanctuary Cliffs Member, Snow Hill Island Formation, NG Sequence. A, oblique panoramic view of the mudstone-dominated Sanctuary Cliffs Member at the type locality; the section is about 200 m thick. B, detailed view of a dense concentration of *Neograhamites* cf. *kiliani* at the base of a tempestite bed.

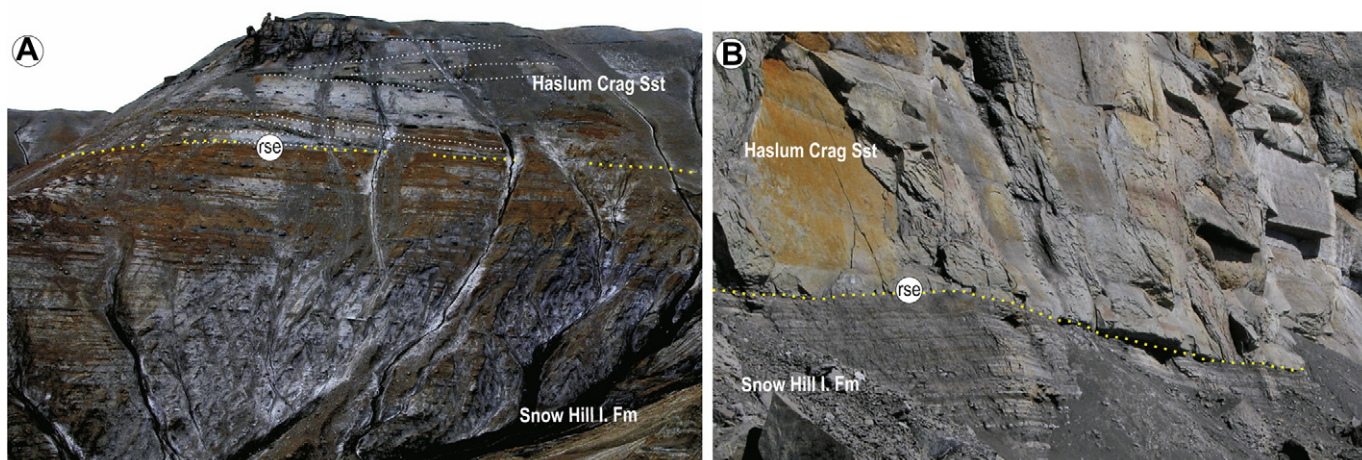


Fig. 12. Architecture and relationships between the Snow Hill Island Formation, Karlens Cliffs Member, and the Haslum Crag Sandstone at Snow Hill Island. A, panoramic view showing the coarsening and thickening upward deltaic mudstone and sandstone of the Karlens Cliffs Member; the regressive surface of erosion (rse) and the large tidal channels with opposite dipping beds are interpreted as epsilon cross-stratification of the Haslum Crag Sandstone; height of cliffs is about 100 m. B, detailed view of the sharp contact (rse) separating interbedded mudstone and sandstone of the Karlens Cliffs Member from massive sandstone of the Haslum Crag Sandstone; height of photograph represents about 15 m.

forced regressive deposits that accumulated during relative sea-level falls, and documents a rare case of sharp-based, tide-influenced sandstones encased in marine and estuarine mudstones (Olivero et al., 2008).

3.2.2. Biostratigraphy

The marked unconformity at the top of the Santa Marta and Rabot formations is associated with a notable change in the Antarctic kossmaticeratid fauna. The relatively diverse fauna dominated by species of *Natalites* of the N Sequence is replaced above the unconformity by a fauna of low diversity, mostly dominated by extremely abundant specimens of the kossmaticeratid genera *Neograhamites* and *Gunnarites* of the NG Sequence. In the distal northwest part of the basin, four successive ammonite assemblages were recognized, namely 8-1: *Neograhamites primus*; 8-2: *Neograhamites cf. kiliani*; 9: *Neograhamites-Gunnarites*; and 10: *Gunnarites* (Olivero and Medina, 2000; Olivero, in press Fig. 2).

The base of Ammonite Assemblage 8-1 is recorded in the basal Hamilton Point Member and it is defined by the FAD of *Neograhamites primus* Olivero. The stratigraphic distribution of this species includes the 0–70-m levels of the Hamilton Point Member, where it is associated with *Baculites delvallei* Riccardi, *Astreptoceras* sp., *Diplomoceras lambi* Spath, *Gaudryceras* sp., *Anagaudryceras* sp., Kossmaticeratinae gen. nov., which may correspond to the material referred by Riccardi (1980) to *Jimboiceras? antarcticum* Riccardi, *Anapachydiscus* sp., and *Eupachydiscus* sp. (Olivero, in press; Fig. 2). At approximately the 390-m level of the Hamilton Point Member the FAD of *Neograhamites cf. kiliani* Spath is recorded. The stratigraphic distribution of this species continues throughout the rest of the Hamilton Point and the Sanctuary Cliffs members (Assemblage 8-2; Fig. 2). In Sanctuary Cliffs, specimens of *N. cf. kiliani* Spath are extremely abundant (Fig. 11B). The associate ammonite fauna consists of a relatively few specimens of phylloceratids, *Baculites* sp., *Astreptoceras* sp., *Polyptychoceras* sp., *D. lambi*, *Phyllopachyceras* sp., *Tetragonites* sp., *Gaudryceras* sp., *Anagaudryceras* sp., and *Pseudophyllites* sp.

In the uppermost part of the Sanctuary Cliffs Member, the FAD of the genus *Gunnarites* associated with *N. cf. kiliani* is recorded. This association defines Ammonite Assemblage 9. The co-occurrence of species of *Gunnarites* and *Neograhamites* in a short stratigraphic interval defines a very distinctive marker horizon

that can be detected across the basin (Ammonite Assemblage 9, Figs. 2 and 5).

