

New evidence of a Campanian age for the Cretaceous fossil-bearing strata of Cape Marsh, Robertson Island, Antarctica

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ARTICLE INFO

Article history:

Received 10 May 2019

Received in revised form

21 October 2019

Accepted in revised form 6 November 2019

Available online 16 November 2019

Keywords:

Cretaceous

Campanian

James Ross Basin

Biostratigraphy

Detrital zircon

Antarctica

ABSTRACT

Cape Marsh, located on the eastern end of Robertson Island to the east of the Antarctic Peninsula, exposes an isolated outcrop of Upper Cretaceous sedimentary strata. The outcrop is approximately 120 km southwest of the much better-studied exposures of similar age on and around James Ross Island (JRI); as such, its remoteness has complicated logistical access to the site and hindered geologic correlations on a regional scale. Here we present the results of fieldwork conducted in 2016 that yielded a more diverse invertebrate fossil assemblage than had been previously recognized, in addition to new U–Pb detrital zircon and magnetostratigraphic data. The invertebrate fauna, particularly the ammonites and inoceramids, support a biostratigraphic correlation of the upper Cape Marsh strata to Ammonite Assemblage 7 previously established on JRI. Detrital zircon U–Pb analysis conducted on a sandstone sample from the same strata indicates a maximum depositional age of 74.2 ± 1.1 Ma, and magnetostratigraphic interpretation of the lower strata suggest a normal magnetochron. These results are all consistent with a Campanian age for the deposition of the upper strata at Cape Marsh, and deposition during magnetochron C33N for the lower layers. However, a slight age inconsistency between the biostratigraphic correlation and the detrital zircon-derived maximum depositional age may imply that the fossils are reworked. Regardless, these new data allow us to correlate the strata at Cape Marsh to the Santa Marta and Rabot formations (or possibly the lower part of the Snow Hill Island Formation) in the northern part of the James Ross Basin.

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1. Introduction

Exposed Cretaceous deposits in Antarctica are restricted to the Antarctic Peninsula and nearby islands, largely in an

archipelago that includes and surrounds James Ross Island (JRI) (e.g., Crame et al., 1991; Elliot, 1988; Olivero, 2012a, 2012b), including the well-known Seymour Island where the Cretaceous–Paleogene boundary is exposed (Elliot et al., 1994; Macellari, 1988; Tobin, 2017). The Lower to Upper Cretaceous sedimentation in the James Ross Basin (JRB) has been studied extensively on JRI and surrounding islands, but exposures on Robertson Island (Fig. 1) further to the south have received very little

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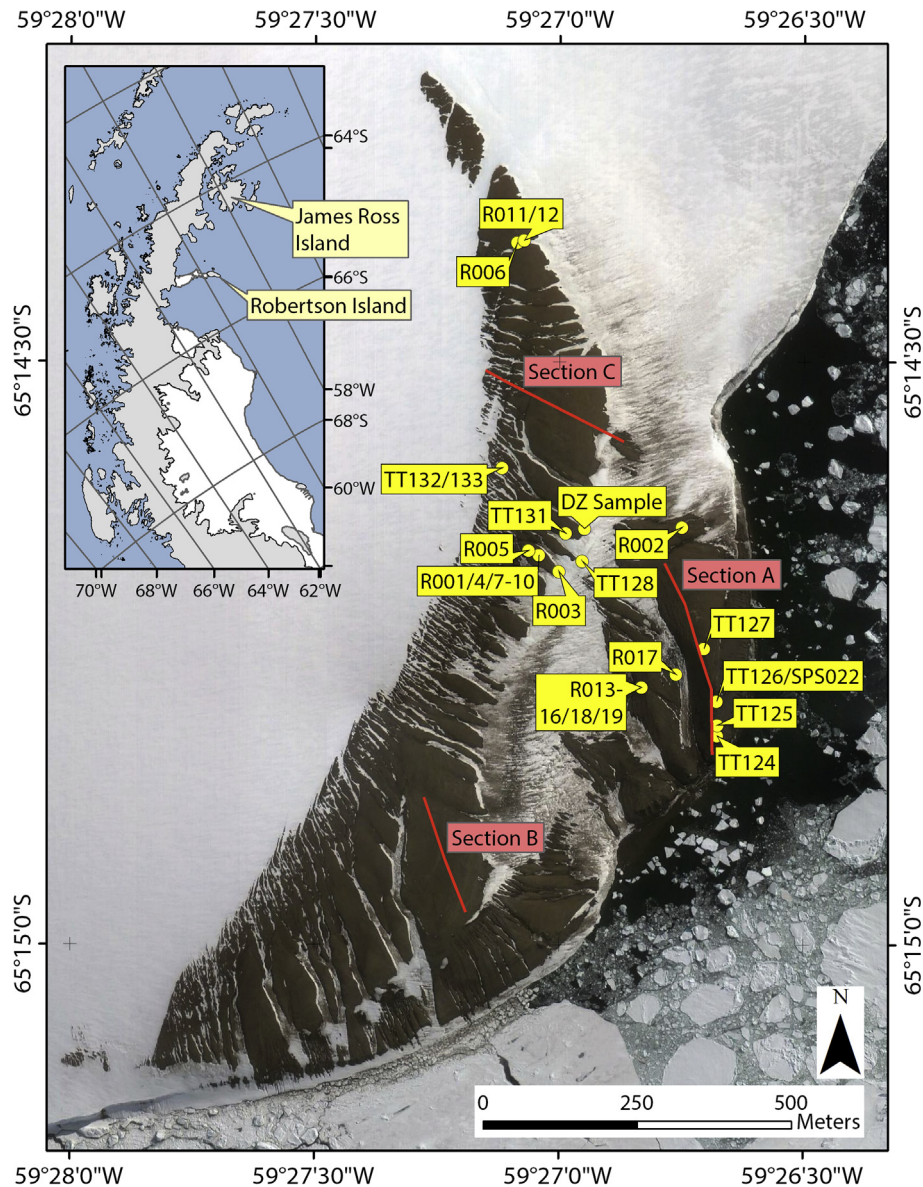


Fig. 1. Satellite image of sedimentary exposures at Cape Marsh on Robertson Island (from Google Earth; Digital Globe, 2019). Red lines represent estimated section traces from schematic map of [del Valle and Medina \(1985\)](#). Yellow circles indicate fossil sampling locations (labeled) and site of detrital zircon (DZ) sampling. Paleomagnetic sampling was restricted to the Section A trace. Inset shows location of Robertson Island versus more intensively studied Cretaceous exposures on and around James Ross Island ~120 km to the northeast. (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

investigation for both logistical and scientific reasons. Specifically, exposed Cretaceous rocks on Robertson Island are limited to a relatively small (0.6 km²) Weddell Sea-facing exposure on the eastern margin of the island in an area known as Cape Marsh, and have received only intermittent study by previous researchers ([Askin, 1984](#); [del Valle and Medina, 1985](#); [Fleet, 1966](#); [Medina and del Valle, 1980](#)). The minimal exposure and substantial distance (~120 km) from the better-studied and more easily accessed JRI-area outcrops has resulted in few researchers dedicating resources to studying this area.

