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MID CAMPANIAN-LOWER MAASTRICHTIAN MAGNETOSTRATIGRAHY OF THE JAMES ROSS BASIN, ANTARCTICA: CHRONOSTRATIGRAPHICAL IMPLICATIONS

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Abstract

The James Ross Basin, in the northern Antarctic Peninsula, exposes which is probably the world thickest and most complete Late Cretaceous sedimentary succession of southern high latitudes. Despite its very good exposures and varied and abundant fossil fauna, precise chronological determination of its infill is still lacking. We report results from a magnetostratigraphic study on shelfal sedimentary rocks of the Marambio Group, southeastern James Ross Basin, Antarctica. The succession studied covers a ~ 1200 m-thick stratigraphic interval within the Hamilton Point, Sanctuary Cliffs and Karlsen Cliffs Members of the Snow Hill Island Formation, the Haslum Crag Formation, and the lower López de Bertodano Formation. The basic chronological reference framework is given by ammonite assemblages, which indicate a Late Campanian – Early Maastrichtian age for the studied units. Magnetostratigraphic samples were obtained from five partial sections located on James Ross and Snow Hill islands, the results from which agree partially with this previous biostratigraphical framework. Seven geomagnetic polarity reversals are identified in this work, allowing to identify the Chron C32/C33 boundary in Ammonite Assemblage 8-1, confirming the Late Campanian age of the Hamilton Point Member. However, the identification of the Chron C32/C31 boundary in Ammonite Assemblage 8-2 assigns the base of the Sanctuary Cliffs Member to the early Maastrichtian, which differs from the Late Campanian age previously assigned by ammonite biostratigraphy. This magnetostratigraphy spans ~ 14 Ma of sedimentary succession and together with previous partial magnetostratigraphies on Early-Mid Campanian and Middle Maastrichtian to Danian columns permits a complete and continuous record of the

Late Cretaceous distal deposits of the James Ross Basin. This provides the required chronological resolution to solve the intra-basin and global correlation problems of the Late Cretaceous in the Southern Hemisphere in general and in the Weddellian province in particular, given by endemism and diachronic extinctions on invertebrate fossils, including ammonites. The new chronostratigraphic scheme allowed us to calculate sediment accumulation rates for almost the entire Late Cretaceous infill of the distal James Ross Basin (the Marambio Group), showing a monotonous accumulation for more than 8 Myr during the upper Campanian and a dramatic increase during the early Maastrichtian, controlled by tectonic and/or eustatic causes.

Keywords: Upper Cretaceous, Marambio Group, Paleomagnetism, Antarctic Peninsula.

Introduction

Located at the northeastern tip of the Antarctic Peninsula (Fig. 1), the James Ross Basin contains one of the most complete and expanded Upper Cretaceous reference sections of the Southern Hemisphere (Crame *et al.*, 1996, 1991; Feldmann & Woodbourne, 1988; Francis *et al.*, 2016; Olivero, 2012a). It is considered a sub-basin of the larger Larsen Basin (del Valle *et al.*, 1992), which has garnered interest as a potential hydrocarbon source since the second half of the 20th century (Behrendt, 1983; Macdonald *et al.*, 1988; Wright & Williams, 1974). The James Ross Basin comprises more than 6 km of marine clastic and volcaniclastic strata, from Early Cretaceous (Barremian) to Paleogene (Eocene) age. The best exposures are located on James Ross, Snow Hill, Seymour (Marambio), and Vega islands as well as other smaller islands of the James Ross archipelago. An important characteristic of the basin is the continuous, abundant, and diverse vertebrate, invertebrate, and plant fossil content. It constitutes a complete record of marine life since Early Cretaceous time providing evidence of non-glacial climates at polar latitudes. It also includes the Cretaceous – Paleogene transition in the upper Marambio Group at Seymour (Marambio) Island (Fig. 1), which makes the basin infill important for paleobiogeographic reconstructions of the Southern Hemisphere and global extinction patterns (Barreda *et al.*, 1999; Crame *et al.*, 1996; Guerra *et al.*, 2015; Iglesias, 2016; Raffi & Olivero, 2016; Reguero *et al.*, 2013; Tobin *et al.*, 2012). Most outcrops in the James Ross Basin are isolated, challenging lithological correlation, and it were decades of work by previous authors what achieved the stratigraphic column for the whole basin, based mainly on biostratigraphic correlations. The reference stratigraphic framework adopted in this work was defined by Olivero (2012a), who was able to establish a stratigraphic scheme for the Marambio Group based on ammonite assemblages (Fig. 2). Although the intra-basin correlation of units has been successfully accomplished, problems of endemism and early extinction of several invertebrate groups (including ammonites) in Antarctica hamper global correlations (Crame *et al.*, 1996; Francis *et al.*, 2006; McArthur *et al.*, 2000; Olivero, 2012a; Olivero & Medina, 2000; Raffi & Olivero, 2016). This uncertainty makes obtaining an independent absolute age framework a necessary requisite to validate biogeographic and paleoclimatological data for the Antarctic Peninsula in Cretaceous and Early Cenozoic times. Strontium isotopes obtained from wellpreserved marine invertebrate fossils have also been used in attempts of chronostratigraphic correlations (Crame *et al.*, 1999; Mcarthur *et al.*, 2000). However, these data come mainly from older successions than those studied here, i.e. Turonian to Early Campanian rocks exposed in the northweast areas of James Ross Island (McArthur *et al.*, 2000). The only age proposed by chemostratigraphy for the Late Campanian to Maastrichtian successions exposed in the southeast areas of the James Ross Basin is a *ca.* 74 Ma age assigned to a giant inoceramid from the Rabot Formation at Rabot Point (southeast James Ross Island), which is somewhat younger than the ages suggested by ammonite assemblages (Olivero, 2012a) and magnetostratigraphy (Milanese *et al.*, 2017). Mac Arthur *et al.* (2000) assigned a 71.3 Ma age to the Cape Lamb Member exposed on Vega Island (northwest James Ross Basin), which is partially equivalent to the Sanctuary and Karlsen Cliffs members of the Snow Hill Island Formation, two of the units covered in this work. Considering this correlation, chemostratigraphic data locate the Campanian - Maastrichtian boundary in the Sanctuary Cliffs Member, younger than the Late Campanian age assigned to this unit by ammonite biostratigraphy (Olivero, 2012a). In this scenario, magnetostratigraphy becomes an irreplaceable tool to obtain precise ages along the whole succession of the James Ross Basin, allowing for precise correlation of Late Cretaceous biota around Gondwana. Previous magnetostratigraphic studies on other partial sections (Milanese *et al.*, 2017, Tobin *et al.*, 2012) have proved to be useful for this goal. We present here a magnetostratigraphic study of the Late Cretaceous Snow Hill Island and Haslum Crag Formations and the basal levels of the López de Bertodano Formation. This study will fill the gap between the magnetostratigraphies from the Early-Mid

Campanian Rabot Formation (Milanese *et al.*, 2017) and from the Late Maastrichtian to Early Paleocene middle and upper levels of the López de Bertodano Formation (Tobin *et al.*, 2012).

Stratigraphic setting

The Cretaceous infill of the James Ross Basin is divided into two major groups: the Aptian-Coniacian Gustav Group and the Santonian-Danian Marambio Group. The coarse–grained, deep marine Gustav Group sediments were deposited in a normal fault - regulated submarine slope apron system located along the Prince Gustav Channel, which separates James Ross Island from the Antarctic Peninsula (Fig. 1). It represents an under - filled back-arc basin generated to the East of the magmatic arc of the Antarctic Peninsula (Ineson, 1989; Ineson *et al.*, 1986; Riding *et al.*, 1998; Riding & Crame, 2002; Scasso *et al.*, 1991; Whitham *et al.*, 2006). Outcrops of the Gustav Group are restricted to western James Ross Island. The fine-grained Marambio Group is more than 3 km thick, encompassing marine, shelfal sediments formed during three main phases of shelf expansion: during the Santonian-Early Campanian, after the Coniacian inversion stage of the basin, and during the Maastrichtian - Danian, when the already fully developed shelf extended for more than 150 km into the Weddell Sea (Olivero, 2012a). The Marambio Group is exposed at many localities across James Ross Island and the rest of the smaller surrounding islands. Figure 2 represents a northwest - southeast transect of the James Ross Basin and summarizes the stratigraphic and geographic distribution of the Group, including the main ammonite assemblages and the N, NG and MG transgressive - regressive sequences (Olivero, 2012a; Olivero & Medina, 2000). These sequences are limited by major unconformities and each one is named after its most characteristic kossmaticeratid ammonite. The stacking of N, NG and MG sequences shows the eastward migration of the coast line during the shelf construction (Olivero, 2012a). A brief lithological description of the Marambio Group units at southeast James Ross Basin is given below, and a simple stratigraphic scheme showing the equivalence between southeast James Ross Basin units involved in this work and their counterparts in the northwest sector of the basin, is given in Supplementary Material (Fig. S1).

The basal Rabot Formation (Lirio *et al.*, 1989; Marenssi *et al.*, 1992; Martinioni, 1992) is exposed at southeast James Ross Island (Figs. 1, 2 – S1) and it is partially equivalent to Santa Marta Formation, located in northwestern James Ross Island (Olivero, 1988, 1984; Olivero *et al.*, 1986; Scasso *et al.*, 1991). The Rabot Formation is composed of an intercalation of mud, sandstones and few conglomerates and tuffs and it was interpreted as a regressive sequence of prograding delta slope, storm-influenced deposits, and external shelf (Martinioni, 1992; Olivero *et al.*, 2010, 1986). The magnetostratigraphic results from this unit have been published by Milanese *et al.* (2017) and will be shown but not described in detail in this paper.

The Snow Hill Island Formation (Pirrie *et al.*, 1997) is above both Santa Marta and Rabot Formations and is represented by different lithologies in northwest and southeast sectors. Above Santa Marta Formation, we find the dinosaur bone – bearing sandstones of the Gamma Member - previously included in the Santa Marta Formation by Olivero *et al.* (1986) - and above Rabot Formation, we find the transgressive off-shore unconsolidated mudstones of the Hamilton Point, Sanctuary Cliffs, and Karlsen Cliffs Members, that together comprise ~ 900 m of unconsolidated mudstones and fine sandstones intercalations (Figs. 2 - S1).

Hamilton Point Member is the basal unit of Snow Hill Island Formation at southeast James Ross Basin. The unconformity that separates it from the underlying Rabot Formation is not exposed but it is defined by the abrupt change from external sandy facies to muddy off-shore facies. It is constituted basically by 500 m of unconsolidated mudstones with the intercalation of sporadic, also unconsolidated, thin tuff beds (< 20 cm thick). Oval carbonate concretions are also abundant, especially in the first 150 m. Their exposures are limited to southeast James Ross Island in three discontinuous sections (Fig. 1, see section 5.b.1 for a detailed description of the exposures). Ammonites are very scarce here, being the serpulids *Rotularia dorsolaevis* Ball and *Rotularia fallax* (Wilckens) the most abundant fossils.

Sanctuary Cliffs Member is exposed exclusively in the namesake nunatak at Snow Hill Island (Fig. 1). It is composed of ~ 200 m of unconsolidated mudstones and sanstones with hummocky stratification, present as a thick (~ 25 m) and continuous package at the base of the section or as ~ 0.5 m thick intercalated beds in the upper half (Fig. 2). Its fossil content is very abundant, with the kossmaticeratid *Neograhamites* cf. *kiliani* Spath being especially frequent.

The Karlsen Cliffs Member exposures are in Snow Hill (Spath Peninsula), James Ross (Ula Point) and Cockburn islands (Fig. 1). It is a coarsening and thickening upward succession of mudstones and sandstones. A very distinctive character of this unit is its orange weathering color, given by clay levels with high pyrite content, and the presence of oblate calcareous concretions of ~ 30 cm in diameter. At the basal levels there is a distinctive bed composed almost exclusively by the bivalve *Thyasira townsendi* (White).

The Haslum Crag Formation, restricted to Snow Hill and Seymour Islands (Figs. 1 - 2), is a ~ 200 m package of sandstones and glauconitic mudstones highly bioturbated with heterolithic stratification. Its base is defined by an erosive unconformity that represents the incision, migration and channel filling during a forced regression. This unit represents the only known to date example of a basal erosion surface carved by tidal action and not by waves, having this case being established as a theoretical possibility only (Olivero *et al.*, 2008; Posamentier *et al.*, 1992).

The López de Bertodano Formation is mostly in Snow Hill and Seymour islands, but a small outcrop is located at Cape Lamb, Vega Island (Figs. 1 - 2). It is constituted by ~ 1000 m of mudstones and very fine sandstones, both mostly unconsolidated. Its base is an unconformity that in some areas cuts up to 60 m over the underlying Haslum Crag Formation. These incisions are filled with lenticular channel bodies with heterolithic stratification, cross lamination, mud drapes, and marine fossils that suggest tide influence. This unit is highly fossiliferous, with several molluscs (bivalves, gastropods, cephalopods) and the serpulid *Rotularia.* Ammonite fauna is scarce, except for specific horizons abundant in the kossmaticeratid *Maorites tuberculatus*. This unit has been interpreted as estuarine transgressive deposits and includes the Cretaceous - Paleogene transition towards the top of the Formation (Fig. 2).