The Cape Lamb and Karlens Cliffs members are very fossiliferous and record Ammonite Assemblage 10, characterized by the dominance of the kossmaticeratid genus *Gunnarites* (Figs. 2 and 5). The accompanying ammonite fauna includes *D. lambi*, *Tetragonites* sp., *Pseudophyllites* sp., *Anagaudryceras* sp., *Maorites* sp., *Grossouvrites* sp., *Jacobites anderssoni* Kilian and Reboul, *J. crofti* Spath and pachydiscids.

In northwest James Ross Island, in the proximal part of the basin, most of the Gamma Member exposures in the Santa Marta Cove area are dominated by sandstone beds that bear rare ammonites, including scarce *Neograhamites primus* and Kossmaticeratinae gen. nov. The stratigraphically equivalent, sandy siltstone beds of the Gamma Member at the Dreadnought Point section record relatively abundant *Astreptoceras* sp., *Polyptychoceras* sp., *Neograhamites primus* sp. nov., and Kossmaticeratinae gen. nov. (Fig. 2, Ammonite Assemblage 8-1). The mud-dominated upper part of the member at Santa Marta Cove bears in succession abundant specimens of *Neograhamites cf. kiliani* Spath, corresponding to Ammonite Assemblage 8-2, and in its uppermost part the association of *Neograhamites cf. kiliani* and *Gunnarites* sp., corresponding to Ammonite Assemblage 9 (Fig. 2; Olivero, in press).

3.2.3. Linkage of contemporaneous depositional systems: development of the shelf

The stratigraphical evolution of the depositional systems in the southeastern part of the basin, i.e., Hamilton Norte-Redonda Point in James Ross Island, and Snow Hill and Seymour islands, documents a further extension of the shelf into the Weddell Sea. At the base of the NG Sequence, the offshore transgressive mudstone of the Hamilton Point Member lies over relatively deeper graded sandstones that probably accumulated at the former shelf edge during deposition of the uppermost regressive facies of the N Sequence. The Cape Lamb, Sanctuary Cliffs and Karlens Cliffs members represent a deltaic wedge that prograded during the time slices encompassed by ammonite assemblages 8–10 for about 80 km to the east, from Santa Marta Cove-Vega Island to Snow Hill-Seymour islands. During the final regressive phases the forced regressive strata of the Haslum Crag Sandstone suggest that the shoreline was at that time located near Seymour Island (Fig. 2; Olivero et al., 2008).

3.3. The MG sequence (early Maastrichtian–Danian)

3.3.1. Lithology and palaeoenvironmental settings

Outcrops of the MG Sequence are mostly restricted to Seymour and Snow Hill islands; minor exposures are located at Cape Lamb, Vega Island. The sequence consists mainly of the ca. 1000-m-thick mudstone and silty, very fine-grained sandstone succession of the López de Bertodano Formation exposed in the east-southeast of the basin (Figs. 1 and 2; Macellari, 1988). Localized outcrops of a very distinctive coarse-grained volcanoclastic unit, the Sandwich Bluff Member, are located at Cape Lamb, Vega Island (Fig. 2; Crame et al., 1991; Pirrie et al., 1991). The base of the MG Sequence is a marked unconformity associated with a deeply incised erosional surface that cuts a maximum of about 60–70 m of the underlying Haslum Crag Sandstone (Pirrie et al., 1997; Olivero et al., 2007, 2008). At the top of the MG Sequence, another marked unconformity also associated with a deeply incised erosional surface separates the Danian beds of the López de Bertodano Formation from the Paleocene Sobral Formation (Figs. 2 and 13).

At Seymour and Snow Hill islands the basal incised relief beneath the López de Bertodano Formation is filled with large, lenticular beds of mudstone, silty sandstone and fine-grained sandstone, roughly equivalent to the informal units 2–4 of Macellari (1988). The abundance of inclined heterolithic stratification, current ripple cross-lamination with evidence of palaeoflow reversals, mud drapes, and channel-shaped sedimentary fills with marine fossils suggest deposition in tidal-influenced settings (Olivero, 1998; Olivero et al., 2007, 2008). Stratigraphically higher, from about 250 to 500 m (Fig. 2), is a monotonous succession of mudstones and glauconitic, silty very fine-grained sandstones that record an increasing abundance of molluscs. Bivalves, represented by the genera *Pinna*, *Nordenskjoldia*, *Oistotrigonia*, and *Thracia*, are relatively common and some horizons bear very abundant specimens of the serpulid *Rotularia* (Macellari, 1988; Zinsmeister and Macellari, 1988; Crame et al., 2004; Olivero et al., 2008). At approximately the 350-m level, a thin horizon preserves abundant specimens of a dimitobelid belemnite (Doyle and Zinsmeister, 1988; Elorza et al., 2001). The ammonite fauna is relatively scarce, but there are localized horizons where the kossmaticeratid *Maorites tuberculatus* Howarth (Fig. 6) is abundant. These lower beds of the López de Bertodano Formation are interpreted as estuarine and shallow marine transgressive deposits (Fig. 2; Olivero et al., 2008).

The stratigraphical interval from the 500-m level up to the K/Pg boundary (Fig. 2), corresponding to the molluscan units of Macellari (1988), is highly fossiliferous and consists of massive mudstones and silty, very fine-grained sandstones interbedded with glauconitic fine sandstone beds and concretionary horizons. Bivalves, gastropods, and marine reptiles are very common in the molluscan units (Macellari, 1988; Zinsmeister and Macellari, 1988). We concur with the interpretation of Macellari (1988) that these beds represent transgressive shelf deposits followed by a regressive trend in the uppermost part of the López de Bertodano Formation (Fig. 2). At Vega Island, the Sandwich Bluff Member of the López de Bertodano Formation consists of near-shore marine deposits that were interpreted as a lateral equivalent of the uppermost beds of the MG Sequence at Seymour Island (Crame et al., 1991; Pirrie et al., 1991).