In early 2016, we conducted two days of field investigation of Cape Marsh via helicopter deployed from the United States Antarctic Program ship *R/V Nathaniel B. Palmer* stationed near JRI. Although multiple sampling goals were explored or attempted (e.g., stable isotope geochemistry, vertebrate paleontology), most proved unsuccessful due to the relatively high level of diagenetic alteration

at Cape Marsh, particularly when compared with the rocks on and around JRI. Zircons were recovered from one sandstone, allowing for U–Pb analysis to constrain the maximum depositional age. A variety of marine invertebrate fossils were also collected, mostly mollusks, some of which had not previously been recognized from Cape Marsh ([Medina and del Valle, 1980](#)) and which have biostratigraphic implications that are further explored below. These new findings may be the result of an increase in rock exposure due to ice melting since previous work was conducted in the 1960s–1980s, a pattern previously noted for small exposures on nearby Snow Hill Island and JRI ([Engel et al., 2019](#); [Tobin et al., 2018](#)). Our new results seek to refine previous work ([del Valle and Medina, 1985](#); [Medina and del Valle, 1980](#)); thus, we refrain from a full systematic paleontological description and instead focus on the stratigraphic relationships of the Cape Marsh sediments to the rest of the JRB.

2. Geologic setting

The Cretaceous geology and sedimentology of Cape Marsh were described in detail by [del Valle and Medina \(1985\)](#), who expanded on their previous description of the invertebrate fauna from that location ([Medina and del Valle, 1980](#)). These two works report shallow marine deposition of approximately 220 m of clastic sandstones and siltstones as well as carbonate muds, though more stratigraphic thickness may now be exposed. Based on these observations, as well as sedimentary structures, ichnofossils, and invertebrate body fossils, the depositional environment was interpreted to be a tidally influenced and lagoonal nearshore setting, including some reported stromatolite-bearing layers, though we did not observe any material that we can confidently describe as stromatolitic during our field work.

[Del Valle and Medina \(1985\)](#) divided the area into three section traces (A–A', B–B', C–C') that they placed on a schematic map and in stratigraphic section in their Fig. 3 and 4, respectively (Fig. 1). The nature of their map, lack of obvious landmarks, our limited field time, and the change in terrestrial and marine ice cover over the last 30+ years makes direct comparisons with our collections challenging. The A–A' section is straightforward to locate (Fig. S1), but the B–B' section may have been covered by snow during our visit, though increased exposure in the area of the C–C' section may have allowed us to sample the stratigraphic equivalent of some or all of the B–B' exposure (Fig. 2). The mapped traces of the B–B' and C–C' sections and their intersection with mapped topography do not correspond well to the measured stratigraphic thickness. Additionally, over 100 stratigraphic meters were recorded as covered. Consequently, it is not clear if many of our samples come from the previously covered interval or from the lateral equivalent of B–B'. Additionally, it is likely that we also sampled strata that extend above the C–C' section due to retreat of permanent snow cover. Fig. 2 shows our attempt to place paleomagnetic, fossil, and detrital zircon sampling localities within the stratigraphic framework of [del Valle and Medina \(1985\)](#), while also indicating a large degree of uncertainty in the placement of samples.

In comparison with the fossils and deposits exposed in the JRI area, the material at Cape Marsh has undergone significantly more diagenetic alteration, and no fossils preserve any original aragonite. In almost all cases, the aragonite shell is not replaced or recrystallized, but is absent entirely, and fossils are preserved as molds and casts, though a few originally aragonitic samples maintain coarsely recrystallized calcite. All of these factors complicate positive identification of the specimens. Originally calcitic material is sometimes preserved, but this preservation is restricted to worm tubes and inoceramid shell fragments. The physical detail of preservation is also generally poorer than that of similarly-aged fossils from the JRI area, which are typically undeformed and usually reveal fine details of shell structure ([Olivero, 1992](#)). Fossils from Cape Marsh, particularly ammonites, are often partially deformed, crushed, or broken, even though they are generally preserved in ferruginous concretions. Deformation prior to cementation may imply that these concretions probably did not form immediately after deposition, as is the case with calcareous concretions observed elsewhere in the JRB, but occurred later in the burial history. Alternatively, these samples may have been crushed or damaged during periods of reworking prior to lithification. The ferruginous concretions do sometimes preserve detailed external molds, which offer some utility in the identification of invertebrate fauna. Despite the increased alteration, these sediments exhibit only minor monoclinal tilting (141°/9°) and no larger-scale structural deformation, similar to those in the rest of the JRB.

3. Invertebrate fauna

Despite the moderate quality of fossil preservation, we are able to recognize a variety of invertebrate fauna that were previously described from Cape Marsh, as well as some additional molluscan fossils known from JRI and nearby islands but not previously from Cape Marsh. Most of the newly-collected invertebrate specimens come from strata above the A–A' section of [del Valle and Medina \(1985\)](#), with the exception of some material from very near the top of Section A–A', which is otherwise dominated by fossils of the annelid genus *Rotularia* (Fig. 2). This division between nearshore deposits dominated by *Rotularia* with very rare molluscan fossils and more offshore deposits without *Rotularia* and common mollusks is also seen in the younger deposits on Seymour Island ([Macellari, 1988, 1984](#)). Table 1 presents a complete list of fauna previously described and newly recognized from Cape Marsh, both of which are further described below. Mediocre physical preservation is common throughout, and many morphotypes are represented by a single specimen, so we have elected to leave many samples in open nomenclature to reflect the inherent uncertainty this situation produces ([Bengtson, 1988](#)). Paleontological samples are deposited at Carnegie Museum of Natural History (CM) and the University of Washington Burke Museum (UWBM).

3.1. Previously recognized fauna

Most of the fauna identified by previous studies are found in our collections, with a few exceptions that are primarily limited to the ichnofauna (Table 1). It should be noted that some of the genera and species have received new taxonomic designations since the publication of the most recent works on the fossil invertebrate fauna of Cape Marsh, and as such these taxonomic names are updated herein.

We find all of the previously described bivalves, including the relatively common *Oistotrigonia antarctica* (Fig. 3A, B; [Fleet, 1966; Medina and del Valle, 1980](#)) and *Nordenskjoldia nordenskjoldi*. [Medina and del Valle \(1980\)](#) considered the latter taxon a “very risky” (“*muy arriesgada*”) assignment for an indeterminate species in their collection. Our collections also include several natural molds showing external ornamentation and overall morphology consistent with *N. nordenskjoldi* as described by [Wilckens \(1910\)](#) and [Zinsmeister and Macellari \(1988\)](#), raising our confidence in recognizing the presence of this species (Fig. 3E). Our collections do not include a convincing example of *Nucula*, but some internal molds are plausibly consistent with this genus. Only one gastropod (*Taioma globus*) has been described in detail from Cape Marsh ([Medina and del Valle, 1980](#)), and we find several examples of this taxon in our collections (Fig. 3F). *Fusus* sp. is listed in a table by [del Valle and Medina \(1985\)](#), but without further description; we find no evidence of *Fusus* in our collections.

Three cephalopods have been previously described, including two nautiloids and one ammonite. *Eutrephoceras dorbignyanum* has been described but not figured ([Cichowolski et al., 2005](#)), and *Cimomia* sp. was listed in a table without further elaboration ([del Valle and Medina, 1985](#)). Given the poor preservation of the nautiloids in our samples (Fig. 4D), we suggest that generic assignment of this material should be considered tentative, and that there may exist only a single nautiloid genus (likely *Eutrephoceras*) at Cape Marsh. The only ammonite previously described from Cape Marsh is *Gaudryceras*, which is the most common cephalopod we located. Unfortunately, despite having multiple samples, the relatively poor preservation (Fig. 4) of three-dimensional shape and umbilical ribbing used to separate species ([Raffi and Olivero, 2016](#)) makes specific assignments of these Cape Marsh specimens within *Gaudryceras* problematic.

Table 1

Summary of recorded fossil occurrences from Cape Marsh, including previously recognized taxa and examples recovered as part of this work. Many taxonomic assignments are challenging due to incomplete and moderate fossil preservation (see Figs. 3–5).