Early extinctions and endemism

Several faunal groups that reach the Maastrichtian in the rest of the world disappeared in Antarctica by the beginning of the middle Campanian: inoceramids, most dimitobelid belemnites and trigoniids, and ammonite families such as Scaphitidae, Baculitidae and Nostoceratidae, as well as the lytoceratid genus *Gaudryceras*, which disappear by the early-late Campanian (Raffi & Olivero, 2016). These early extinctions were accompanied by both an increment in the abundance and diversification of endemic species of the ammonite family Kossmaticeratidae. According to Witts *et al.* (2016, 2015), Olivero (2012), Olivero & Medina (2000) and Tobin *et al.* (2012), this Middle – Campanian early extinction was a consequence of a sea water cooling, but the precise age for the initiation of this cooling trend was not known due to the lack of a detailed chronostratigraphic framework in the basin. Olivero & Medina (2000) defined 15 ammonite assemblages for the Upper Cretaceous Marambio Group, most of them based on the first appearance datum (FAD) of a particular kossmaticeratid genus or on the co-occurrence of several genera. Olivero (2012a,b) refined these assemblages and used them to correlate the intra-basin outcrops and to establish a robust stratigraphic scheme for the Marambio Group, summarized in Figure 2.

Methodology

In order to obtain a continuous magnetostratigraphic column of the Marambio Group, taking into account the already produced partial magnetostratigraphies in the Rabot and López de Bertodano Formations (Milanese *et al.*, 2017, Tobin *et al.*, 2012), we carried out a systematic magnetostratigraphic sampling along five independent sections (Fig. 2). Three of them, *HC*, *HE* and *HD*, *are* located in the southeast area of James Ross Island and correspond to the basal unit of Snow Hill Island Formation, the Hamilton Point Member. The other two are on Snow Hill Island. The fourth section, *SCF*, corresponds to the Sanctuary Cliffs Member and the fifth section, *SP*, includes the Karlsen Cliffs Member, the Haslum Crag Formation and the lower part of López de Bertodano Formation, reaching up to Unit 4 of Macellari (1988). The general bedding attitude for the basin infill is 10-12° dipping to the E-SE. Despite local bedding variations and small scale normal and reverse faulting, all sections are homoclinal, with gently dipping strata becoming younger from northwest to southeast. Although there is no physical continuity between partial sections, special care was taken, both by field and image observations, to constrain the stratigraphic correlation between them. The potentially missed sedimentary thickness is unknown. From trigonometric calculations, the gap between sections is ≤ 40 m, except for the interval between *HD* and *SCF*, which could be under water, eroded, or even masked by tectonic structures. Sampling was carried out using portable gasoline-powered drills. We collected a total of 262 standard paleomagnetic cores oriented *in situ* with sun and magnetic compasses, each of them corresponding to a discrete stratigraphic level, precisely determined using a Jacob's staff and Abney hand level surveying tool. Although the lithology of the Marambio Group is mostly unconsolidated, hard sandstone beds and isolated spherical concretions are common and allowed sampling. Standard paleomagnetic specimens with a volume of 5.5 cm^3 were demagnetized using the routine described by Tobin *et al.* (2012) and Milanese *et* *al.* (2017). Measurements were carried out at the Paleomagnetics and Biomagnetics laboratory of the California Institute of Technology (USA), using an automatic 3-axis DC-SQUID moment magnetometer system, housed in a magnetically shielded room. The demagnetization routine started with two low-temperature cycling steps (samples were cooled to 77 K in liquid N_2 in a low field space) to remove viscous magnetizations carried by multidomain magnetite, followed by three low-intensity alternating field (AF) steps (from 2.3 to 6.9 mT) to remove secondary magnetizations acquired during collection and transportation of samples. Based on experience from previous studies in the Marambio Group, the main demagnetization process was thermal, from 80 °C to 575 °C in 15-10 °C steps, with samples being demagnetized in a trickle of N_2 gas above 120 °C to minimize oxidation. At the same laboratory we carried out IRM/Backfield curves up to 1 T and anhysteretic remanent magnetization (ARM) acquisition curves (AF_{MAX} 100 mT and 10 different continuous fields). Low (-200 to 20 °C) and high (0 to 700 °C) temperature thermomagnetic curves were obtained for representative samples using a Kappabridge™ multi-function susceptibilitimeter at the Laboratorio de Paleomagnetismo Daniel A. Valencio of the Instituto de Geociencias Básicas, Aplicadas y Ambientales de Buenos Aires (University of Buenos Aires - CONICET, Argentina). High temperature curves were carried out in an Ar atmosphere. Hysteresis cycles were obtained for 17 samples with a LakeShore 7404 magnetometer (H_{max} ¼ 2000 mT) located at the Laboratorio de Magnetismo of the Instituto de Física de La Plata (National University of La Plata, Argentina).

Treatment of paleomagnetic data was conducted throw PaleoMag 3.1 software (Jones, 2002) and Paleomagnetism.org online portal (Koymans *et al.*, 2016).

5. Results

5.a Magnetic properties

5.a.i Thermomagnetic curves

Each ferromagnetic mineral has its own variation pattern of bulk magnetic susceptibility (k) *vs*. temperature (T), making thermomagnetic curves a useful tool to identify the magnetic minerals in a sample. High temperature thermomagnetic curves give information about the Curie temperature (T_C) of the ferromagnetic minerals. Representative curves of Figure 3A show irreversible behaviors: in all cases, k values are higher in cooling than in heating curves. The susceptibility increase observed between 400 and 500 °C in heating curves, occurs in a temperature range close to (Ti) magnetite Curie's point (very pronounced in Fig. 3A, milder in Fig. 3B). This could be due to the increase in superparamagnetic behaviors just below Curie temperature, known as *Hopkinson's peak* (Hopkinson, 1889). However, being consistent with observations of magnetic instability during natural remanence thermal demagnetization approximately around those temperatures, and considering the irreversible character of thermomagnetic curves, this bump probably indicates formation of new-minerals during experimental heating. Cooling curves suggest that magnetite is the most likely newly-formed ferromagnetic mineral (T_C ~ 580 °C). Due to the high clay content in the upper Marambio Group rocks, especially in deep-marine facies, chemical transformation of clay minerals during heating could be the explanation for this magnetite formation (Pan *et al.*, 2000). An important observation in Fig. 3A is the absence of a mineral with T_C < 400 °C, which rules out significant amounts of many secondary magnetization common carriers (*e.g.*, maghemite, pyrrhotite, etc.). Additional thermomagnetic curves are provided in Supplementary Material (Fig. S2).

5.a.ii Isothermal remanent magnetization

Remanence coercivity (B_{CR}) and saturation field (B_{SAT}) are parameters that can be obtained from isothermal remanent magnetization (IRM) and backfield curves. Two examples of IRM curves from Marambio Group samples are shown in Fig. 3B. Magnetic parameters are summarized in Table 1 (*Grain sizes* section). B_{CR} values are around ~ 40 - 50 mT and from slope-corrected hysteresis cycles data coercivity (B_C) values between 14 and 22 mT are observed. This is consistent with the presence of a ferrimagnetic phase, probably titanomagnetite (s.l.). See Supplementary Material for additional IRM/Backfield curves and hysteresis cycles (Figs. S3 – S4).

5.a.iii Lowrie-Fuller tests and Day diagram

From several rock magnetic analyses, Milanese *et al.* (2017) ruled out the presence of greigite in the Rabot Formation samples, confirming that the most likely remanence carrier is some mineral of the titanomagnetite series. Lowrie-Fuller tests (Johnson *et al.*, 1975; Lowrie & Fuller, 1971) for the Marambio Group (Fig. 3C) show that anhysteretic magnetization is more resistant to AF demagnetization than IRM, characteristic behavior of SD or PSD magnetite. Additional Lowrie-Fuller tests are presented in Figure S5.

5.a.iv Grain size

B_{SAT}, B_{CR}, J_R and J_{SAT} were obtained from hysteresis cycles and IRM/backfield curves (Table 1). As already proposed by Dunlop (2002), it is not frequent that the PSD nature of the magnetic minerals in a sedimentary rock is due to a particular "PSD size and composition" of the grains. If the magnetic parameters of a rock indicate a PSD state, it is probably because a mix of single-domain (SD), multi-domain (MD), and superparamagnetic (SP) grains integrate the magnetic fraction. According to the Day diagram modified by Dunlop (Day *et al.*, 1977; Dunlop, 2002) of Figure 4, all samples belong to the PSD field, with variable proportions of SD, MD and SP. These results agree with those of Lowrie-Fuller tests, which are consistent with a PSD character of the magnetic fraction.

From the rock magnetic analyses described above, it can be inferred that the magnetization carrier of the Marambio Group sedimentary rocks belongs to the ferrimagnetic group. Greigite was already ruled out as significant in previous work (Milanese *et al.*, 2017). Hysteresis parameters, IRM curves, thermomagnetic curves and Lowrie-Fuller tests results are consistent with a mixture of single domain plus multi-domain or superparamagnetic titanomagnetite grains. Similar conclusions were obtained by Milanese *et al.* (2017) for the underlying Rabot Formation and by Tobin *et al.* (2012) for the overlying López de Bertodano Formation.

5.b Magnetostratigraphy

The Rabot Formation is partially equivalent to the upper part of the Santa Marta Formation, located at NW James Ross Island. These units correspond to the N sequence (Olivero & Medina, 2000), which is thicker in the proximal facies of the basin (Figs. 1 - 2). The C33r/C33n reversal was identified in Rabot Formation by Milanese *et al.* (2017), assigning it to the Middle Campanian and yielding an age of 79.9 Ma to a particular horizon in the middle part of the unit. Contrary to what occurs in N, the NG and MG sequences are thicker in the distal part, i.e. those exposed in the southeast sector of the basin. The magnetostratigraphic results presented here include three localities of the southeast sector of the basin, encompassing the whole NG sequence and the lower part of MG (Fig. 2). Characteristic remanence (ChRM) directions were calculated by means of principal components analysis (PCA, Kirschvink, 1980). Only those with maximum angular deviation (MAD) values under 10° were accepted. In a few cases, great circle analysis (McFadden & McElhinny, 1988) was performed to constrain the remanence direction along an arc. Most samples had a single magnetic component, although in many cases a small viscous remanence was removed with the first steps of low-temperature demagnetization, AF or thermal cleaning up to 150 °C. Thermal demagnetization could not proceed further than 400 - 480 °C in most cases, due to a random directional behavior above those temperatures produced, most likely, by chemical changes in clay minerals upon heating (Pan *et al.*, 2000; see also Fig. 3A).

Regarding polarity assignment to stratigraphic intervals, we calculated from every paleomagnetic direction the corresponding virtual geomagnetic pole (VGP) and their corresponding angular distance (paleocolatitude) to each locality paleomagnetic pole. After placing both mean paleopoles in the South Pole, paleolatitudinal position of VGPs were used to define the geomagnetic polarity for each stratigraphic level. Two or more continuous stratigraphic levels with the same polarity were required to assign such polarity to the corresponding interval in the stratigraphic column.

5.b.i Hamilton Point Member at Hamilton Point (NG sequence)

The Snow Hill Island Formation is composed by three members, in upward stratigraphical order: Hamilton Point, Sanctuary Cliffs and Karlsen Cliffs. The first one is exposed at Hamilton and Ekelof points, the second at Sanctuary Cliffs Nunatak, and the third along the Spath Peninsula (as well as at Cockburn Island and Ula Point, see Figs. 1- 2). The Hamilton Point Member was sampled along three partial sections: *HC*, *HE*, and *HD* (Fig. 5A), located at ~ 2.5 km from each other and reaching a total stratigraphic thickness of ~ 500 m. The section consists in 400 basal meters of unconsolidated mudstones and 100 upper meters of sandstones. Where beds were unconsolidated, paleomagnetic sampling was carried out on spherical concretions or concretionary layers. Pictures of the outcrops are presented in Figures 5B, C, D - E.

Figure 6 shows declination, inclination and maximum angular deviation (MAD) from paleomagnetic directions obtained in this unit. This member presents dominant negative inclinations, only disrupted by two thin intervals: one at 300 m, close to the top of *HE*, and the other at 340 m, at the base of *HD*. An isolated positive inclination can be identified at the base of *HC* section (~ 40 m level). The corresponding VGPs and the magnetostratigraphic interpretation are presented in section 6.

Almost all remanence directions were obtained by PCA, and great circle analysis were used in a single case. Characteristic paleomagnetic behaviors of Hamilton Point Member are shown in Figure 6. MAD were over 6° (but under 11°) in less than a dozen cases. *In situ* and stratigraphic (bedding corrected) mean paleomagnetic directions for Hamilton Point Member are shown in Table 2. A reversal test yields to an indeterminate result (McFadden & McElhinny, 1988). Stereographic projections with ChRMs distribution can be found in Supplementary Material (Fig. S6).

5.b.ii Sanctuary Cliffs Member at Sanctuary Cliffs

The only known outcrop of the Sanctuary Cliffs Member is the namesake nunatak on Snow Hill Island (Fig. 7A). The magnetostratigraphic column covers 210 meters of an homoclinal continuous section of unconsolidated mudstones, except for 30 meters of fine sandstones in the base of the succession and some intercalated sandstone levels at the upper part of the section. Views of the outcrops are shown in Figure 7B. Most of the paleomagnetic directions were isolated using PCA (e.g. sample SCF65, Fig. 8), with a few exceptions in which great circle analysis was used. An example of a direction obtained by this method can be observed in Figure 8 (sample SCF04). Declination, inclination and MAD for paleomagnetic directions along the stratigraphic section of Sanctuary Cliffs Member are also shown in Figure

8. Sanctuary Cliffs column presents dominantly positive inclinations, except for two brief intervals at the base and at the 25 – 30 m interval (Fig. 8). The corresponding VGPs and the magnetostratigraphic interpretation are presented and discussed in section 6. *In situ* and stratigraphic mean paleomagnetic directions for Sanctuary Cliffs Member are presented as a part of Snow Hill Island locality data (Table 2). Stereographic projections with ChRMs distribution can be found in Supplementary Material (Fig. S7).