3.3.2. Biostratigraphy

At the base of the López de Bertodano Formation, the FAD of the kossmaticeratid *Maorites tuberculatus* Howarth marks the base of Ammonite Assemblage 11. The marker species is distributed up to the 500 m level of the López de Bertodano Formation. The accompanying ammonite fauna consists of *D. lambi*, *Neophylloceras* sp., *Pseudophyllites* sp., *Anagaudryceras* sp., *Kitchinites* sp., *Maorites densicostatus* (Kilian and Reboul), *M. seymourianus* (Kilian and Reboul) and *Grossouvrites gemmatus* (Huppé) (Fig. 2; Ammonite Assemblage 11).

Following the pachydiscid ammonite zonation of Macellari (1986, 1988), the interval from the 500 m level up to the K/Pg boundary is subdivided into ammonite assemblages 12, *Pachydiscus ootacodensis* (Stoliczka), 13, *P. riccardii* Macellari and 14, *P. ultimus* Macellari (Fig. 2). The early–late Maastrichtian boundary was tentatively located by Crame et al. (2004) at the level with dimitobelid belemnites based on a Sr isotopic age of 67.5 Ma. However, preliminary palaeomagnetic studies suggest that the boundary between chrons 31R and 31N is located much higher in the section, close to uppermost range record of *P. ootacodensis* (Kirschvink et al., 2010).

In the stratigraphical interval corresponding to ammonite assemblages 12–14 the ammonite fauna is dominated by the kossmaticeratids *M. densicostatus*, *M. seymourianus*, and *G. gemmatus* (Fig. 6). Associated or recorded at various levels (see Macellari, 1986; Zinsmeister and Feldmann, 1996; Fig. 2) are *P. riccardii*, *P. ultimus*,

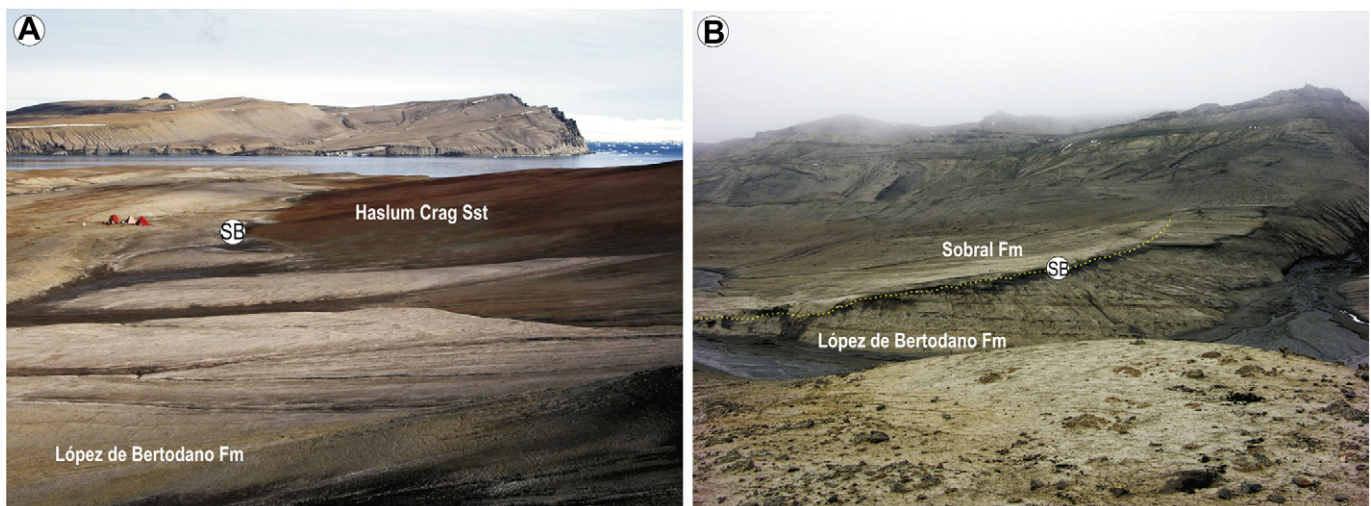


Fig. 13. The unconformities at the base and top of the López de Bertodano Formation, MG Sequence, at Seymour Island. A, the basal unconformity (SB) atop the Haslum Crag Sandstone; Snow Hill Island in the background. B, high-relief unconformity (SB) separating the Danian beds of the López de Bertodano Formation from Paleocene beds of the Sobral Formation.

Diplomoceras maximum Olivero and Zinsmeister, *Anagaudryceras seymouriensis* Macellari, *Zelandites varuna* (Forbes), *Kitchinites darwini* (Steinmann), *K. laurae* Macellari, and *Pseudophyllites loryi* (Kilian and Reboul).

3.3.3. Linkage of contemporaneous depositional systems: development of the shelf

At the beginning of the MG Sequence the shoreline was probably located near Seymour Island, an interpretation that is strengthened by the occurrence of basal estuarine deposits of the López de Bertodano Formation. During the ensuing transgression the shoreline shifted to the west, as interpreted from the origin of the basal lag conglomerate at Vega Island (Olivero et al., 1992; Marensi et al., 2001). During the regressive uppermost part of the sequence, and particularly during the elaboration of the deeply incised erosional surface at its top (Fig. 13B), the shoreline was probably located farther to the east of Seymour Island (Fig. 2). Consequently, it is interpreted that the MG Sequence represents a further increment of the shelf area into the Weddell Sea.