	Previously described?	In 2016 collections
Cephalopoda		
<i>Eutrephoceras</i> (?)	Cichowolski et al. (2005) as <i>E. subplicatum</i> ; del Valle and Medina (1985) as <i>Cimomia</i> sp.	Yes (Fig. 4)
<i>dorbignyanum</i> (?)	Medina and del Valle (1980)	Yes (Fig. 4)
<i>Gaudryceras</i> sp.	No	Yes (Fig. 4)
<i>Neokosmaticeras</i> (?)	No	Yes (Fig. 4)
<i>redondensis</i> (?)	No	Yes
<i>Natalites</i> (?) sp. (?)	No	Yes (Fig. 4)
Ammonoidea indet.	No	Yes (Fig. 4)
Scaphopoda		
Scaphopoda indet.	No	Yes
Bivalvia		
<i>Oistotrigonia antarctica</i>	Fleet (1966) as <i>Trigonia</i> ; Medina and del Valle (1980) as <i>Linotrigonia</i> (<i>Oistotrigonia</i>)	Yes (Fig. 3)
<i>Nucula</i> cf. <i>suboblonga</i>	Medina and del Valle (1980)	?
<i>Nordenskjoldia nordenskjoldi</i>	Medina and del Valle (1980) as indet. sp.	Yes (Fig. 3)
<i>Pinna anderssoni</i>	No	Yes (Fig. 3)
<i>Panopea</i> (?) <i>clausa</i> (?)	No	Yes (Fig. 3)
<i>Antarcticeramus</i> (?)	No	Yes (Fig. 5)
<i>rabotensis</i> (?)	No	Yes (Fig. 5)
Gastropoda		
<i>Taioma globus</i>	Medina and del Valle (1980)	Yes (Fig. 3)
<i>Fusus</i> sp.	del Valle and Medina (1985)	No
Annelida		
<i>Rotularia shackletoni</i>	Fleet (1966) as <i>R. callosa</i> ; Medina and del Valle (1980)	Yes
Ichnofossils		
<i>Ophiomorpha</i>	del Valle and Medina (1985)	No
<i>Tisooa</i>	del Valle and Medina (1985)	No
<i>Cylindrichum</i>	del Valle and Medina (1985)	No
<i>Phycodes</i>	del Valle and Medina (1985)	No
<i>Chondrites</i>	Medina and del Valle (1980) as "forma B"	Yes (Fig. 5)
<i>Teredolites</i>	No	Yes (Fig. 5)

One of the first fossils noted from Cape Marsh were serpulid worms of the genus *Rotularia* that are common throughout the JRB. Initially assigned to *R. callosa* (Fleet, 1966), the samples from Cape Marsh are probably better assigned to *R. shackletoni* (Macellari, 1984).

In addition to body fossils, several ichnogenera have been described from Cape Marsh, including *Chondrites* and an unidentified holdfast structure (Medina and del Valle, 1980), as well as *Ophiomorpha*, *Tisooa*, *Cylindrichum*, and *Phycodes* (del Valle and Medina, 1985). It should be noted that there is dispute as to whether *Tisooa* is biogenic (Knaust, 2019) or an abiogenic structure indicative of methane seep emissions (van de Schootbrugge et al., 2010). We found examples of *Chondrites* (Fig. 5B) but no representatives of the other previously described trace fossils.

3.2. Newly recognized fauna

A variety of previously unrecognized invertebrate taxa were collected by our team during the 2016 field campaign at Cape Marsh, most notably bivalves and ammonites. These samples

appear to come from the same stratigraphic intervals as analyzed in previous studies, though it seems likely that overall surface exposure has increased due to snow and ice melt. The newly collected material is summarized in Table 1 and more fully described below.

Several ammonite taxa were found at Cape Marsh for the first time, and though poor preservation hinders their positive identification in several cases, sufficient morphological detail is preserved to enable the recognition of several forms: two kossmaticeratids and one compressed, involute form of unknown affinity.

We tentatively assign the first kossmaticeratid form to *Neokosmaticeras* (?) *redondensis* (?), as the overall phragmocone morphology and ornamentation (including ribbing and constrictions) are the best match within the Kossmaticeratidae described for the JRB (Olivero, 1992, 2012a, 2012b). The presence of well-defined, slightly flexuous ribbing and deep constrictions is consistent with though not diagnostic of *Neokosmaticeras*. Whorl morphology measures for the uncrushed portions of this specimen, including umbilicus/diameter ratio (0.35) and width/height ratio (0.95), are consistent with the macroconch parameters outlined by Olivero (2012b). Unfortunately, the essential diagnostic characters on the inner whorls are not preserved, the detail of the ornamentation towards the umbilicus is obscured, and only a single specimen was recovered (Fig. 4B), hence its uncertain identification. Similarly, another kossmaticeratid, *Natalites* (?) sp., is represented by a single, poorly-preserved specimen, but its ornamentation patterns are most consistent with other *Natalites* in the JRB.

A third new ammonite morphotype was also recovered, which consists of a simple external mold of a highly compressed, involute, and apparently unornamented taxon with no preserved constrictions (Fig. 4A). The full curvature of both the umbilicus and venter are not preserved, and the specimen is significantly weathered due to recent surface exposure. Any further identification of this specimen is impossible, but given the lack of ornamentation and the flat flanks, the most morphologically similar genera recorded elsewhere from the JRB are *Placenticeras*, *Metaplacenticeras*, or *Oiophyllites* (though most known *Oiophyllites* are smaller than this specimen) (Spath, 1953; Olivero, 1992, 2012a).

Three bivalve species new to Cape Marsh were also collected, including several fragments of a large inoceramid clam (Fig. 5C, D). Although no large body fossils of inoceramids were collected, these shell fragments preserve clear prismatic structures. Based on the thickness of the fragments and the large radius of curvature of the shell, the fragments must have come from a very large (>0.5 m) inoceramid. Only one such large inoceramid, *Antarcticeramus rabotensis*, has been recorded from JRI (Crame, 1997), and it is likely that these Cape Marsh fragments also pertain to *A. rabotensis* given the lack of other sufficiently large inoceramid taxa elsewhere in the JRB. Two other bivalves are newly identified from Cape Marsh, *Pinna anderssoni* and *Panopea* (?) *clausa* (?) (Fig. 3D, C), both of which had previously been identified from Snow Hill Island in the JRB (Wilckens, 1910). The *Pinna anderssoni* sample is sufficiently well-preserved to distinguish it from *Pinna freneixae* given the ribbing density. However, *Panopea* (?) *clausa* (?) is less well preserved and thus its identification is considered tentative.

Additionally, *Teredolites* borings were identified in fossil wood, though the body fossils of the bivalve borers themselves were not preserved (Fig. 5A). A single poorly preserved scaphopod was also collected.

Fig. 2. Simplified stratigraphic column for Cape Marsh, modified from del Valle and Medina (1985). The original stratigraphic column was not exactly to scale, so meter markers should be interpreted as approximate rather than exact. Locality positions to right of column indicate approximate stratigraphic positions of samples collected for paleontological and detrital zircon (DZ) analyses in this study; dashed lines indicate uncertainty in position relative to the previous stratigraphic column, though stratigraphic order of localities is correct. Note the 100 m covered zone between sections A–A' and B–B' in original column. Magnetostratigraphic and DZ results are summarized with their sample locality position, whereas fossil occurrences are shown as ranges but should be interpreted to have the same stratigraphic uncertainty as their respective sample localities.