5.b.iii Karlsen Cliffs Member, Haslum Crag Formation and López de Bertodano Formation at Spath Peninsula

At Spath Peninsula, a continuous section containing the Karlsen Cliffs Member (the upper unit of the Snow Hill Island Formation), the Haslum Crag Formation and the basal units (lower 150 meters) of the López de Bertodano Formation, was sampled. This constitutes the uppermost levels of the Marambio Group exposed in that location (Fig. 9). The sampled levels of the latter formation reach up to Unit 4 of Macellari (1988). ChRM of most samples was isolated using PCA (Fig. 10) and the whole 510 m of the succession, except for one sample at the ~ 80 m level, presents positive inclinations. Views of the outcrops are shown in Figures 7C, D – E.

In situ and stratigraphic mean values for these three units are shown in Table 2, as a part of Snow Hill Island locality data. The stratigraphic mean leads to an indeterminate reversal test. Stereographic projections with ChRMs distribution are given in Supplementary Material (Fig. S7).

The magnetostratigraphic results and polarity interpretation are shown in Figure 11, together with the rest of the units, and discussed in the next section.

6. Discussion

Characteristic remanence directions from the analyzed stratigraphic sections lead to positive or indeterminate reversal tests when considered within each locality, which, together with the rock magnetic studies, points to a primary condition for the isolated ChRMs. However, they fail the test when considered altogether. Mean direction from Hamilton Point Member matches with previous ones obtained from Rabot (Milanese *et al.*, 2017) and Santa Marta Formations Milanese (2018), located at southeast and northwest James Ross Island, respectively. These mean directions also are similar tothe one obtained by Tobin *et al.* (2012) in upper López de Bertodano Formation on Seymour Island. However, the mean direction computed from the sections sampled at Snow Hill Island is discordant and suggests that such island may have been affected by a counter-clockwise tectonic rotation around a vertical axis. Discussion and interpretation of the tectonic implications of these pole positions exceeds the aim of this contribution. The reader is referred to Milanese (2018) for a detailed discussion of this issue.

Figure 11 shows the stratigraphic distribution of the virtual geomagnetic poles (VGPs) paleolatitudes computed from the paleomagnetic directions shown in Figures 6, 8 and 10, the interpreted magnetic polarity, and the proposed correlation between the integrated local magnetostratigraphic columns of the southeast sector of James Ross Basin presented in this study and the Global Polarity Time Scale

(Ogg *et al.*, 2016). VGPs paleolatitudes were computed with respect to the paleomagnetic pole at each locality (68.2ºS, 215.6ºE, A_{95} :12.9º for southeast James Ross Island, and 53.4ºS, 39.9ºE, A_{95} :12.9º, for Snow Hill Island). Based on these calculations, an interval was considered normal (reverse) when at least two consecutive stratigraphic levels presented VGPs with paleolatitudes > 0° (< 0°). Figure 11 also shows a gray stripe centered at 0° in the VGP paleolatitude column. This stripe is 20° wide and is derived from applying a filter based on a secular variation model (Vandamme, 1994). VGP's falling within were considered transitional. The geomagnetic inclination predicted by a geocentric axial dipole (GAD) of the sampling area is -76.5°.

The studied succession is dominated by normal polarities in the lower ~ 550 m with two brief intervals of reversed polarity at 250-300 meters (represented by two stratigraphic levels) and 550-560 m (represented by several stratigraphic levels). These characteristics, magnetostratigraphic results from the underlying Rabot Formation and ages suggested by biostratigraphic data permit a correlation of this part of the section with C32 Chron (Fig. 11). There seems to be little doubt that the higher reverse interval should correspond to sub-chron C32n.1r (Ogg *et al.*, 2016), meanwhile that at 250-300 m is correlated with subchron C32r.2r. At the ~ 350 m level just one stratigraphic interval presents a reversed VGP, followed by several intervals of transitional character or low paleolatitude. We tentatively consider this interval as corresponding to subchron C32r.1r. However, since its determination is more uncertain, is represented in gray in the polarity column and its correlation indicated with a question mark (Fig. 11). The Campanian-Maastrichtian boundary is, therefore, placed in the lowermost part of the Sanctuary Cliffs Member.

The upper half of the sampled succession presents only reversed polarities which is correlated to Chron C31r, and implies that the upper two members of the Snow Hill Island Formation, the Haslum Crag Formation and the lower levels of the López de Bertodano Formation are Maastrichtian.

Our magnetostratigraphy was integrated with previous results, from Milanese *et al.* (2017) from the underlying levels and Tobin *et al.* (2012) from the overlying ones, to give a full chronostratigraphic picture of the distal deposits of the Marambio Group (Fig. 12). The lower levels of Marambio Group are not recorded as its basal contact with the Gustav Group is not exposed in this area of the basin. The composite column permits the determination of precise ages for the whole succession. Given the finding of the C33r/C33n reversal in the Rabot Formation (Fig. 12; Milanese *et al.*, 2017) and the Late Campanian age assigned to Ammonite Assemblages 8-1 and 8-2, the only plausible correlation for the basal normal interval of the Hamilton Point Member, as mentioned, is with C33n (Fig. 12). Normal polarities dominate along the section and extend to the base of the Sanctuary Cliffs Member of the Snow Hill Island Formation, with the only exception of two brief reverse intervals at the top of *HE*, and the base of *HD* sections at intermediate levels of the Hamilton Point Member. A third brief reverse interval is found near the base of the Sanctuary Cliffs Member (Fig. 11). The only possible correlation of this predominantly normal interval is with chron C32.

Ammonite Assemblage 9 is recognized at the upper levels of the Sanctuary Cliffs Member and is confirmed by the short co-ocurrence of *Neograhamites* cf. *kiliani* and *Gunnarites*. This assemblage is also present in the proximal facies of the basin (Fig. 2) and has been postulated as an important correlation horizon, assigned by

(Olivero, 2012a) to the Late Campanian. Our magnetostratigraphic results indicate, however, that this assemblage corresponds to the reversed C31 Chron, *i.e.* Early Maastrichtian. Furthermore, the uppermost levels of Assemblage 8-2 also are Maastrichtian, which is consistent with the basal Maastrichtian age proposed for the Sanctuary Cliffs Member by Sr stratigraphy (Crame *et al.*, 1999; Mcarthur *et al.*, 2000). The long reversed interval that extends from lower-middle levels of the Sanctuary Cliffs Member to Unit 4 of López de Bertodano Formation correlates with C31r, consistent with the magnetostratigraphic results of Tobi*n et al.* (2012) on Seymour (Marambio) Island, that identified the same Chron and its transition to C31n in Unit 7 of that formation.

All the established correlations in this work should permit computing sedimentary accumulation rates (SAR) for the Marambio Group. Although our and previous samplings of the Marambio Group have been systematic and continuous, gaps between sections exist, as already mentioned, and therefore estimated SAR values should be considered minimum ones, when nothing is indicated otherwise. From a simple cartesian diagram of accumulated thickness *vs.* ages (Fig. S8), we have obtained SARs of 9 cm/kyr for the C33n + C32 Chrons interval, 50 cm/kyr for C31r, and 13 cm/kyr for C31n + C30 + C29r. To make these calculations, we included previous magnetostratigaphic results from Rabot Formation exposed in southeast James Ross Island and López de Bertodano Formation in Seymour Island. The boundaries used in the calculation are given in Table S1. A rather monotonous and low SAR value characterizes the lower third of the Marambio Group, in particular the upper half of the Rabot Formation and the whole Hamilton Point Member of the Snow Hill Island Formation. This suggests that the distal areas of the James Ross

Basin developed in a tectonically and eustatically quiescent first-order scenario for almost nine Myr (from around 80 to 71.5 Ma, Fig. 12). This is consistent with the fine-grain and nearly uniform sediments of the upper Rabot and lower Snow Hill Island Formations. A major change in SAR is exposed by data from strata encompassing Chron C31r, which yield values four to five times higher than the ones obtained from the rest of the composite section. To equate SAR values, it could be considered the possibility that Chron C32 does not begins in middle Hamilton Point Member, but rather that the entire Rabot Formation was deposited during C32. This option was already discussed by Milanese *et al.* (2017) and is invalidated by magnetostratigraphic and biostratigraphic data. A long basal reverse interval was identified in three independent sections of Rabot Formation (Fig. 12 shows Redonda Point and Hamilton Norte sections only, see Milanese, 2018) that turns unlikely the possibility to extend C32 to the base of Rabot Formation. In this scenario, C33n would be completely missing. Furthermore, it would imply that Ammonite Assemblages 6 and 7 are of very late Campanian ages. This also is extremely unlikely, since ammonites from Assemblage 7 (upper half of Rabot Formation, Fig. 12) are cosmopolitans or with Indo-Pacific affinities, being the James Ross Basin endemism developed after Middle Campanian. The base of Assemblage 7, *Neokossmaticeras redondensis*, has the ammonites *Baculites subanceps* Matsumoto and Obata, *Metaplacenticeras subtilistriatum* (Jimbo), and *Hoplitoplacenticeras sp.,* which are guide fossils indicative of the base of Middle Campanian elsewhere in the world (cf. Matsumoto, 1984; Olivero, 1992) and a C33r/C33n boundary proxy, consistent with the magnetostratigraphic interpretation of Milanese *et al.* (2017), reproduced in Figure 12. These ammonites are in continuity with typical Santonian (Ass. 1) and Early Campanian (Ass. 2, 3, 5 and 6) assemblages from southeastern and northwestern James Ross Basin (see Fig. 2). Therefore, the major change in SAR in the upper members of the Snow Hill Island Formation seems unavoidable. Unfortunately, this value is only determined by the base and top of Chron C31r, so that low stratigraphic resolution of exact time of SAR change is available. Furthermore, it is very likely that different SAR should correspond to different stratigraphic units comprised in that interval that cannot be resolved with our data. Despite these limitations, it is notorious that a significant sedimentological change has been described in detail for the uppermost Snow Hill Island and Haslum Crags Formations (Olivero *et al.*, 2008) and interpreted as influenced by enhanced subsidence of the basin, probably due to tectonic causes. The marked increase in SAR could be likely related to the deltaic and estuarine paleoenvironments of Sanctuary Cliffs, Karlsen Cliffs, Haslum Crag, and lower López de Bertodano, which are commonly characterized by very high sedimentation rates (e.g. Einsele, 1992). Olivero *et al.* (2008) have described the Karlsen Cliffs member of the Snow Hill Island Formation as coarsening and thickening upward successions of prograding deltaic lobes, meanwhile the overlying, above a marked unconformity, Haslum Crag Formation would record the incision, migration, and filling of relatively large and deep subtidal channels during a forced regression. In turn, these sandstones were later deeply incised and covered by the basal levels of the López de Bertodano Formation assigned to transgressive estuarine and shallow marine deposits that fill a previous fluvially and/or tidally scoured depression. These authors proposed that the great thicknesses of tide-influenced forced regressive deposits (Haslum Crag Formation) and the transgressive, estuarine deposits (lower López de Bertodano Formation) should be related to the occurrence of several high-frequency sea-level changes, probably driven by tectonic processes. This marked contrast in the sedimentological and basin infill conditions with respect to the previous Rabot and, mainly, lower Snow Hill Island Formation deposits coincides with the conspicuous increase in the SAR of the James Ross Basin at these localities as determined by our study. This major change in the basin infill conditions probably marks an end to the apparent tectonic quiescence in this part of the basin that lasted until the early Maastrichtian. Olivero *et al.* (2008) associated this change to a coeval major pulse of tectonic uplift recorded in the Fuegian Andes of southern South America, which by the latest Cretaceous was very close and probably in crustal continuity with the Antarctic Peninsula (e.g. Gao *et al.*, 2018). However, the major change in SAR could also have been influenced by (glaci?) eustatic changes as is coincidental with an important shift towards globally cooler waters as determined by $\delta 0^{18}$ during the Early Maastrichtian (C31r) that has been interpreted as causing the development of the first Antarctic ice sheet (Miller *et al.*, 1999).

7. Conclusions

Our detailed magnetostratigraphic study focused on the Late Cretaceous Marambio Group exposed in the SE sector of the James Ross Basin near the Antarctic Peninsula. Samples encompassed the Snow Hill Island and Haslum Crag Formations and the basal 150 meters of the López de Bertodano Formation, covering over 1200 meters of an almost complete stratigraphic succession. Our results, together with previous work on the underlying Rabot Formation and the overlying middle and upper levels of the López de Bertodano Formation creates a composite magnetostratigraphic column of the whole Marambio Group, except for the lowermost levels not exposed in this area. The magnetostratigraphic data yield a robust and precise chronostratigraphic framework for the Upper Cretaceous marine units at the SE sector of the James Ross Basin which was previously based almost exclusively on ammonite assemblages and Sr isotopes studies. Seven geomagnetic polarity reversals were identified, and the unambiguous determination of C33/C32 and C32/C31 limits allowed assigning precise chronostratigraphic positions to the kossmaticeratid assemblages. According to Gradstein *et al.* (2012) GPTS, ages are: a) 74.3 Ma (Late Campanian) to Ammonite Assemblage 8-1, at middle levels of the Hamilton Point Member and b) 71.4 Ma (Early Maastrichtian) to Ammonite Assemblage 8-2, at the base of the Sanctuary Cliffs Member. Previous studies in James Ross and Seymour (Marambio) Islands had determined that the C33r/C33n reversal occurs at intermediate levels of the Rabot Formation and that the Cretaceous-Paleocene boundary lies within Unit 7 of the López de Bertodano Formation.