4. Diversity and composition of the ammonite fauna

The sequence stratigraphic framework established for the Santonian–Danian of the James Ross Basin (Fig. 2) is intended as a preliminary framework constructed on the basis of a large-scale dataset. It probably represents a low cyclicity frequency, of second or third-order cycles. The time involved is probably of the order of 7–8 Ma for the N Sequence, beginning of the Santonian to the early–late Campanian boundary; about 8–9 Ma for the NG Sequence, late Campanian–early Maastrichtian; and about 5 Ma for the MG Sequence, early Maastrichtian–Danian. Continuing systematic studies of the ammonite fauna would probably result in a further refinement of the biostratigraphic scheme used herein. In this regard, the use of the genus level for the ammonite diversity analysis is intended to overcome possible biases due to the large-scale stratigraphical framework of the ammonite dataset. Using this stratigraphical framework and results, the changes in abundance, composition, and generic richness of the ammonite fauna for each of the 15 ammonite assemblages recognized in the Santonian–Maastrichtian of the James Ross Basin are given in Fig. 14.

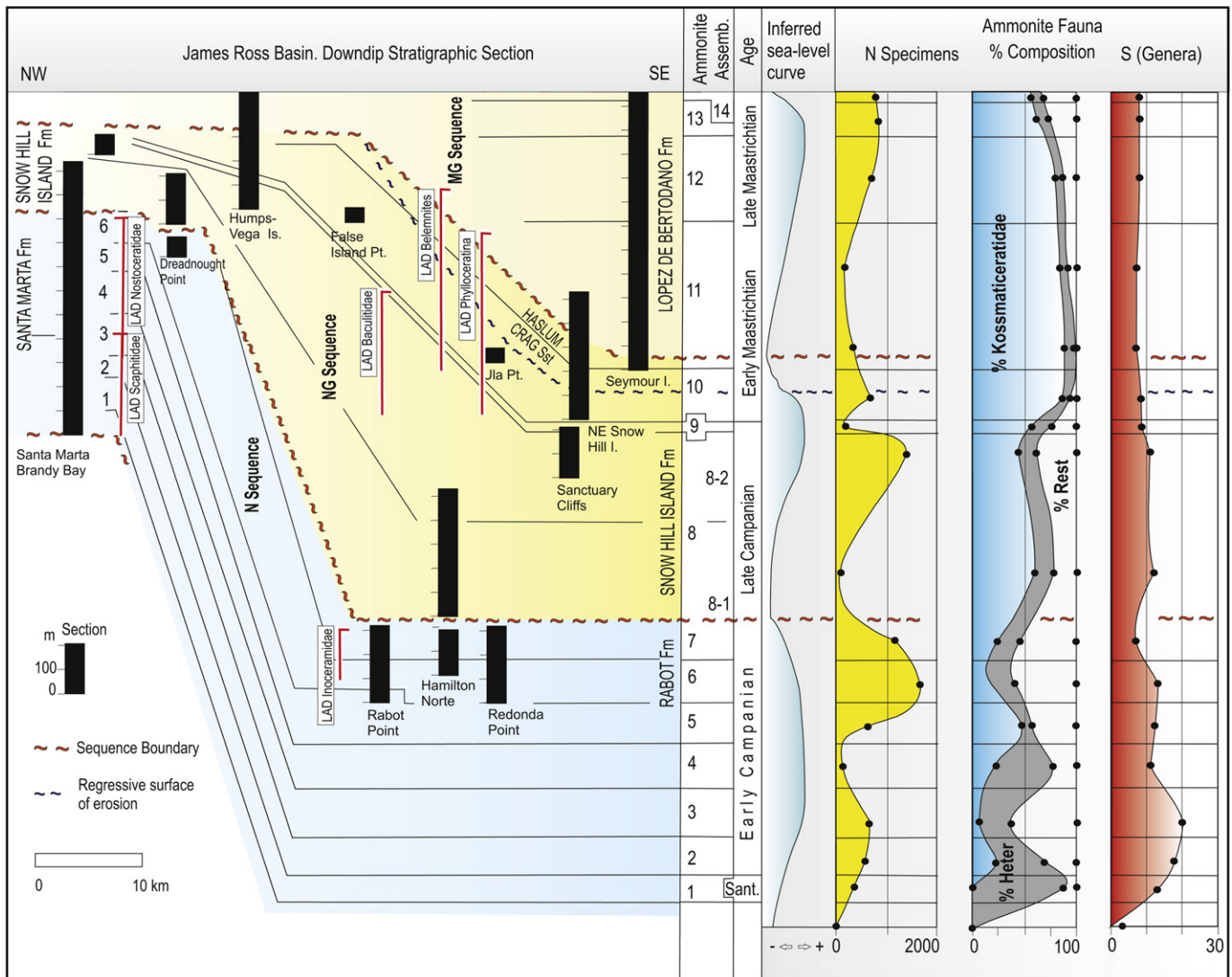


Fig. 14. Ammonite faunal changes during the Santonian–Maastrichtian of the James Ross Basin, Antarctica. The total number of specimens studied (N), the percentage composition of the fauna, and the generic richness (S) are plotted for each stratigraphic interval corresponding to ammonite assemblages 1–14. A schematic version of the down-dip section across the basin of Fig. 2 is shown for reference to the left, together with the last occurrence datum (LAD) of several taxa that disappear from Antarctica exceptionally earlier than elsewhere in the world. Note the large number of specimens studied and the absolute dominance of kossmaticeratids and reduced generic richness in the NG and MG sequences.