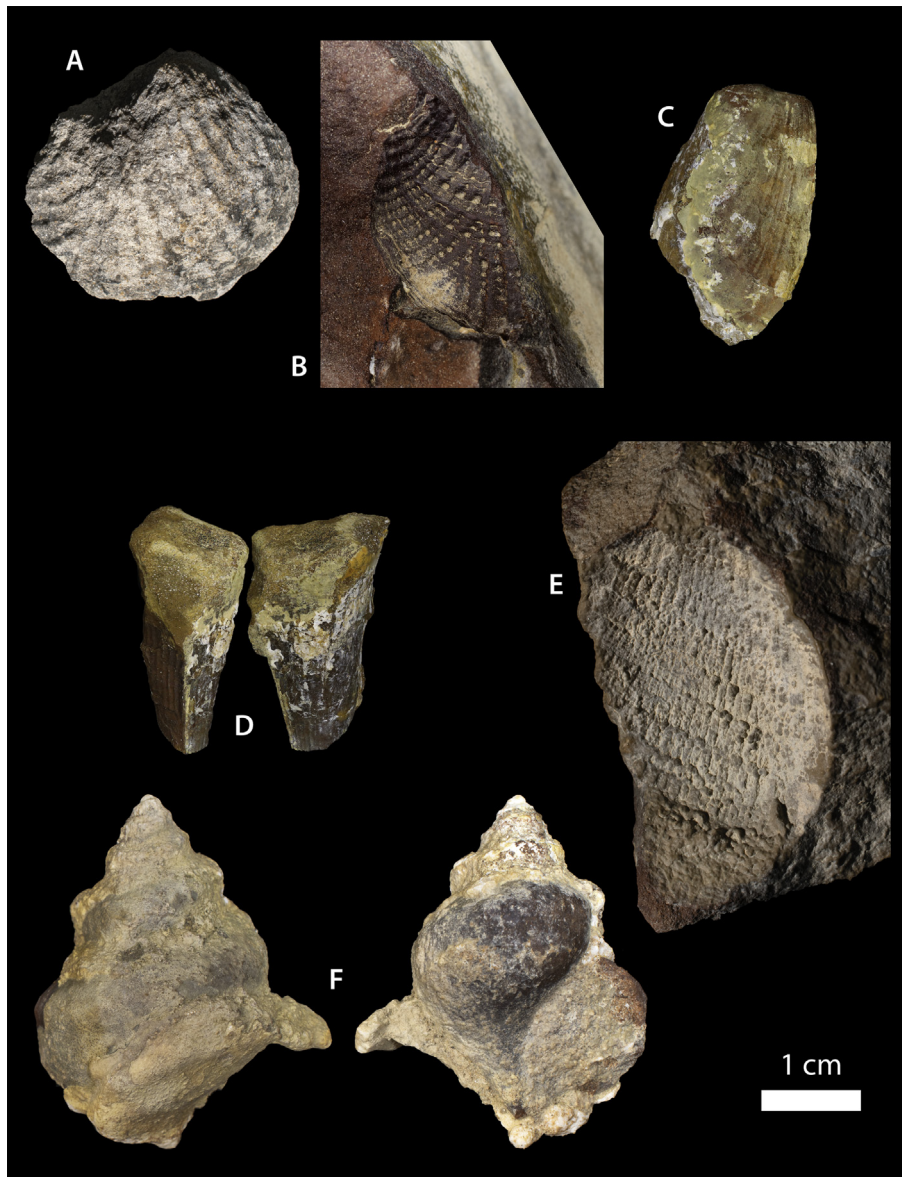


Fig. 3. Benthic mollusks from Cape Marsh: (A) *Oistotrigonia antarctica* (UWBM-109976); (B) external mold, likely of *O. antarctica* (UWBM-109980); (C) poorly preserved specimen of *Panopea* (?) *clausa* (?) (CM 59425); (D) *Pinna anderssoni* (CM 59430); (E) external mold of cucullaeid shell ornamentation (UWBM-109979), likely *Nordenskjoldia nordenskjoldi*; (F) *Taioma globus* (UWBM-109975).

4. U–Pb detrital zircon geochronology

4.1. U–Pb detrital zircon methods

A single 1.5 kg sample of medium-grained sandstone was collected from the Upper Cretaceous succession on Cape Marsh (S 65°14.642'; W 59°26.949', Figs. 1 and 2). The sample was collected from a fossiliferous interval in the upper part of the stratigraphic section, from a thin, ferruginous, calcareous-cemented medium-grained sandstone bed that may correlate to the B–B' stratigraphic section or the lower covered interval (Fig. 2) published by del Valle and Medina (1985). Heavy mineral separation was conducted at James Cook University, Townsville, Australia (JCU), which involved crushing, milling, Wilfley table sorting, and magnetic and heavy liquid separations. Individual zircons were then picked from the heavy

concentrates under a binocular microscope, with special emphasis placed on picking the freshest, most acicular grains in order to maximize chances for analyzing syndepositional volcanic ash-derived phenocrysts.

The samples were mounted using epoxy resin, polished to expose the zircons, and then imaged using a scanning electron microscope with cathodoluminescence detector (SEM-CL) to identify the best grains and locations for analyses (Fig. S2). U–Pb geochronology was performed using laser ablation inductively coupled plasma mass spectrometry (LA-ICP-MS) on a Teledyne Analyte G2 193 nm Excimer Laser with HeLex II Sample Cell and a Thermo iCAP-RQ ICP-MS at the Advanced Analytical Centre at JCU. The analytical results were processed using Iolite (<https://iolite-software.com/>). The software was used for downhole fractionation calibration, instrumental drift correction, and propagated error estimation (Paton et al.,