Sediment accumulation rates were computed for the development of the James Ross Basin infill at these localities. A monotonous rate of 9 cm/kyr characterizes the sedimentation during nearly 9 Ma, along the whole Late Campanian (upper Rabot and lower Snow Hill Island Formations). A major increase to a mean of 50 cm/kyr is observed for the upper Snow Hill Island, Haslum Crag and lower Lopez de Bertodano Formations deposited during the early Maastrichtian. This change is consistent with the sedimentological features of these units and could be related either to a tectonic uplift pulse in the Fuegian Andes and/or (glaci?) eustatic processes governed by a significant global cooling during C31r. By late Maastrichtian-Danian times, accumulation rates diminished to a mean of 13 cm/kyr.

Our magnetostratigraphic data offers an unprecedented high-resolution chronostratigraphy for the Mid Campanian-Maastrichtian interval of the James Ross Basin, which can be used to make precise correlations with key paleoclimatological and paleobiological events around Gondwana in general and the Southern Atlantic and Indian Oceans in particular.

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9. References

Barreda, V.D., Palamarczuk, S. & Medina, F.A. (1999) Palinología de la Formación Hidden Lake (Coniaciano-Santoniano), isla James Ross, Antártida. Revista Española de Micropaleontología 31, 53–72.

Behrendt, J.C. (1983) Petroleum and Mineral Resources of Antarctica. U.S. Geological Survey Circular 909, 75 pp.

Crame, J.A., Lomas, S.A., Pirrie, D. & Luther, A. (1996) Late Cretaceous extinction patterns in Antarctica. Journal of the Geological Society 153, 503–506. doi:10.1144/gsjgs.153.4.0503

Crame, J.A., McArthur, J.M.M., Pirrie, D. & Riding, J.B. (1999) Strontium isotope correlation of the basal Maastrichtian Stage in Antarctica to the European and US biostratigraphic schemes. Journal of the Geological Society 156, 957–964. doi:10.1144/gsjgs.156.5.0957

Crame, J.A., Pirrie, D., Riding, J.B. & Thomson, M.R.A. (1991) Campanian-Maastrichtian (Cretaceous) stratigraphy of the James Ross Island area, Antarctica. Journal of the Geological Society 148, 1125–1140. doi:10.1144/gsjgs.148.6.1125

Day, R., Fuller, M. & Schmidt, V.A. (1977) Hysteresis properties of titanomagnetites: Grain-size and compositional dependence. Physics of the Earth and Planetary Interiors 13, 260–267. doi:10.1016/0031-9201(77)90108-X

del Valle, R.A., Elliot, D.H., Macdonald, D.I.M. & (1992) Sedimentary basins on the east flank of the Antarctic Peninsula: proposed nomenclature. Antarctic Science 4, 477–478. doi:10.1017/S0954102092000695 do Monte Guerra, R., Concheyro, A., Lees, J., Fauth, G., de Araujo Carvalho, M. & Rodriguez Cabral Ramos, R. (2015) Calcareous nannofossils from the Santa Marta Formation (Upper Cretaceous), northern James Ross Island, Antarctic Peninsula. Cretaceous Research 56, 550–562. doi:http://dx.doi.org/10.1016/j.cretres.2015.06.009

Dunlop, D.J. (2002). Theory and application of the Day plot (Mrs/Ms versus Hcr/Hc) 1. Theoretical curves and tests using titanomagnetite data. Journal of Geophysical Research 107, 1–22. doi:10.1029/2001JB000486

Einsele, G. (1992) Sedimentary Basins. Springer, Berlin.

Feldmann, R.M. & Woodbourne, M.O. (1988) Geology and paleontology of Seymour Island, Antarctic Peninsula. The Geological Society of America Memoirs 169.

Francis, J.E., Crame, J.A. & Pirrie, D. (2006). Cretaceous-Tertiary high-latitude palaeoenvironments, James Ross Basin, Antarctica: introduction. Geological Society of London, Special Publications 258, 1–5.

Gao, L., Zhao, Y., Yang, Z., Liu, J., Liu, X., Zhang, S.H. & Pei, J. (2018) New paleomagnetic and 40Ar/39Ar geochronological results for the South Shetland Islands, West Antarctica, and their tectonic implications. Journal of Geophysical Research: Solid Earth 123, 4–30. doi:10.1002/2017JB014677

Gradstein, F.M., Ogg, J.G., Schmitz, M.D. & Ogg, G.M. (2012) The Geologic Time Scale 2012. Elsevier, Oxford. doi:10.1016/B978-0-444-59425-9.01001-5

Hopkinson, J., 1889. Magnetic and other Physical Properties of Iron at a High Temperature.

Iglesias, A. (2016) New Upper Cretaceous (Campanian) Flora from James Ross

Island, Antarctica. Ameghiniana 53. doi:10.5710/AMGH.17.02.2016.2930

Ineson, J.R. (1989) Coarse-grained submarine fan and slope apron deposits in a Cretaceous back-arc basin, Antarctica. Sedimentology 36, 793–819. doi:10.1111/j.1365-3091.1989.tb01747.x

Ineson, J.R., Crame, J.A. & Thomson, M.R.A. (1986) Lithostratigraphy of the Cretaceous Strata of West James Ross Island, Antarctica. Cretaceous Research 7, 141–159.

Johnson, H.P., Lowrie, W. & Kent, D.V. (1975). Stability of anhysteretic remanent magnetization in fine and coarse magnetite and maghemite particles. Geophysical Journal International 41, 1–10.

Jones, C.H. (2002) User-driven Integrated Software Lives: “PaleoMag” Paleomagnetics Analysis on the Macintosh. Computers and Geosciences 28, 1145–1151.

Kirschvink, J.L. (1980) The least-squares line and plane and the analysis of palaeomagnetic data. Geophysical Journal of the Royal Astronomical Society 62, 699–718.

Koymans, M.R., Langereis, C.G., Pastor-galán, D., Hinsbergen & D.J.J. Van (2016) Computers & Geosciences Paleomagnetism . org : An online multi-platform open source environment for paleomagnetic data analysis. Computers and Geosciences 93, 127–137. doi:10.1016/j.cageo.2016.05.007

Lirio, J.M., Marenssi, S.A., Santillana, S. & Marshall, P. (1989) El Grupo Marambio en el Sudeste de la isla James Ross, Antártida. Contribución del Instituto Antártico Argentino.

Lowrie, W. & Fuller, M. (1971) On the alternating field demagnetization characteristics of multidomain thermoremanent magnetization in magnetite. Journal of Geophysical Research. doi:10.1029/JB076i026p06339

Macdonald, D.I.M., Barker, P.F., Garrett, S.W., Ineson, J.R., Pirrie, D., Storey, B.C., Whitham, A.G., Kinghorn, R.R.F. & Marshall, J.E.A. (1988). A preliminary assessment of the hydrocarbon potential of the Larsen Basin, Antarctica. Marine and Petroleum Geology 5, 34–53. doi:10.1016/0264-8172(88)90038-4

Macellari, C.E. (1988) Stratigraphy, sedimentology, and paleoecology of Upper Cretaceous/Paleocene shelf-deltaic sediments of Seymour Island. Geological Society of America Memoirs 16, 25–54. doi:10.1130/MEM169-p25

Marenssi, S.A., Lirio, J.M., Santillana, S., Martinioni, D.R. & Palamarczuk, S. (1992) El Cretácico Superior del sudeste de la isla James Ross, Antártida, in: Geología de La Isla James Ross. Instituto Antártico Argentino, pp. 77–85.

Martinioni, D.R. (1992) La Formación Rabot (Cretácico superior, Isla James Ross, Antártida): Un ciclo transgresivo-regresivo de plataforma con dominio de procesos de tormenta, in: Rinaldi, C.A. (Ed.), Geología de La Isla James Ross, Antártida. Instituto Antártico Argentino, Buenos Aires, pp. 101–123.

Matsumoto, T. (1984) Some ammonites from the Campanian (Upper Cretaceous) of northern Hokkaido. Paleontological Society of Japan, Special Paper 27, 1–93.

Mcarthur, J.M., Crame, J.A. & Thirlwall, M.F. (2000). Definition of Late Cretaceous stage boundaries in Antarctica using strontium isotope stratigraphy. The Journal of Geology 108, 623–640. doi:10.1086/317952

McFadden, P.L.L. & McElhinny, M.W., (1988) The combined analysis of remagnetization circles and direct observations in palaeomagnetism. Earth and Planetary Science Letters 87, 161–172. doi:10.1016/0012-821X(88)90072-6

Milanese, F.N. (2018) Magnetoestratigrafía del Cretácico Superior de la Magnetoestratigrafía del Cretácico Superior de la cuenca James Ross, Antártida. Universidad de Buenos Aires.

Milanese, F.N., Olivero, E.B., Kirschvink, J.L. & Rapalini A.E. (2017) Magnetostratigraphy of the Rabot Formation, Upper Cretaceous, James Ross Basin, Antarctic Peninsula. Cretaceous Research 72, 172–187. doi:10.1016/j.cretres.2016.12.016

Miller, K.G., Barrera, E., Olsson, R.K., Sugarman, P.J. & Savin, S.M. (1999) Does ice drive early Maastrichtian eustasy? Geology 27, 783–786. doi:10.1130/0091-7613(1999)027<0783:DIDEME>2.3.CO;2

Ogg, J.G., Ogg, G.M. & Gradstein, F.M. (2016) A Concise Geologic Time Scale: 2016. Elsevier.

Olivero, E.B. (2012a) Sedimentary cycles, ammonite diversity and palaeoenvironmental changes in the Upper Cretaceous Marambio Group, Antarctica. Cretaceous Research 34, 348–366. doi:10.1016/j.cretres.2011.11.015

Olivero, E.B. (2012b) New Campanian kossmaticeratid ammonites from the James Ross Basin, Antarctica, and their possible relationships with Jimboiceras? antarcticum Riccardi. Revue de Paleobiologie 31, 133–149.

Olivero, E.B. (1992). Asociaciones de Amonites de la Formación Santa Marta (Cretácico Tardío), Isla James Ross, Antártida. In: Rinaldi, C.A. (Ed.), Geología de La Isla James Ross. Instituto Antártico Argentino, Buenos Aires, pp. 45–75.

Olivero, E.B. (1988) Early Campanian heteromorph ammonites from James Ross Island, Antarctica. National Geographic Research 4, 259–271.

Olivero, E.B. (1984) Nuevos amonites campanianos de la Isla James Ross, Antártida. Ameghiniana 21, 53–84.

Olivero, E.B., López Cabrera, M.I. & Torres Carbonell, P.J. (2010) Graphoglyptids from shallow marine, high-energy, organic-rich, and bioturbated turbidites, Fuegian Andes, Argentina. Acta Geologica Polonica 60, 77–91.

Olivero, E.B. & Medina, F.A. (2000) Patterns of Late Cretaceous ammonite biogeography in southern high latitudes: the family Kossmaticeratidae in Antarctica. Cretaceous Research 21, 269–279. doi:10.1006/cres.1999.0192

Olivero, E.B., Ponce, J.J. & Martinioni, D.R. (2008) Sedimentology and architecture of sharp-based tidal sandstones in the upper Marambio Group, Maastrichtian of Antarctica. Sedimentary Geology 210, 11–26. doi:10.1016/j.sedgeo.2008.07.003

Olivero, E.B., Scasso, R.A. & Rinaldi, C.A. (1986) Revision of the Marambio Group, James Ross Island, Antarctica. Contribution del Instituto Antártico Argentino 331, 27 pp.

Pan, Y., Zhu, R., Banerjee, S.K., Gill, J. & Williams, Q. (2000) Rock magnetic properties related to thermanl treatment of siderite: Behavior and interpretation. Journal of Geophysical Research 105, 783–794.

Pirrie, D., Crame, J.A., Riding, J.B. & Lomas, S.A. (1997) Late Cretaceous stratigraphy of the Admiralty Sound region, James Ross Basin, Antarctica. Cretaceous Research 18, 109–137. doi:10.1016/0195-6671(91)90036-C

Posamentier, H.W., Allen, G.P., James, D.P. & Tesson, M. (1992) Forced regressions in a sequence stratigraphic framework: concepts, examples, and exploration signifi- cance. American Association of Petroleum Geologists Bulletin 73, 1678–1709.