In the N Sequence there is a steady increase in the number of ammonite specimens from ammonite assemblages 1–3, accompanied by an increasing diversity trend that reaches a maximum of 20 genera at the transgressive facies of Ammonite Assemblage 3. In these stratigraphic intervals, the ammonite fauna is dominated by heteromorphs, lytoceratids and pachydiscids, which together represents about 75% of the fauna. The drop in the number of ammonite specimens and generic richness in Ammonite Assemblage 4 is probably a result of poor conditions of fossil preservation in the re-sedimented conglomerates and debris flow of the lower interval of the Beta Member. In the succeeding intervals, there is an increase in the number of ammonite specimens reaching a maximum of about 1800 studied specimens in Ammonite Assemblage 6, and then a decrease to about 1150 studied specimens in Ammonite Assemblage 7. In spite of the large number of specimens, there is a steady decrease in the generic richness from 13 genera in Ammonite Assemblage 6 to seven in Ammonite Assemblage 7. In these stratigraphic intervals, the faunal composition is still dominated by lytoceratids and heteromorphs, but the kossmaticeratids start to form an important component of the fauna (Fig. 14).

A remarkable fact of the N Sequence is the early disappearance of important ammonite groups in the lower Campanian of Antarctica which are recorded in the Maastrichtian elsewhere in the world. Among them are the Scaphitidae, with a last record in Ammonite Assemblage 3, and the Nostoceratidae, with a last record in Ammonite Assemblage 6. The latter assemblage also records the last appearance in Antarctica of many Trigonidae, including the genera *Austrotrigonia*, *Nipponitrigonia*, *Pacitrigonia* and *Pterotrigonia*. Ammonite Assemblage 7 records the last appearance of the inoceramids in Antarctica (Fig. 14).

In the NG Sequence, the number of specimens is relatively low in the basal Hamilton Point Member, totalling 170 studied specimens in Ammonite Assemblage 8-1. The generic richness reaches a maximum of 12 ammonite genera in this member. Ammonites are relatively abundant in Ammonite Assemblage 8-2, with about 1300 studied specimens from the Sanctuary Cliffs and Gamma members. In spite of the large number of specimens, the generic richness is less than in the lower part of the member, with 11 ammonite genera recorded. The composition of the fauna is highly distinctive, with an absolute dominance of specimens of a single kossmaticeratid genus, *Neograhamites*, which constitutes about 50% of the total specimens studied (Figs. 11B and 14). Dominance of the kossmaticeratids is incremented in the succeeding ammonite assemblages 9 and 10; the latter with an absolute dominance of kossmaticeratids, which constitute more than 80% of about 800 studied specimens. This corresponds to the prolific *Gunnarites* horizon of Ammonite Assemblage 10, where specimens of *Gunnarites* greatly outnumber those of *Maorites*, *Grossouvrites*, and *Jacobites*. The generic richness in ammonite assemblages 9 and 10 remains constant, with nine genera recorded (Fig. 14). The last appearance datum (LAD) of the Antarctic Baculitidae is recorded within Ammonite Assemblage 9.

At the base of the MG Sequence, the basal estuarine and shallow marine beds of the López de Bertodano Formation record a relatively low number of ammonite specimens. Nonetheless, about 600 specimens were studied from localized horizons within the stratigraphic interval of Ammonite Assemblage 11. The composition of the ammonite fauna indicates an absolute dominance of kossmaticeratids, which constitute more than 75% of the fauna. Most of the kossmaticeratid specimens belong to the single species *M. tuberculatus* (Fig. 6). Compared to the absolute dominance of kossmaticeratids the generic richness is relatively low, displaying only seven genera. The last appearance datum of Antarctic phylloceratids and belemnites is recorded in Ammonite Assemblage 11 (Fig. 14).

There is a steady increment in the abundance of ammonite specimens in the rest of the MG Sequence. In spite of the large number of studied specimens, the generic richness remains relatively low, with only eight genera recorded. Kossmaticeratids still constitute the dominant ammonites, mostly represented by species of *Maorites* and *Grossouvrites*, but showing a diminishing abundance trend from about 80% in the Ammonite Assemblage 12 to about 50% in the Ammonite Assemblage 14 (Fig. 14). In the latter, the rest of the fauna corresponds to heteromorphs, pachydiscids, lytoceratids, and desmoceratids.

5. Inoceramid extinction in Antarctica and Tierra del Fuego

The extinction level of the inoceramid bivalves in Antarctica (Crame and Luther, 1997) and Tierra del Fuego (Olivero et al., 2003, 2009) is not well calibrated, but certainly in both regions the extinction level occurs in much older strata, probably late Campanian to early Maastrichtian, than the well-calibrated, mid-Maastrichtian extinction level in the Southern Ocean (MacLeod et al., 1996).

In Antarctica, the large form *A. rabotensis* Crame and Luther, represents the last of the inoceramid bivalves. As described above (see also Crame et al., 1996; Crame and Luther, 1997; Olivero and Medina, 2000), these large inoceramids are mostly recorded in dense concentrations in mid-outer shelf deposits of informal member II of the Rabot Formation and inner shelf deposits of the uppermost Beta Member of the Santa Marta Formation. In both units these inoceramids are associated with intensively bioturbated, storm-influenced silt- and very fine-grained sandstones, which imply well-oxygenated bottoms. However, in the uppermost beds of member II of the Rabot Formation in the localities of Punta Redonda and Hamilton Norte, the last horizon with *Antarcticceramus* consists of about 40 m of dark grey non-bioturbated mudstone, implying a poorly oxygenated bottom. Owing to poor preservation it is not possible to evaluate whether these large bivalves belong to the same species recorded in lower levels, but in any case this particular occurrence suggests that they were able to tolerate poorly oxygenated palaeoenvironmental settings as well. Interestingly, these last from Punta Redonda have an unusual shell structure. Shell microstructure of inoceramid bivalves is normally characterized by alternating thin bands that represent continuous and cyclic increments of shell growth. However, the specimens from Punta Redonda are characterized by marked growth breaks, which have been interpreted to reflect conditions of strong environmental stress (Elorza et al., 2001).