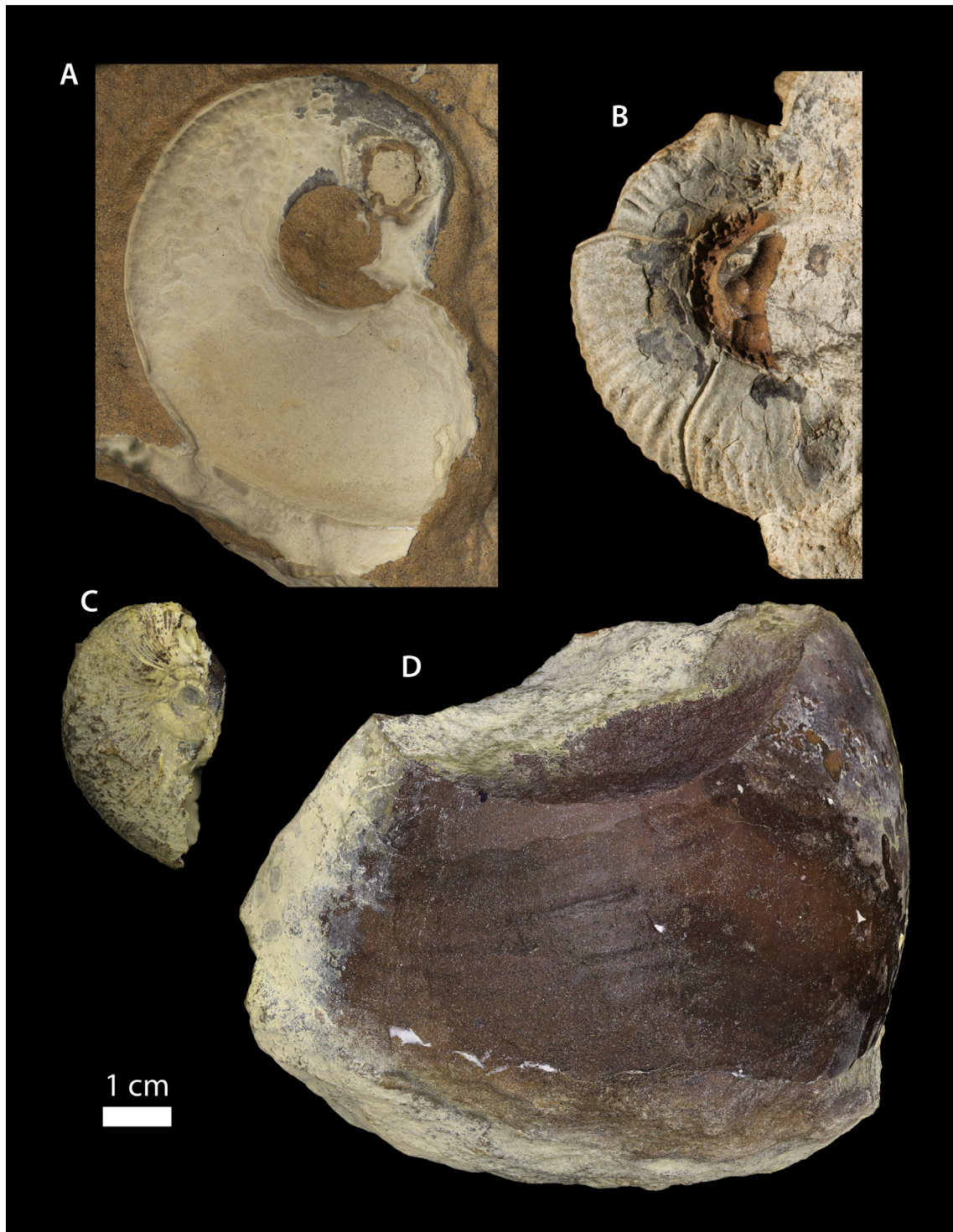


Fig. 4. Cephalopods from Cape Marsh: (A) external mold of highly compressed, fairly involute, unornamented ammonite (UWBM-109981) of uncertain taxonomy, but possibly referable to *Metaplacenticeras*, *Placenticeras*, or *Karapadites*; (B) *Neokossmaticeras* (?) *redondensis* (?) (UWBM-109974); (C) *Gaudryceras* sp. (CM 59407); (D) indeterminate nautiloid body chamber (CM 59406), possibly *Eutrephoceras* (?).

2011). Probability density plots and weighted mean ages were calculated using Isoplot (Ludwig, 2008). Maximum depositional ages were calculated by determining the weighted mean of the youngest cluster of concordant grains (where $n \geq 3$) with overlapping ages (within 1σ error) for each sample (Dickinson and Gehrels, 2009; Tucker et al., 2013).

4.2. U–Pb detrital zircon results

A total of 102 zircons were analyzed from the Cape Marsh sample (Cape Marsh-1), which produced 89 concordant ages (Fig. 6). The youngest single grain age is 72.7 ± 2.3 Ma, whereas the youngest coherent zircon population ($n = 4$), including this youngest grain, yields a weighted mean age of 74.2 ± 1.1 Ma (mean

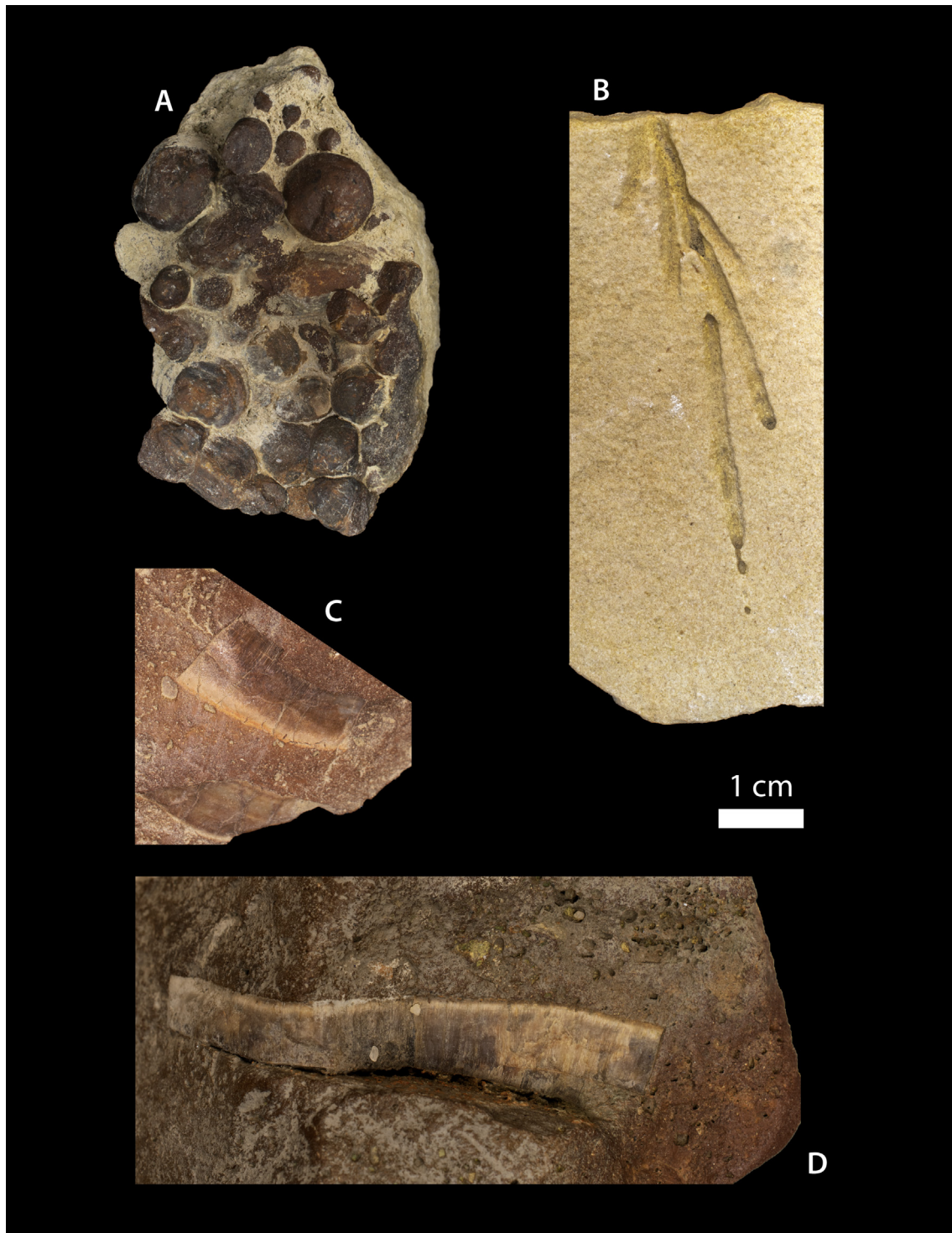


Fig. 5. Trace fossils and inoceramid fragments from Cape Marsh: (A) molds of *Teredolites* burrows, original wood substrate not preserved (UWBM-109977); (B) bedding plane view of *Chondrites* (UWBM-109978); (C, D) cross sections through inoceramid shell fragments, *Antarcticeramus* (?) *robotensis* (?), on same sample (UWBM-109982), showing elongate calcite prisms. Part of (C) shows both top view and side view or prisms.

squared weighted deviation [MSWD] = 0.78) (Fig. 6B). The youngest population of detrital zircons ($n = 4$) are all generally euhedral with fresh edges indicative of minimal transport, and show typical igneous growth zoning patterns under cathodoluminescence (Fig. S2), consistent with a volcanic origin (Corfu et al., 2003). Moreover, one of these young grains (Cape Marsh-98; Fig. S2) stood out for its extreme acicular nature and presence of large melt

inclusions, both of which are typically regarded as features of explosive eruptive phase zircons. This young zircon population was likely sydepositionally derived from airfall volcanic ash delivered into the backarc JRB from volcanic centers located in the Mesozoic Graham Land arc, now on the Antarctic Peninsula. Among the maximum depositional age-defining zircons, one grain is mildly discordant, but the plotted lower intercept age (73.9 Ma) is