Raffi, M.E. & Olivero, E.B. (2016) The ammonite genus Gaudryceras from the Santonian-Campanian of Antarctica: Systematics and biostratigraphy. Ameghiniana 53, 375–396. doi:10.5710/AMGH.29.02.2016.2972

Reguero, M., Goin, F.J., Hospitaleche, C.A., Marenssi, S.A. & Dutra, T. (2013) Late Cretaceous/Paleogene West Antarctica Terrestrial Biota and its Intercontinental Affinities, in: Springer Briefs in Earth System Sciences. Springer, pp. 19–25. doi:10.1007/978-94-007-5491-1_1

Riding, J.B. & Crame, J.A. (2002) Aptian to Coniacian (Early-Late Cretaceous) palynostratigraphy of the Gustav Group, James Ross Basin, Antarctica. Cretaceous Research 23, 739–760. doi:10.1006/cres.2002.1024

Riding, J.B., Crame, J.A., Dettmann, M.E. & Cantrill, D.J. (1998) The age of the base of the Gustav Group in the James Ross Basin, Antarctica. Cretaceous Research 19, 87–105. doi:10.1006/cres.1998.0098

Scasso, R.A., Olivero, E.B. & Buatois, L.A., (1991) Lithofacies, biofacies, and ichnoassemblage evolution of a shallow submarine volcaniclastic fan-shelf depositional system (Upper Cretaceous, James Ross Island, Antarctica). Journal of South American Earth Sciences 4, 239–260. doi:10.1016/0895-9811(91)90034-I

Tobin, T.S., Ward, P.D., Steig, E.J., Olivero, E.B., Hilburn, I.A., Mitchell, R.N., Diamond, M.R., Raub, T.D. & Kirschvink, J.L. (2012) Extinction patterns, δ 18

O trends, and magnetostratigraphy from a southern high-latitude Cretaceous–Paleogene section: links with Deccan volcanism. Palaeogeography, Palaeoclimatology, Palaeoecology 350–352, 180–188. doi:10.1016/j.palaeo.2012.06.029

Vandamme, D. (1994) A new method to determine paleosecular variation. Physics of the Earth and Planetary Interiors 85, 131–142. doi:10.1016/0031-9201(94)90012-4

Whitham, A.G., Ineson, J.R. & Pirrie, D. (2006) Marine volcaniclastics of the Hidden Lake Formation (Coniacian) of James Ross Island, Antarctica: an enigmatic element in the history of a back-arc basin. Geological Society of London, Special Publications 258, 21–47. doi:10.1144/GSL.SP.2006.258.01.03

Witts, J.D., Bowman, V.C., Wignall, P.B., Crame, J.A., Francis, J.E. & Newton, R.J. (2015) Evolution and extinction of Maastrichtian (Late Cretaceous) cephalopods from the López de Bertodano Formation, Seymour Island, Antarctica. Palaeogeography, Palaeoclimatology, Palaeoecology 418, 193–212. doi:10.1016/j.palaeo.2014.11.002

Witts, J.D., Whittle, R.J., Wignall, P.B., Crame, J.A., Francis, J.E., Newton, R.J. & Bowman, V.C. (2016) Macrofossil evidence for a rapid and severe Cretaceous-Paleogene mass extinction in Antarctica. Nature Communications 7, 1–9. doi:10.1038/ncomms11738

Wright, N.A. & Williams, P.L. (1974) Mineral Resources of Antartica. Geological Survey Circular 705, 1–36.

Table 1. Magnetic parameters for samples of the Marambio Group: saturation magnetization (J_{SAT}), remanent magnetization (J_R) and coercivity (B_C) were obtained from hysteresis cycles and remanence coercivity (B_{CR}) from IRM/Backfield curves.

Sample	J_{SAT} (A/m)	J_R(A/m)	B_C (mT)	B_{CR} (mT)	J_R/J_{SAT}	B_{CR}/B_C
Ra16-3	9.81	1.11	9.49	41.30	0.11	4.35
Ra16-4	4.98	0.68	9.07	33.30	0.14	3.67
Ra16-12	1.33	0.46	21.78	47.40	0.35	2.18
Ra16-19	1.94	0.31	13.91	41.70	0.16	3.00
Ra16-20	1.70	0.06	15.02	40.10	0.04	2.67
Ra16-26	28.83	0.89	3.72	19.50	0.03	5.24
Ra16-27	31.39	0.93	3.03	15.20	0.03	5.02
Ra16-42	7.14	1.25	18.66	49.20	0.18	2.64
Ra16-45	1.56	0.24	14.65	44.10	0.15	3.01
HC7	0.68	0.16	21.12	69.49	0.24	3.29
HC63	4.06	0.18	14.40	72.13	0.04	5.01
SCF19	3.84	0.30	16.29	90.70	0.08	5.57
SCF28	2.21	0.32	30.44	95.90	0.14	3.15
SCF30	2.84	0.29	22.84	95.54	0.10	4.18
SCF48	4.00	0.48	11.42	36.29	0.12	3.18
SCF65	1.68	0.36	9.34	65.85	0.21	7.05
SP63	0.98	0.09	6.41	49.08	0.09	7.66

Table 2. Paleomagnetic means. *In situ* and stratigraphic (bedding corrected) values for Hamilton Point and Snow Hill Island localities and for both localities treated together. Reversal tests (McFadden & McElhinny, 1988) are positive within each locality, but fail when all directions are combined. See section 6 for a detailed explanation. ChRM calculation and reversal tests were conducted with software PaleoMag 3.1 software (Jones, 2002). ChRM directions tables and stereographic projections are given in Supplementary material.

Hamilton Point Member at Hamilton Point at southeast James Ross Island

	Dec (°)	Inc (°)	α_{95}	κ	N
***In situ* mean**	71.6	-68.7	7.8	5.6	70
Stratigraphic mean	46.8	-72.2	7.8	5.7	70

	Critical Angle (°)	Observed Angle (°)	Condition
Reversal test from stratigraphic mean	54.6	29.1	Indeterminate

Sanctuary Cliffs Member, Karlsen Cliffs Member, Haslum Crag Formation and López de Bertodano Formation at Snow Hill Island

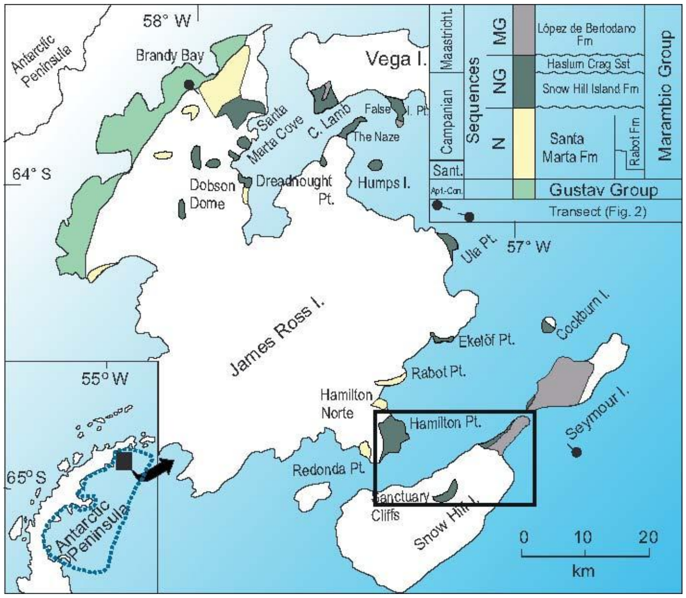
	Dec (°)	Inc (°)	α_{95}	κ	N
***In situ* mean**	132.3	74.2	5	6.7	139
Stratigraphic mean	125.1	74.2	5.2	6.4	139

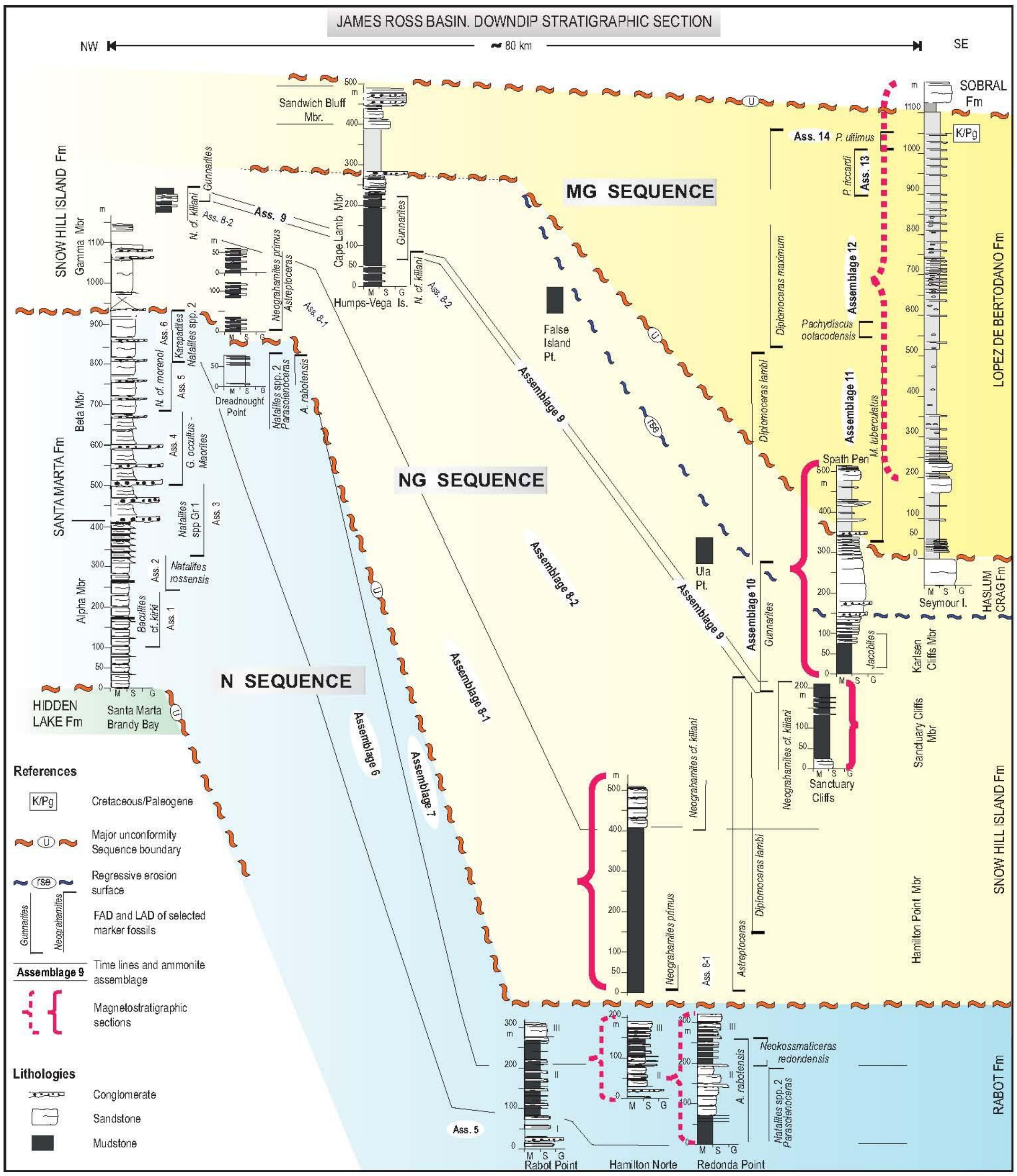
	Critical Angle (°)	Observed Angle (°)	Condition
Reversal test from stratigraphic mean	19.7	11.2	Positive (Class C)

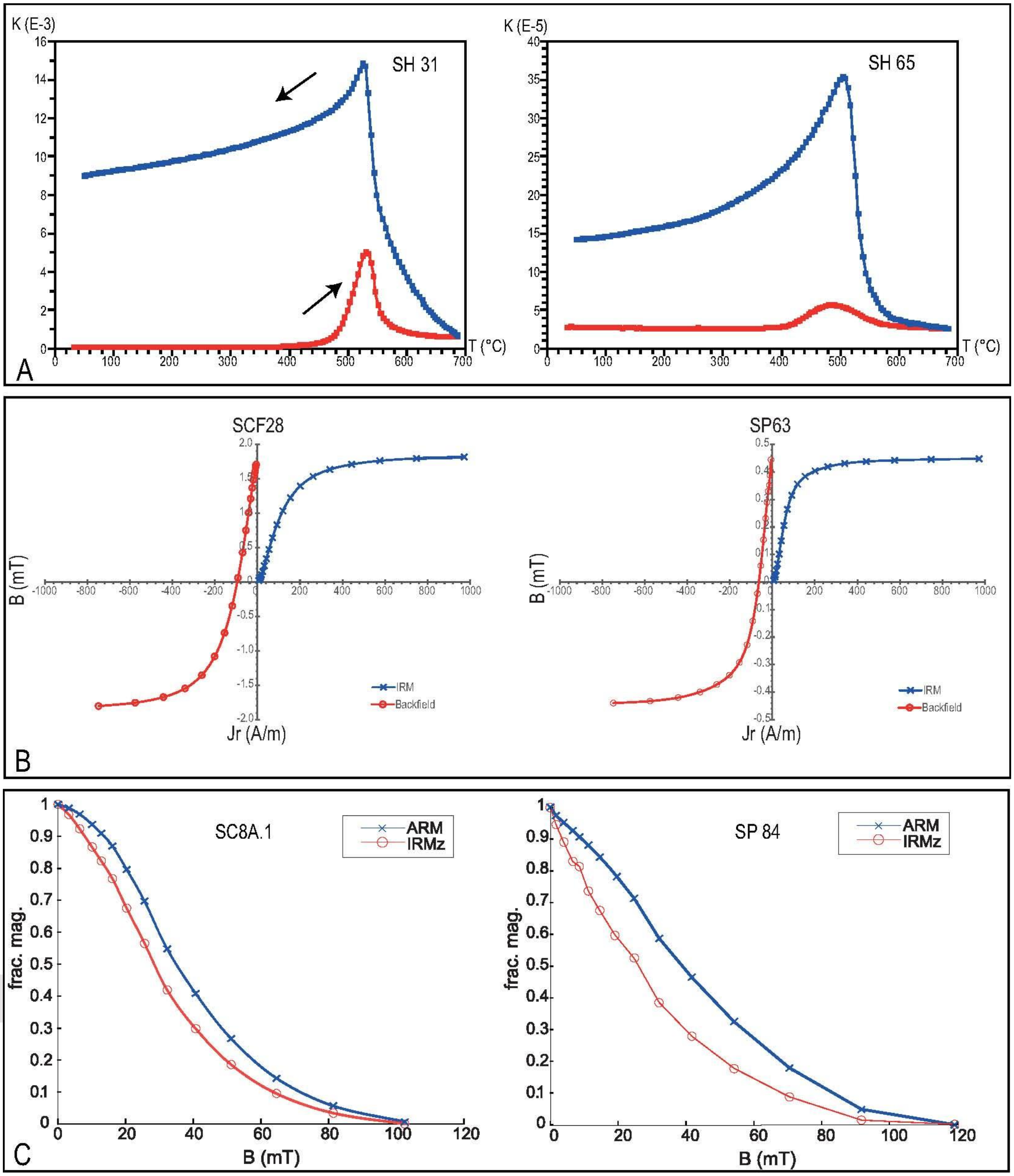
Southeast James Ross Island and Snow Hill Island