In the Austral Basin of southern Tierra del Fuego, the last inoceramid bivalves were recovered from Santonian–early Campanian, deep-marine, anoxic–dysoxic black shales of the “Estratos de Buen Suceso” where they consists of large forms of *Inoceramus* (*Platyceramus*) sp. (Fig. 15A) and *Sphenoceramus* sp. (Olivero and Medina, 2001). However, in the subsurface of northern Tierra del Fuego inoceramid prisms are well known up to lower mid-part, late Campanian–Maastrichtian? deposits, of the Cabeza de León Formation, informally known in pioneering oil-exploration studies as “Upper *Inoceramus*”, which is an age-equivalent of the late Campanian–early Maastrichtian? Bahía Thetis Formation exposed in southern Tierra del Fuego. Stratigraphically above the Bahía Thetis Formation, the silty mudstones and fine-grained sandstones of the Policarpo Formation record Maastrichtian foraminifera and the ammonites *Diplomoceras* sp., *Anagaudryceras* sp., *Maorites* sp., and *Pachydiscus* (*Neodesmoceras*) sp. (Olivero et al., 2009). Based on palynomorphs the top of the unit is referred to the Danian (Olivero et al., 2003). Inoceramid bivalves are not present in the Policarpo Formation and they are not known either in the upper, Maastrichtian, part of the Cabeza de León Formation in the subsurface. Calcareous fossils are not preserved in the anoxic–dysoxic,

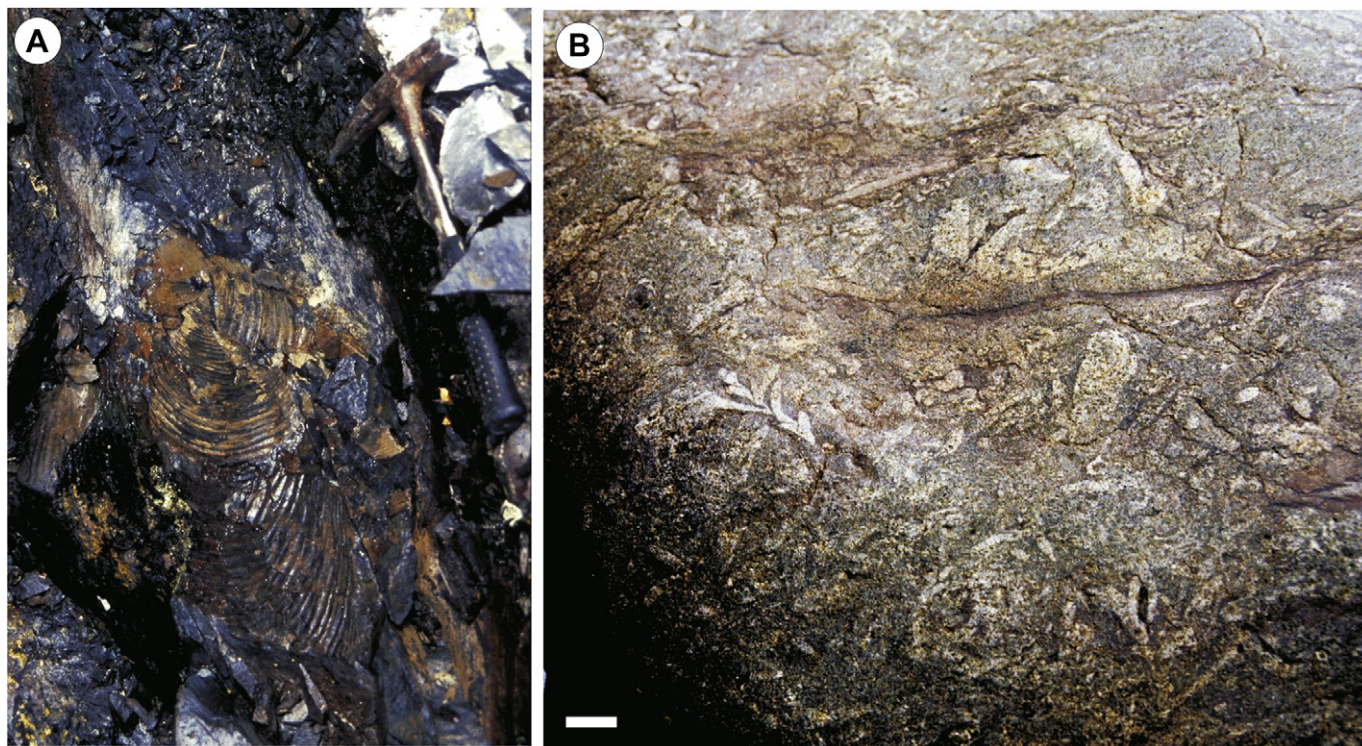


Fig. 15. Inoceramids and facies in the Santonian–lower Campanian and Maastrichtian of eastern Tierra del Fuego. A, large specimen of *Inoceramus* (*Platyceramus*) sp. in Santonian–lower Campanian black, laminated and non-bioturbated, dysoxic–anoxic slates of the “Estratos de Buen Suceso”; hammer for scale is 40 cm in length. B, thoroughly bioturbated beds of the Maastrichtian–Danian Policarpo Formation indicating well-ventilated bottom conditions.

deep-water, black slaty mudstones, sandstones and conglomerates of the Bahía Thetis Formation; thus the apparent lack of inoceramid bivalves in this unit could be an artefact of preservation. Based on regional correlations with the inoceramid-bearing part of the Cabeza de Cabeza de León Formation it is interpreted that in southern Tierra del Fuego the extinction level of the inoceramids is within the Bahía Thetis Formation (Olivero et al., 2003).