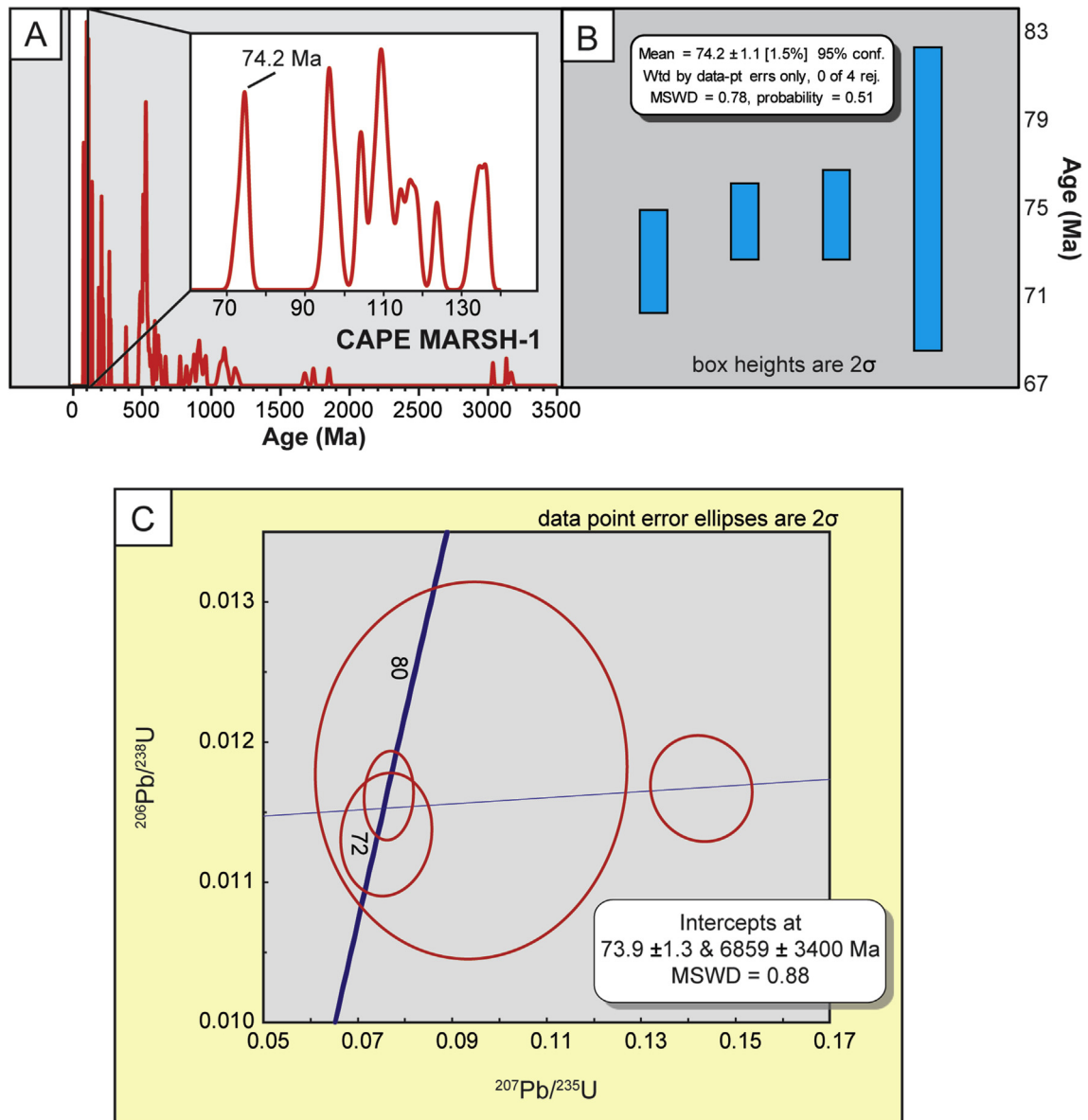


Fig. 6. (A) relative probability plot of the full Cape Marsh detrital zircon sample, with expanded view of the youngest Cretaceous age spectra (inset); (B) weighted mean of the youngest coherent detrital zircon population composed of four Campanian-aged grains; (C) U–Pb Concordia diagram for the same detrital zircon population.

consistent and within error of the calculated age, providing confidence in the results (Fig. 6C). The fine-grained shallow shelf setting located in the distal portion of the JRB would not have facilitated the rapid transport of freshly eroded volcanic detritus, thus suggesting that the young, isolated population of ~74 Ma grains was syndepositionally derived from airfall ash and therefore likely represents a close approximation of the true depositional age.

5. Paleomagnetism for magnetostratigraphy

5.1. Paleomagnetic methods

Samples ($n = 31$) were collected from carbonate concretions and calcified siltstone for paleomagnetic analyses along the basal 45 m of Section A–A' (del Valle and Medina, 1985). Samples were measured on a 2G Enterprises SQUID magnetometer in the Caltech Paleomagnetism Laboratory using the RAPID consortium's

automatic sample changer (Kirschvink et al., 2008). For each specimen, the natural remanent magnetization was measured, followed by two low-temperature cycling steps in liquid nitrogen, low alternating field demagnetization up to 7.5 mT, and then thermal demagnetization up to 380 °C in 12 steps of 50 °C or 20 °C in a controlled nitrogen atmosphere. Paleomagnetic directions were calculated using the least squares method with anchored lines and planes (Kirschvink, 1980) combined with Fischer statistics (e.g., McFadden and McElhinny, 1990) using the PmagPy software (Tauxe et al., 2016). Additional rock magnetic measurements were performed on select sister specimens of samples representing a range of demagnetization behaviors using a 2G Enterprises SQUID magnetometer following the RAPID protocols, and analyzed using the RAPID Matlab scripts (Kirschvink et al., 2008). The protocol includes measurements of alternating field demagnetization of the natural remanent magnetization, rotational remanent magnetization acquisition and demagnetization (RRM), anhysteretic