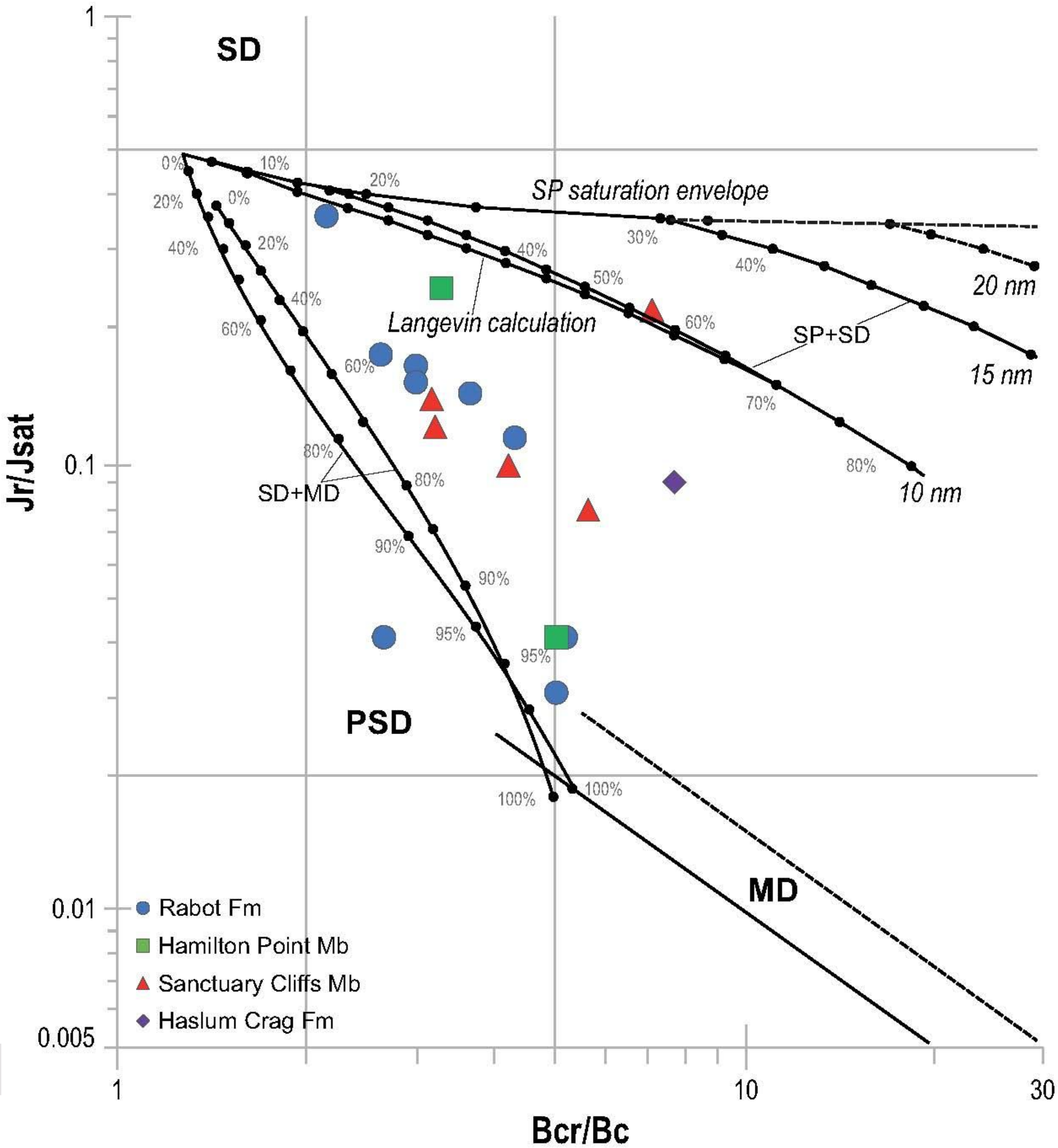
	Dec (°)	Inc (°)	α_{95}	κ	N
***In situ* mean**	170.2	80.9	4.6	5.4	209
Stratigraphic mean	142.1	71.7	4.8	5.1	209

	Critical Angle (°)	Observed Angle (°)	Condition
Reversal test from stratigraphic mean	17.0°	31.1°	Negative

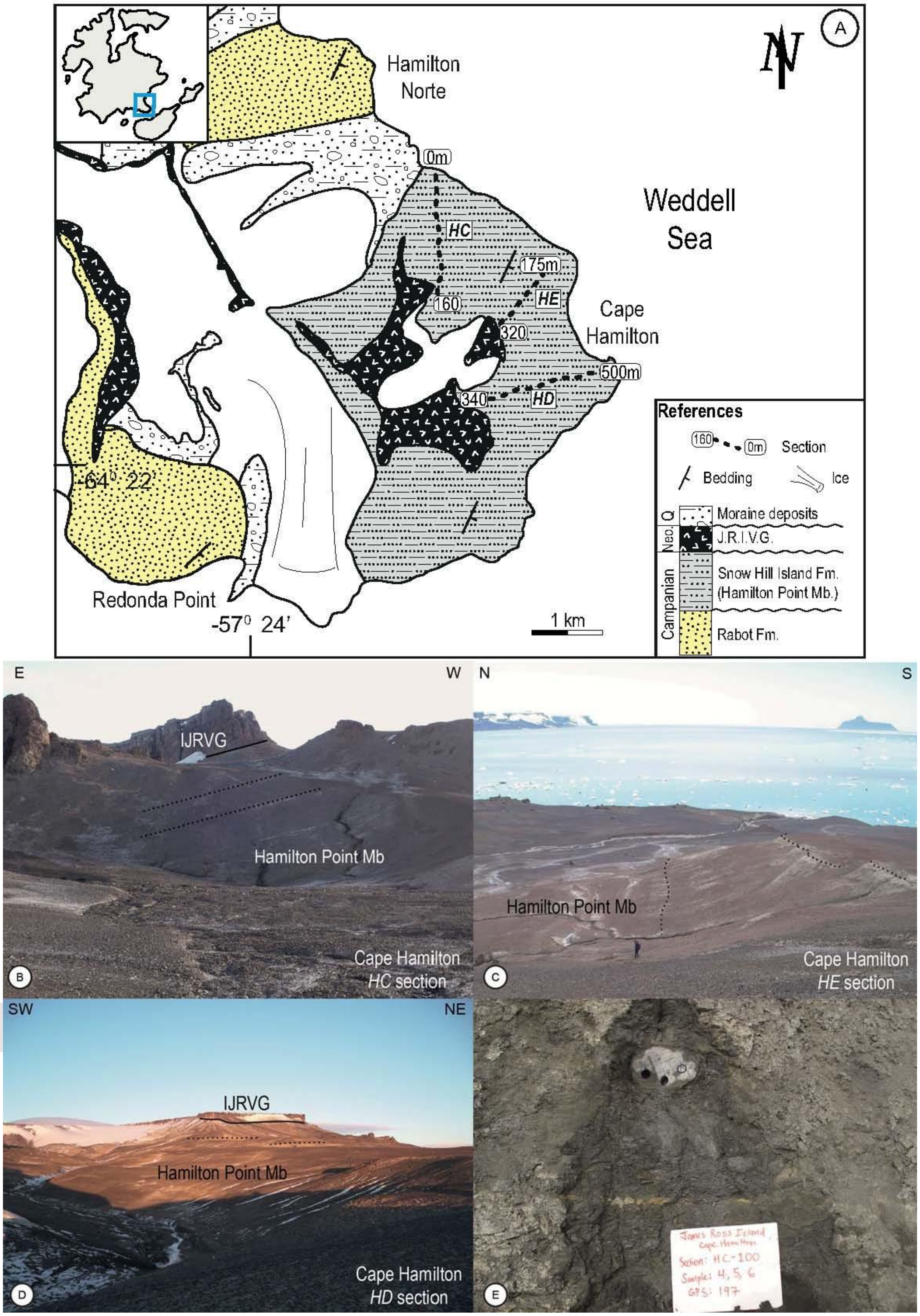

58° W
Antarctic Peninsula
Brandy Bay
Vega I.
Santa Marta Cove
C. Lamb
False I. Pt
The Naze
64° S
Dobson Dome
Dreadnought Pt.
Humps I.
Ula Pt.
57° W
James Ross I.
Eketöf Pt.
Cockburn I.
Rabot Pt.
Hamilton Norte
Hamilton Pt.
Seymour I.
Redonda Pt.
Sanctuary Cliffs
Snow Hill I.
0
10
20
km
55° W
65° S
Antarctic Peninsula
Maastricht.
Campanian
Sant.
Apt-Con.
Sequences
MG
NG
N
López de Bertodano Fm
Haslum Crag Sst
Snow Hill Island Fm
Santa Marta Fm
Rabot Fm
Marambio Group
Gustav Group
Transect (Fig. 2)