The organic-rich, late Campanian–Maastrichtian? black slates of the Bahía Thetis Formation contain abundant radiolaria and more restricted foraminifera of dysoxic environments. The slates preserve a delicate sedimentary banding and generally lack trace fossils, except for rare *Stelloglyphus* (Olivero et al., 2003). By contrast, the Maastrichtian–Danian Policarpo Formation is thoroughly bioturbated (Fig. 15B); in addition to a dense mottled structure, the trace fossils *Chondrites*, *Phycosiphon*, *Phymatoderma*, *Rhizocorallium*, *Schaubcylindrichnus*, *Spirophyton*, *Tasselia*, and *Zoophycos* are recorded (Olivero et al., 2003, 2009). The notable change in the density of bioturbation between the scarcely or non-bioturbated black slates of the Bahía Thetis Formation and the thoroughly bioturbated Policarpo Formation is a remarkable palaeoecological feature implying a strong change from anoxic–dysoxic to well-ventilated sea bottom conditions (Olivero et al., 2003).

6. Final remarks and conclusions

Ammonites were probably stenotopic organisms very sensitive to environmental changes, and since the classical work of Newell (1967) several workers have postulated a particular relationship between fluctuations in ammonite diversity and sea-level changes. Invoked potential mechanisms are the expansion and reduction of the shelf area during transgression and regressions, respectively, and the expansion of the oxygen minimum zone onto the

continental shelf during transgressions (e.g., Kauffman, 1977; Hallam, 1987; House, 1993; Hallam and Wignall, 1999). In the first mechanism, an increase of the neritic area during transgressions promotes diversification or radiation, whereas falling sea level and the consequent reduction of the shelf area promote extinction driven by increased competition for space and resources. This diversity–area effect, reflected in a steady increase in diversity during transgressions followed by a drop during regressions, has been successfully tested in many sedimentary cycles of Palaeozoic, Jurassic, and Cretaceous ammonites (Kauffman, 1977; Hallam, 1987; House, 1993; Hallam and Wignall, 1999).

This pattern of ammonite fluctuations with sea-level changes has been questioned on the basis that major sea-level changes also alter the nature of the geological and fossil record (e.g., Smith et al., 2001 and the bibliography therein). A taphonomic megabias can alter the ratio of shallow- to deep-marine continental shelf deposits preserved in the rock record both regionally and globally. This implies that shallow and deep-water facies are differentially preserved in the rock record; whereas the first are generally eroded in cratonic areas the latter are preserved in the deepest part of the basin, given the idea that diversity increase is related to rising sea level (Smith et al., 2001). However, this is not the case in Antarctica, where shallow water facies are not “perched” onto cratonic areas and the expansion of the shelf area gave plenty of accommodation, so that inner shelf and mid-outer shelf strata are similarly represented in the basin (Figs. 1–3). In addition, ammonites are abundant in both the regressive and transgressive facies and the number of ammonite specimens recovered from shallow and deep shelf facies is approximately the same (Fig. 14).

Fluctuations in ammonite generic richness (S) and faunal composition show contrasting patterns in the three Santonian–Maastrichtian Antarctic sequences studied. In the N Sequence ammonite generic richness is at a minimum in the Santonian

($S = 14$); it then increases gradually to an early Campanian maximum ($S = 20$) and finally decreases in the latest early Campanian ($S = 7$; Fig. 14). This pattern is typical for transgressive–regressive cycles where broadening of the shelf during peak transgression controls maximum diversity. By contrast, the late Campanian–Maastrichtian ammonites of the NG and MG sequences are dominated by kossmaticeratids, in both generic richness (which is much lower than in the N Sequence) and specimen abundance, but their diversity patterns do not reflect the expansion of the shelf during peak transgression. In spite of the large number of ammonite specimens studied, the generic richness of these two sequences is relatively low, with S varying between 12 and 9 in the NG Sequence and between seven and eight in the MG Sequence. In contrast to this diversity pattern of the more stenotopic organisms, such as the ammonites, fluctuations in diversity of the more eurytopic organisms, such as bivalves and gastropods, do accompany the changes in the shelf area during the sedimentary cycle. It is interesting to note that when the diversity of the whole macrofauna of the MG Sequence is plotted at the specific level (Macellari, 1988), diversity fluctuates within the sequence, showing a steady increase from a minimum at its base to a maximum in the most transgressive facies and then a decrease again in the most regressive facies at the top of the Sequence (Fig. 16).

The very peculiar set of conditions that characterize the Santonian–Maastrichtian in Antarctica, including patterns of ammonite diversity fluctuations, radiation of the kossmaticeratids in the NG and MG sequences, the early disappearance in the early Campanian or basal late Campanian of the scaphitids, baculitids, nostoceratids, most trigoniids and inoceramids, and the last record in the early Maastrichtian of the phylloceratids and belemnites, are indeed intriguing. Two main hypothesis have been put forward to explain these phenomena: a combination of a regional shallowing event and a pronounced phase of Campanian–Maastrichtian cooling (Crame et al., 1996) and the development of new environmental conditions associated with global cooling (Olivero and Medina, 2000; Zinsmeister and Feldmann, 1996).

Data presented herein indicate that the construction of the shelf and its expansion into the Weddel Sea was punctuated by three major second- or third-order cycles, so that during the Santonian–Danian there were at least three shallowing events, but they do not seem to be correlated with major biotic crises. Radiation of the kossmaticeratids in the NG and MG sequences seems to be independent of the respective shallowing events at their tops, and the K–Pg mass extinction predates the important Danian shallowing of the basin at the top of the MG Sequence (Figs. 2, 13 and 14). In addition, the level of extinction of the inoceramids in the Redonda Point and Hamilton Norte section is associated with the deepest facies recorded in the basin (Figs. 2 and 14).