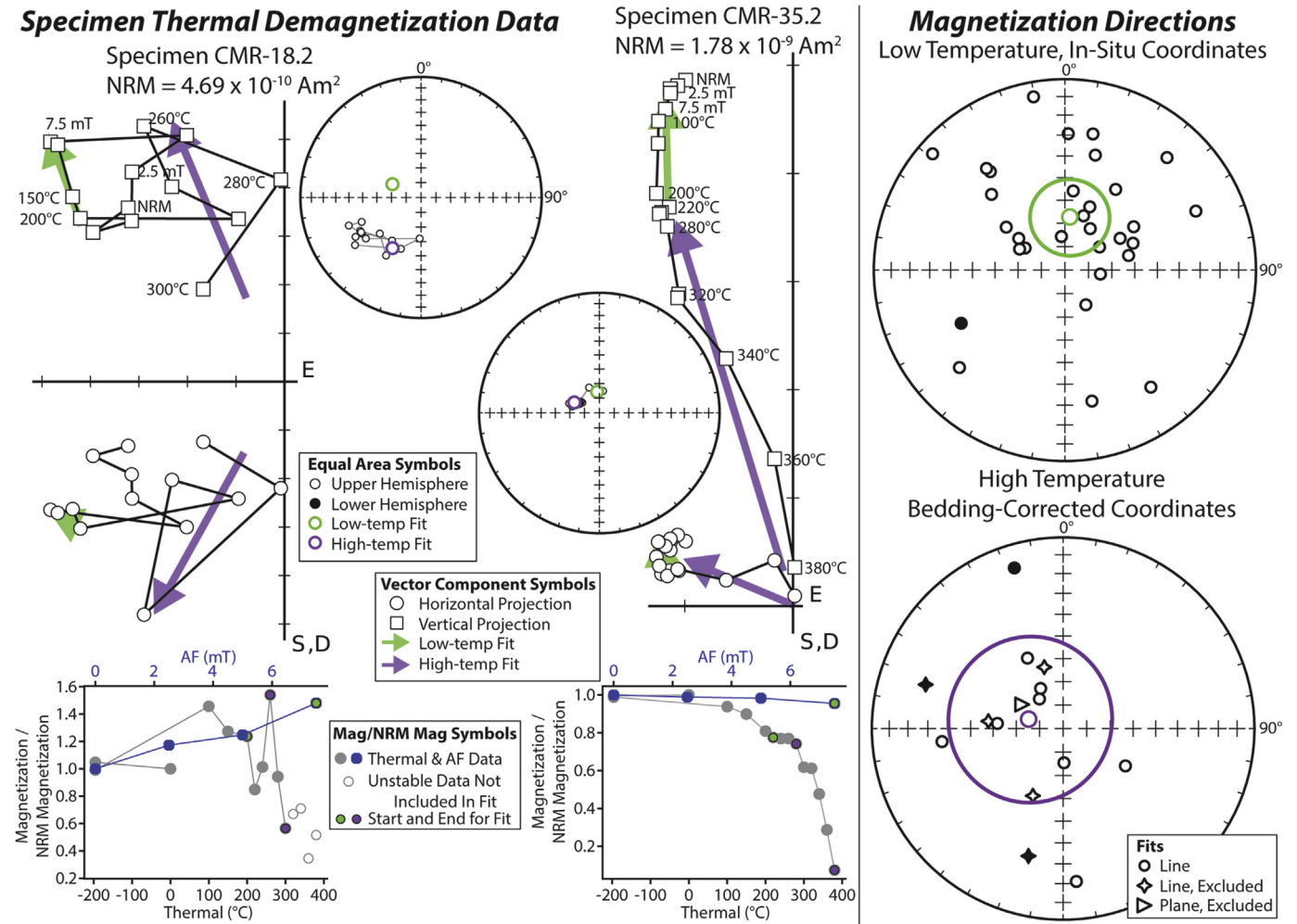


Fig. 7. Paleomagnetic data and directions. Vector component, equal area, and magnetization/natural remanent magnetization (NRM) plots are shown for two example specimens in situ coordinates. CMR-18.2 at 2.7 m is a noisy sample that could still be fit with two components including an origin-trending high-temperature component. As its maximum angular deviation (MAD) is greater than 10, it was not included in magnetostratigraphic interpretations. CMR-35.2 at 37.5 m is one of the best samples with a well-defined origin-trending high-temperature component. Fitted magnetization directions are shown on equal area plots on the right. Low-temperature directions had a Fischer mean of $D = 5.2^\circ$, $I = -67.2^\circ$, $\alpha_{95} = 16.6^\circ$, $N = 31$ (in situ). High-temperature directions were found for 15 samples and those with $MAD \leq 10$ (or $MAD \leq 15$ for plane fits) gave a Fischer mean of $D = 285.3^\circ$, $I = -74.8^\circ$, $\alpha_{95} = 35.5^\circ$, $N = 9$ (bedding-corrected for tilt of $141^\circ/9^\circ$).

remanent magnetization acquisition and demagnetization, isothermal remanent magnetization (IRM) acquisition and demagnetization, and backfield IRM acquisition.

5.2. Paleomagnetic results

Coercivity spectra, backfield IRM measurements, and RRM data suggest the main ferromagnetic mineral is (titano)magnetite (Fig. S3). Additional rock magnetic experiments suggest it is of detrital origin and falls in the single-domain or vortex state size range, consistent with rock magnetic data from JRB sediments (Fig. S3) (Milanese et al., 2017, 2018). All samples contained a low-temperature magnetic direction ($D = 7.1^\circ$, $I = -67.2^\circ$, $\alpha_{95} = 16.6^\circ$, $N = 31$) that was demagnetized by 200–240 °C; this is interpreted as a present-local field overprint (Fig. 7). Above this temperature, many samples continued to smoothly demagnetize before becoming unstable with irreproducible, random directions and magnetizations (Fig. 7); presumably, this is due to the formation of ferromagnetic minerals from decomposition of clays or Fe-carbonate phases during the thermal demagnetization process. By 380 °C, only five samples

were still stable, all but one were heading toward the origin, and measurements were halted. In total, 15 samples had reached or were trending toward the origin; these samples lost between 63 and 93% of their initial magnetization by 380 °C. These high-temperature directions were predominantly normal polarity with an uncertain polarity interval at the bottom of the section (Fig. 8). Samples near the top of the section had much lower error and stronger magnetizations, suggesting a change in magnetic mineralogy, crystal shape, abundance or post-depositional processing; however, similar rock magnetic characteristics rule out the first two options. The <90% loss of magnetization and low-unblocking temperature of the Cape Marsh magnetic directions raises concerns about whether they are primary detrital remanent magnetizations or more recent remagnetizations (viscous or surface weathering/chemical). Prior magnetostratigraphic analyses from JRB sediments noted similar unblocking temperatures in sections where reversal tests were possible (Milanese et al., 2017, 2018; Tobin et al., 2012); however, the Cape Marsh sediments have a distinct diagenetic history so caution must be taken when interpreting these magnetic analyses as primary.