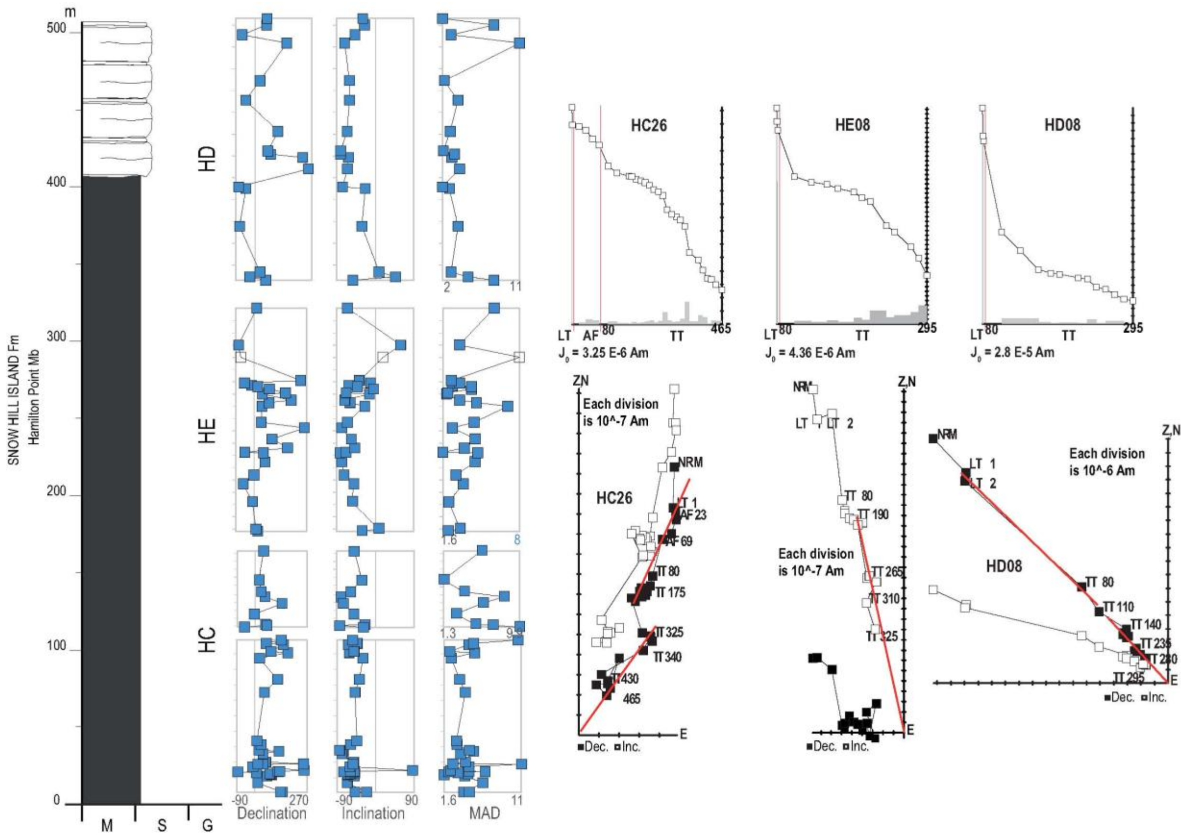

JAMES ROSS BASIN. DOWNDIP STRATIGRAPHIC SECTION
NW
~ 80 km
SE
MG SEQUENCE
NG SEQUENCE
N SEQUENCE
SNOW HILL ISLAND Fm
Gamma Mbr
Beta Mbr
SANTA MARTA Fm
Alpha Mbr
HIDDEN LAKE Fm
Santa Marta Brandy Bay
Sandwich Bluff Mbr.
Cape Lamb Mbr
Humps-Vega Is.
Dreadnought Point
False Island Pt.
Ula Pt.
Spath Pen
Seymour I.
SOBRAL Fm
K/Pg
LOPEZ DE BERTODANO Fm
HASLUM CRAG Fm
Karlsen Cliffs Mbr
Sanctuary Cliffs Mbr
Sanctuary Cliffs
Hamilton Point Mbr
SNOW HILL ISLAND Fm
RABOT Fm
Rabot Point
Hamilton Norte
Redonda Point
Assemblage 6
Assemblage 7
Assemblage 8-1
Assemblage 8-2
Assemblage 9
Assemblage 10
Assemblage 11
Assemblage 12
Ass. 13
Ass. 14
Ass. 5
Ass. 1
Ass. 2
Ass. 3
Ass. 4
Ass. 5
Ass. 6
Ass. 8-1
Ass. 8-2
Ass. 9
Baculites cf. kirki
Natalites rossensis
Natalites spp Gr 1
G. occultus - Maorites
N. cf. morenoi
Kanpadites
Natalites spp. 2
N. cf. kilani
Gunnarites
Neograhamites primus
Astreptoceras
Natalites spp. 2 Parasolenoceras
A. rabotensis
Neograhamites cf. kilani
Diplomoceras lambi
Jacobites
M. tuberculatus
Pachydiscus ootacodensis
Diplomoceras maximum
P. riccardi
P. ultimus
Neokossmaticeras redondensis
References
Cretaceous/Paleogene
Major unconformity Sequence boundary
Regressive erosion surface
FAD and LAD of selected marker fossils
Time lines and ammonite assemblage
Magnetostratigraphic sections
Lithologies
Conglomerate
Sandstone
Mudstone


K (E-3)
SH 31
T (°C)
A
K (E-5)
SH 65
T (°C)
SCF28
B (mT)
Jr (A/m)
IRM
Backfield
SP63
B (mT)
Jr (A/m)
IRM
Backfield
B
SC8A.1
ARM
IRMz
frac. mag.
B (mT)
SP 84
ARM
IRMz
frac. mag.
B (mT)
C

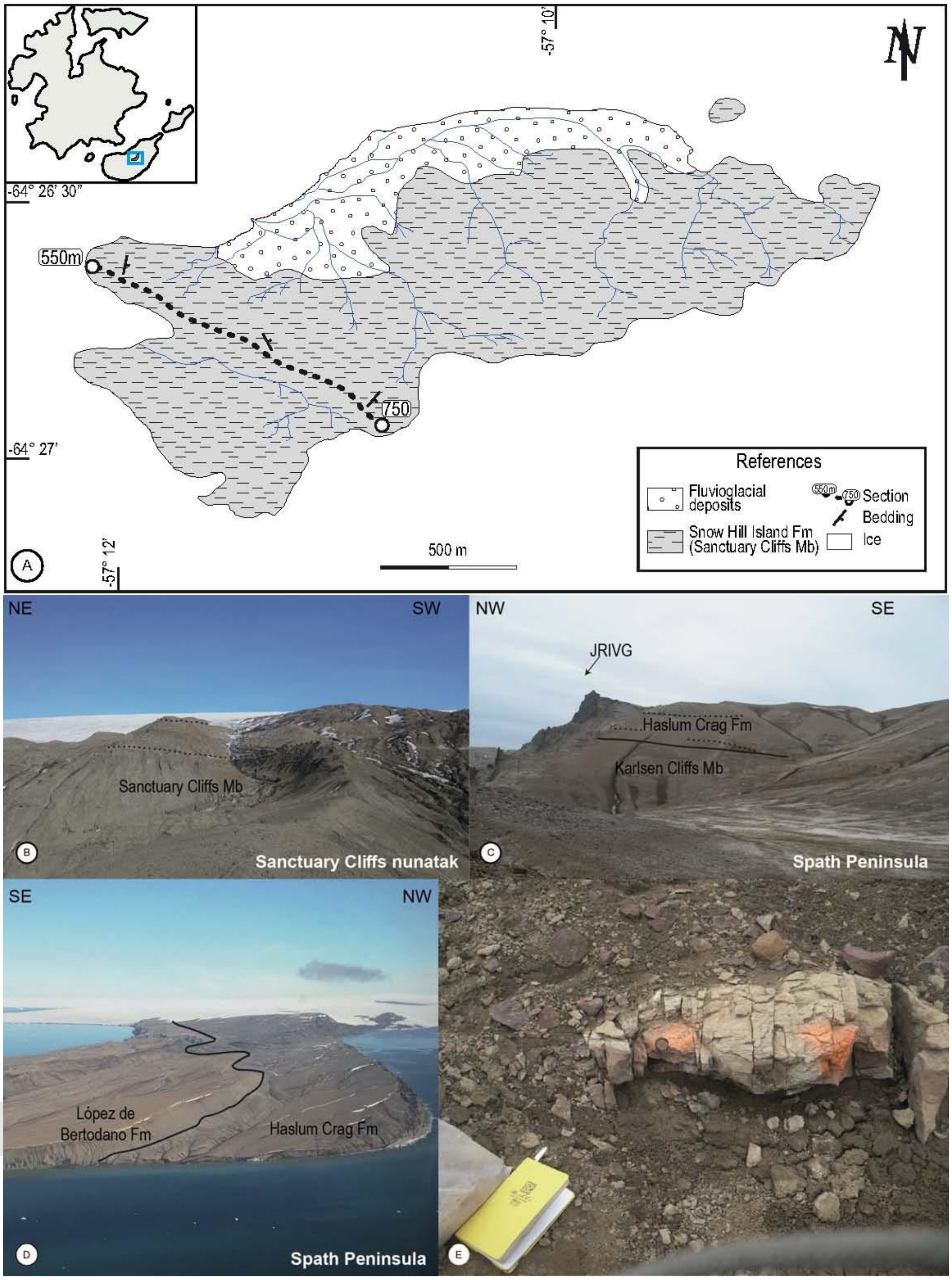


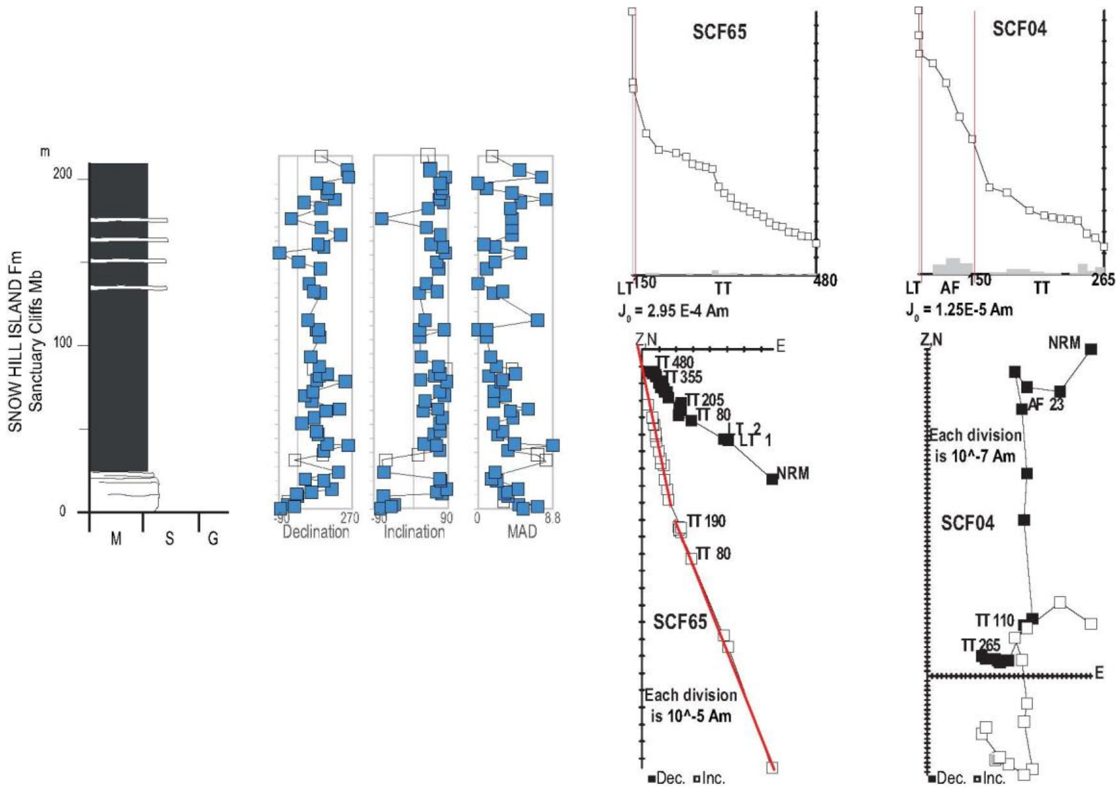
SD
PSD
MD
SP saturation envelope
Langevin calculation
SP+SD
SD+MD
20 nm
15 nm
10 nm
0%
10%
20%
30%
40%
50%
60%
70%
80%
90%
95%
100%
Jr/Jsat
Bcr/Bc
1
0.1
0.01
0.005
10
30
Rabot Fm
Hamilton Point Mb
Sanctuary Cliffs Mb
Haslum Crag Fm

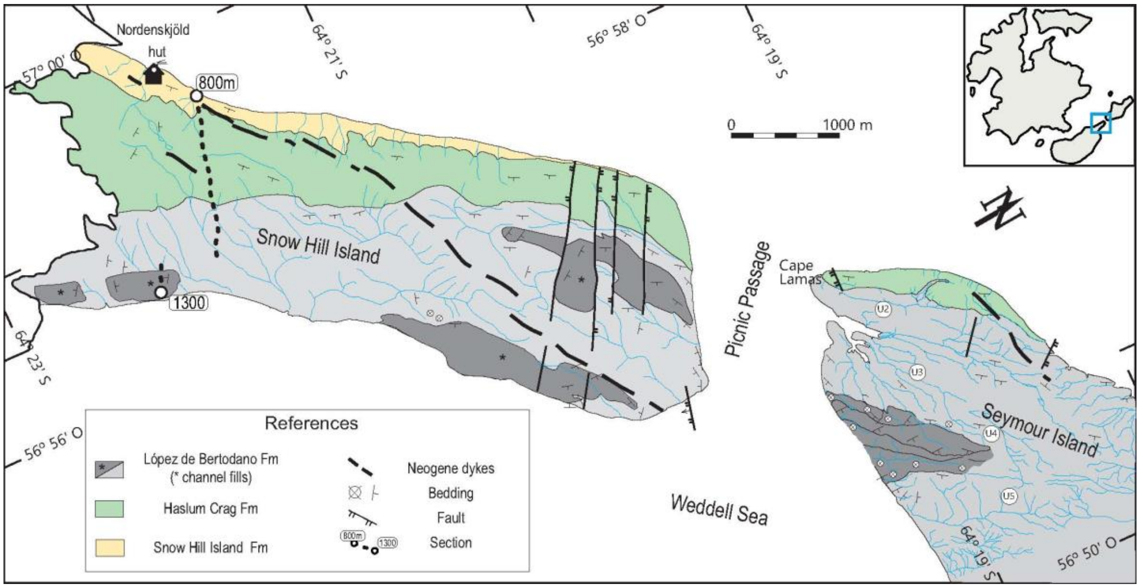

A
Hamilton Norte
0m
HC
175m
160
HE
320
Weddell Sea
Cape Hamilton
500m
340
HD
-64° 22'
Redonda Point
-57° 24'
1 km
References
160 0m Section
Bedding
Ice
Q
Moraine deposits
Neo.
J.R.I.V.G.
Campanian
Snow Hill Island Fm. (Hamilton Point Mb.)
Rabot Fm.
E
W
IJRVG
Hamilton Point Mb
Cape Hamilton HC section
B
N
S
Hamilton Point Mb
Cape Hamilton HE section
C
SW
NE
IJRVG
Hamilton Point Mb
Cape Hamilton HD section
D
E