Oxygen stable isotope data from southern high-palaeolatitudes, i.e., between 58° and 65° S, reveals extremely warm surface waters from the Turonian to the early Campanian and a long-term cooling of surface waters throughout the late early Campanian–Maastrichtian (Huber et al., 1995; see also Ditchfield et al., 1994 and Barrera and Sabin, 1999). It is envisaged that this long-term cooling of polar seawaters promoted a major, long-lasting ecological change during the Late Cretaceous that can best explain a set of seemingly disparate facts, including the early extinction of several cosmopolitan taxa and the radiation of the kossmaticeratid ammonites in Antarctica.

In lower latitudes the inoceramids disappeared during the mid-Maastrichtian, but the extinction pulse is diachronous, vanishing first in southern high-latitudes (MacLeod et al., 1996). It is thought that deep-marine inoceramids were adapted to some kind of chemosymbiotic mode of life in poorly oxygenated bottoms. Their extinction then is explained by progressive cooling and circulation

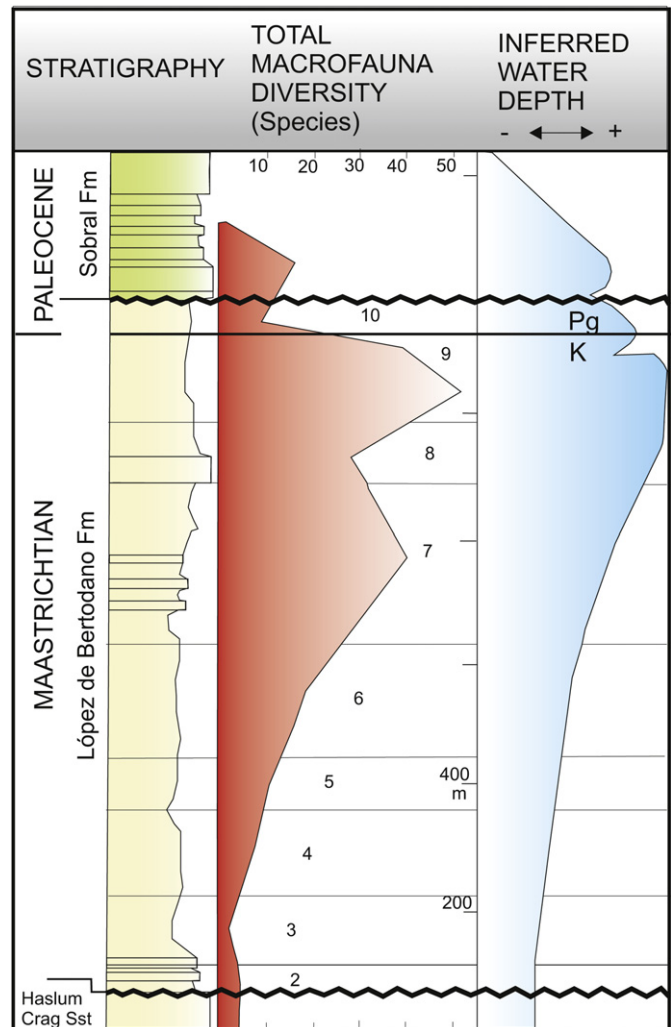


Fig. 16. Macrofaunal diversity of the Maastrichtian–Danian López de Bertodano Formation. Stratigraphical intervals 2–10 correspond to the informal units of Macellari (1988). Note that contrary to the ammonite diversity curve (Fig. 14) for the same time slice, the shape of the total macrofauna diversity reflects the postulated area–diversity effect. Modified from Macellari (1988).

of deep Antarctic waters to lower latitudes so that enhanced bottom ventilation disrupted their mode of life (MacLeod et al., 1996). However, most of the last Antarctic inoceramids inhabited well-oxygenated bottoms; thus the extinction of *Antarcticeramus* cannot be explained by enhanced ventilation (Crame and Luther, 1997). Nevertheless, the shell microstructure of the very last *Antarcticeramus* is characterized by marked growth breaks, which have been interpreted as reflecting conditions of strong environmental stress, particularly thermal stress (Elorza et al., 2001). On this basis, we concur with the ideas of Crame and Luther (1997) that falling seawater temperatures probably made the secretion of the large calcareous shell of *Antarcticeramus* physiologically impractical. The extinction of the deep-water forms of inoceramids from Tierra del Fuego is best explained by the hypothesis of MacLeod et al. (1996). Indeed, the change from anoxic–dysoxic to well-ventilated bottoms conditions, approximately at the interpreted extinction level in Tierra del Fuego is striking, and can be inferred by the abrupt change from laminated, organic-rich, and scarcely or non-bioturbated beds in the Bahía Thetis Formation to thoroughly bioturbated beds in the Policarpo Formation (Fig. 15).

Dominance of the Kossmaticeratidae in the late Campanian–Maastrichtian, concomitant with the known Austral temperature decline in the seawater, supports the idea that kossmaticeratids were stenothermal ammonites that flourished in Antarctica when the water masses had attained their preferred temperature and were displaced towards lower latitudes when a certain minimum threshold temperature was reached in the late Maastrichtian (Olivero and Medina, 2000). These diversity changes and local extinctions closely match temperature-cooling trends in the southern ocean and the oxygenation event at the inoceramid extinction level in Tierra del Fuego probably reflects cooling and enhanced bottom ventilation, promoted by circulation of deep Antarctic waters.

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