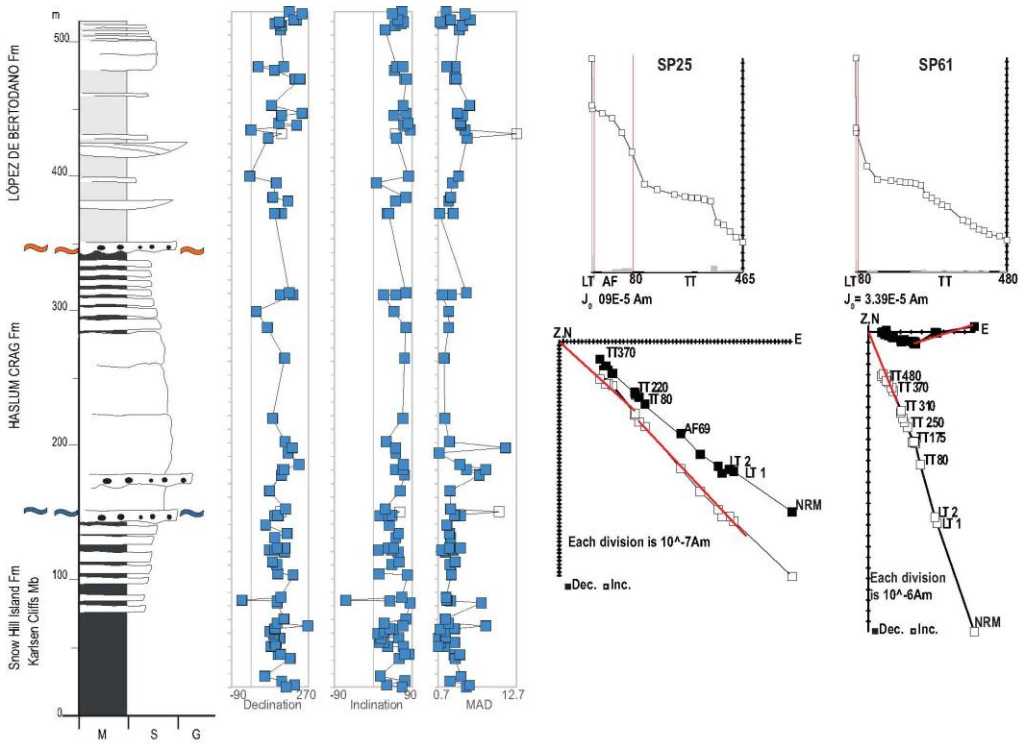


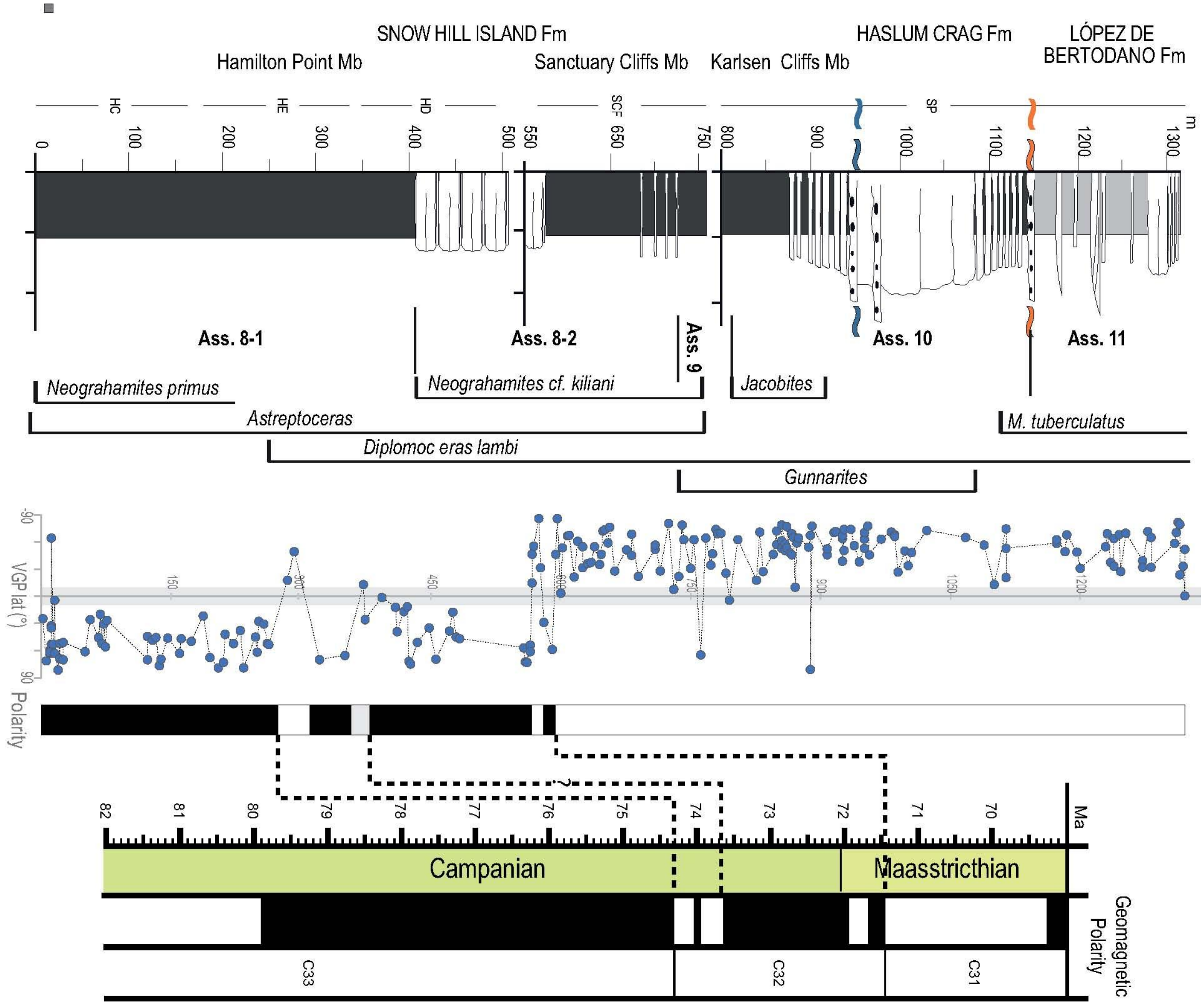
SNOW HILL ISLAND Fm
Hamilton Point Mb
HD
HE
HC
Declination
Inclination
MAD
M
S
G
HC26
HE08
HD08
J0 = 3.25 E-6 Am
J0 = 4.36 E-6 Am
J0 = 2.8 E-5 Am
Each division is 10^-7 Am
Each division is 10^-7 Am
Each division is 10^-6 Am
Dec.
Inc.

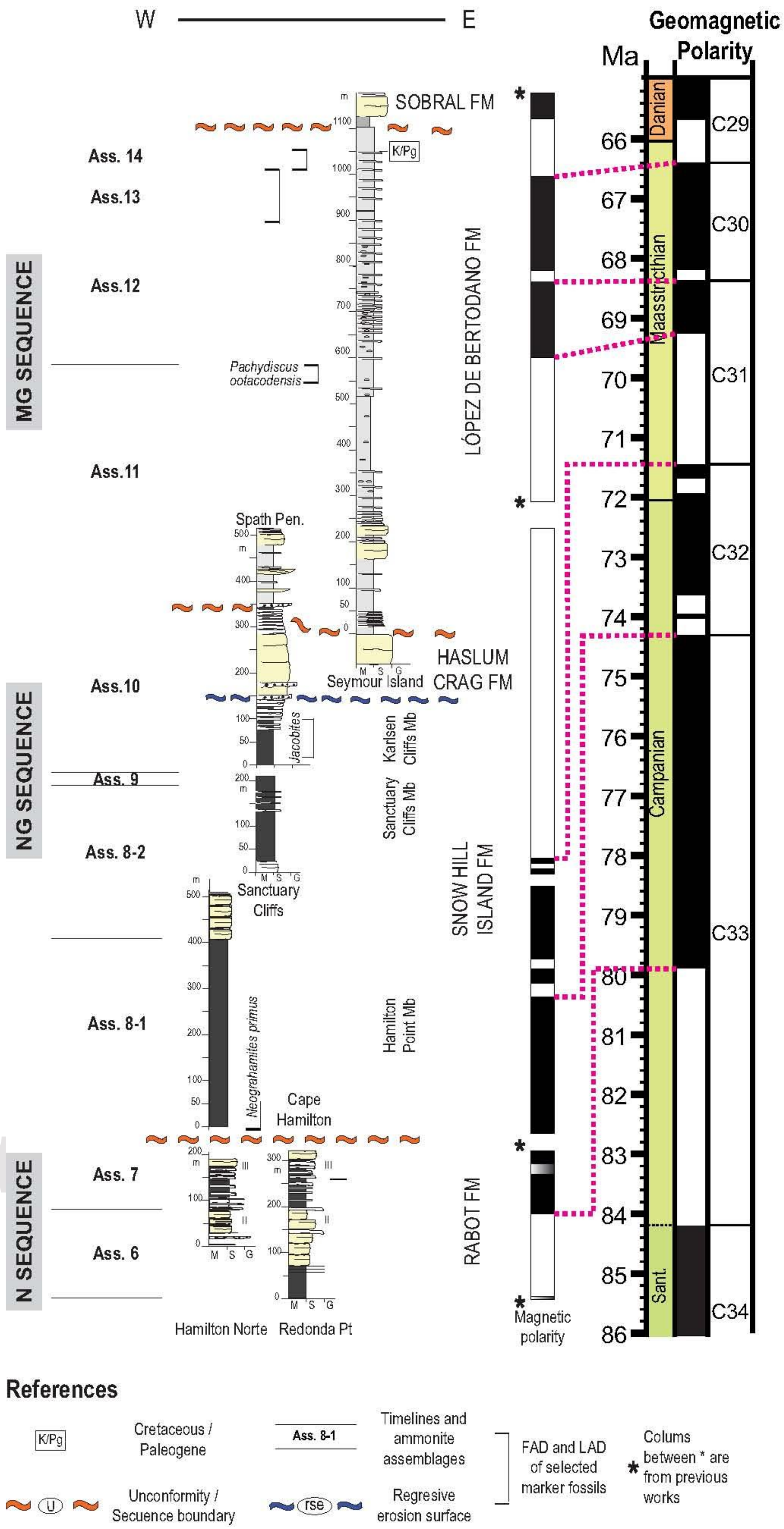

-57° 10'
-64° 26' 30"
550m
750
-64° 27'
References
Fluvioglacial deposits
Snow Hill Island Fm (Sanctuary Cliffs Mb)
Section
Bedding
Ice
500 m
-57° 12'
A
NE
SW
Sanctuary Cliffs Mb
B
Sanctuary Cliffs nunatak
NW
SE
JRIVG
Haslum Crag Fm
Karlsen Cliffs Mb
C
Spath Peninsula
SE
NW
López de Bertodano Fm
Haslum Crag Fm
D
Spath Peninsula
E


m
200
100
0
SNOW HILL ISLAND Fm
Sanctuary Cliffs Mb
M
S
G
-90
270
Declination
-90
90
Inclination
0
8.8
MAD
SCF65
LT 150
TT
480
J0 = 2.95 E-4 Am
SCF04
LT
AF 150
TT
265
J0 = 1.25E-5 Am
Z,N
E
TT 480
TT 355
TT 205
TT 80
LT 2
LT 1
NRM
TT 190
TT 80
SCF65
Each division is 10^-5 Am
Dec.
Inc.
Z,N
NRM
AF 23
Each division is 10^-7 Am
SCF04
TT 110
TT 265
E
Dec.
Inc.


Nordenskjöld hut
800m
64° 21' S
56° 58' O
64° 19' S
57° 00' O
0
1000 m
Snow Hill Island
1300
64° 23' S
Picnic Passage
Cape Lamas
Seymour Island
56° 56' O
References
López de Bertodano Fm
(* channel fills)
Haslum Crag Fm
Snow Hill Island Fm
Neogene dykes
Bedding
Fault
Section
Weddell Sea
64° 19' S
56° 50' O


LÓPEZ DE BERTODANO Fm
HASLUM CRAG Fm
Snow Hill Island Fm
Karlsen Cliffs Mb
M
S
G
Declination
Inclination
MAD
SP25
SP61
J0 09E-5 Am
J0 = 3.39E-5 Am
Each division is 10^-7Am
Each division is 10^-6Am
Dec.
Inc.
NRM


SNOW HILL ISLAND Fm
Hamilton Point Mb
Sanctuary Cliffs Mb
Karlsen Cliffs Mb
HASLUM CRAG Fm
LÓPEZ DE BERTODANO Fm
HC
HE
HD
SCF
SP
m
0
100
200
300
400
500
550
650
750
800
900
1000
1100
1200
1300
Ass. 8-1
Ass. 8-2
Ass. 9
Ass. 10
Ass. 11
Neograhamites primus
Neograhamites cf. kiliani
Jacobites
Astreptoceras
M. tuberculatus
Diplomoc eras lambi
Gunnarites
VGP lat (°)
-90
90
Polarity
82
81
80
79
78
77
76
75
74
73
72
71
70
Ma
Campanian
Maastricthian
C33
C32
C31
Geomagnetic Polarity



W
E
Geomagnetic Polarity
Ma
SOBRAL FM
K/Pg
Ass. 14
Ass.13
Ass.12
Ass.11
Ass.10
Ass. 9
Ass. 8-2
Ass. 8-1
Ass. 7
Ass. 6
MG SEQUENCE
NG SEQUENCE
N SEQUENCE
Pachydiscus ootacodensis
LÓPEZ DE BERTODANO FM
Spath Pen.
Seymour Island
HASLUM CRAG FM
Jacobites
Karlsen Cliffs Mb
Sanctuary Cliffs Mb
Sanctuary Cliffs
SNOW HILL ISLAND FM
Neograhamites primus
Hamilton Point Mb
Cape Hamilton
RABOT FM
Hamilton Norte
Redonda Pt
Magnetic polarity
Danian
Maastrichtian
Campanian
Sant.
C29
C30
C31
C32
C33
C34
References
Cretaceous / Paleogene
Timelines and ammonite assemblages
FAD and LAD of selected marker fossils
Colums between * are from previous works
Unconformity / Secuence boundary
Regresive erosion surface