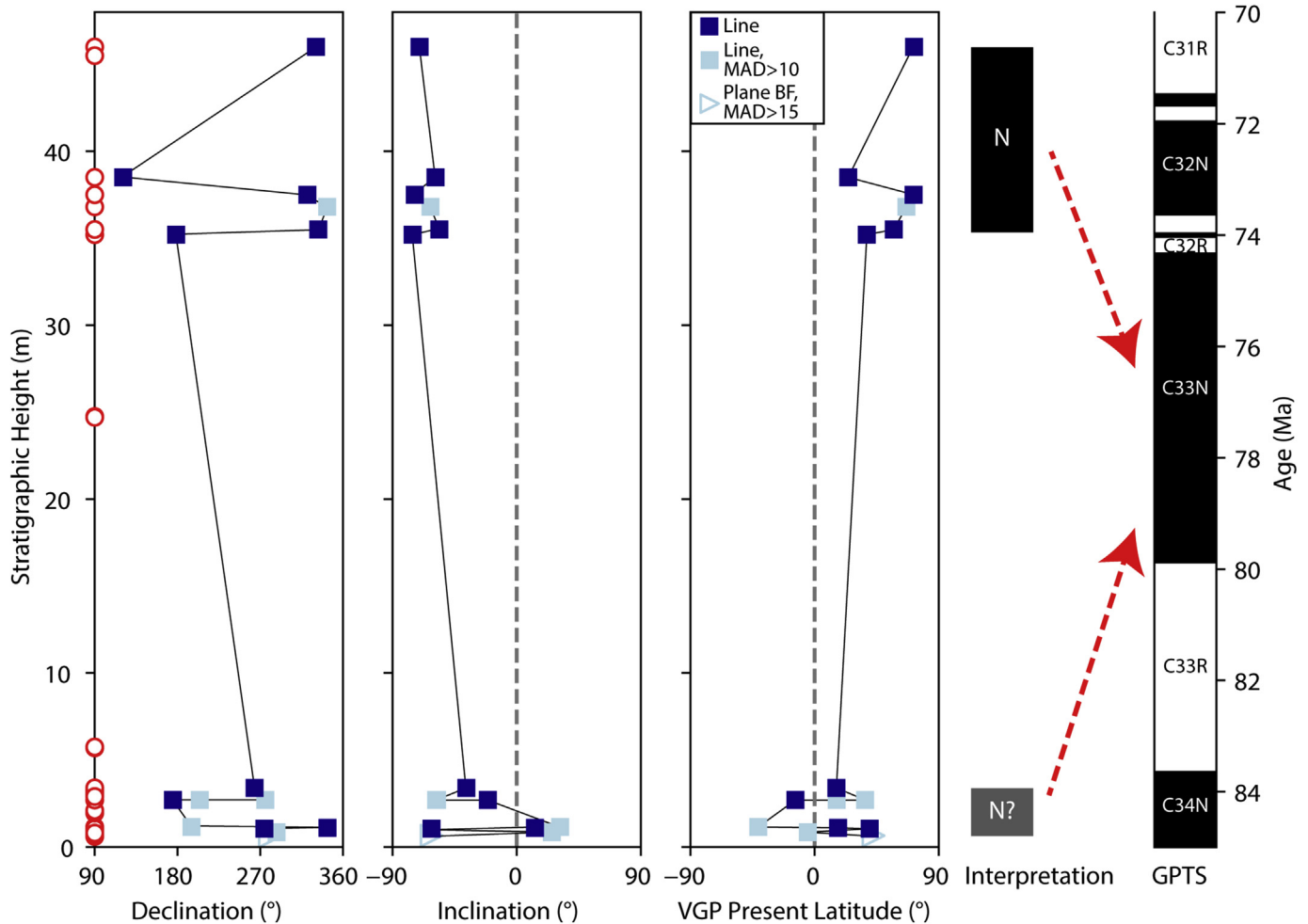


Fig. 8. Magnetostratigraphy from basal Cape Marsh Section A–A'. Samples placed in stratigraphic context are indicated by red dots on leftmost vertical axis. High-temperature magnetization directions that reached or were trending to the origin are shown for 15 samples, 14 line fits and one plane fit shown as best fit (Plane BF); they are colored based on the maximum angular deviation (MAD) for these anchored fits wherein samples with MAD>10 for line fits and MAD>15 for plane fits are lighter-colored and not utilized for the interpretation. Not all samples preserved a high-temperature magnetization direction. The Virtual Geomagnetic Pole (VGP) latitude in present-day coordinates calculated from these directions is shown. Polarity interpretations are noted as normal near the top of the section or uncertain, possibly normal, near the bottom of the section and are tentatively correlated to the global polarity time scale (GPTS) Chron 33N (C33N). (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

6. Discussion

6.1. Paleoenvironmental implications

New fossil data from our 2016 expedition are generally consistent with inferences related to depositional environment that were drawn from the more detailed sedimentological work of del Valle and Medina (1985). Thus, we attribute new taxonomic occurrences to increased surface exposure and not an improvement in collection or sampling protocols. As described above, the lower part of the Cape Marsh section is depauperate in molluscan fossils, and is dominated by *Rotularia*, similar to the “*Rotularia* units” described on Seymour Island (Macellari, 1988). The transition into the upper layers with more abundant mollusks mirrors that on Seymour Island, and probably reflects a general deepening trend at a regional scale, from nearshore and tidally influenced in the lower strata to shallow- to moderate-depth shelf in the upper. The possible presence of *Antarcticeramus rabotensis* and a greater ammonite diversity may indicate that any newly exposed outcrop near the top of the section is indicative of deeper water, though further sedimentological work is necessary to evaluate this hypothesis.

The strata at Cape Marsh were originally assigned to the López de Bertodano Formation, as was the entire Santonian–Maastrichtian interval from the JRB at that time (Medina and del Valle, 1980). Subsequent work has subdivided the Upper Cretaceous sediments of the JRB into a variety of lithostratigraphic units, the history of which was well-summarized by Milanese et al. (2017). Medina et al. (1989) proposed a Campanian age for the strata at Cape Marsh, but suggested a correlation with the López de Bertodano Formation was most likely. Given more recent work, an assignment or correlation to the López de Bertodano Formation is likely no longer valid, but limited field time precludes us from definitively assigning the Cape Marsh deposits to an existing or novel formation. An assignment to the Santa Marta Formation is most likely given the similar proximal depositional setting and age of the Beta Member of this formation, though see discussion below.

6.2. Age implications

Fleet (1966) first correlated the Cape Marsh outcrops to those on Snow Hill Island based on the co-occurrence of *Oistotrigonia*

antarctica, but did not constrain the age of these rocks beyond Late Cretaceous. This age was later refined to the “Senonian” (i.e., Coniacian–Maastrichtian; Medina and del Valle, 1980) and later the Campanian (del Valle and Medina, 1985; Medina et al., 1989), and we further refine this age to the late Campanian, though our data are not fully consistent with reports from elsewhere in the JRB.

6.2.1. Biostratigraphic age implications

Based on the newly recovered fossils described above, the Cape Marsh outcrops—specifically the upper, mollusk-rich sections (B–B' and C–C' of del Valle and Medina, 1985)—are best assigned to Ammonite Assemblage 7 of Olivero (2012a). Specifically, the presence of *Neokosmaticeras* (?) and *Antarcticeramus* (?) *rabotensis* (?) supports this assignment, which is consistent with the presence of *Natalites* (?). The indeterminate involute ammonite morphotype could be an example of *Placenticeras* or *Metaplacenticeras*, both of which are also known primarily from Ammonite Assemblage 7 of Olivero (2012a). An alternative identification, *Oiophyllites*, is also consistent with this age assignment, though that genus is longer-ranging. Given that these identifications incorporate some uncertainty, caution is warranted, but it is unlikely that the Cape Marsh strata are as young as Ammonite Assemblage 9 or 10 of Olivero (2012a), both of which contain *Gunnarites*. *Gunnarites* is found broadly across the JRB and does not appear to be facies-limited or -restricted (Olivero, 2012a). Moreover, when *Gunnarites* is present, it is generally a very abundant member of low-diversity assemblages, particularly when a site has received little previous and dedicated paleontological investigation (Tobin et al., 2018). As such, the absence of *Gunnarites* from Cape Marsh provides circumstantial (albeit negative) evidence supporting deposition of these strata prior to the beginning of Ammonite Assemblage 9. The non-inoceramid bivalves (Table 1) are all known primarily from Snow Hill Island (Wilckens, 1910) in areas that are primarily in ammonite assemblages 8–10 (Olivero, 2012a), suggesting that these benthic species are longer-ranging and that their presence in the fossil record is likely facies-controlled.

Ammonite Assemblage 7 has been correlated with C33N (79.9–74.3 Ma) (Ogg, 2012) from the Rabot Formation on south-eastern exposures of JRI (Milanese et al., 2019). While not formally constrained within C33N, linear sedimentation rate estimates would place Ammonite Assemblage 7 within the lower half of this magnetochron, with an age range of ~80 to ~77 Ma. It should be noted that the diagnostic ammonites from this assemblage are found in the Santa Marta Formation on northwestern JRI only, in the form of reworked fossils at a sequence boundary.

6.2.2. U–Pb detrital zircon geochronology implications

The oldest possible depositional age suggested by the U–Pb constraints is 74.2 ± 1.1 Ma, although this age is generated from a relatively small population of grains. Given the uncertainty, this date could plausibly be within the later portion of C33N, or all of C32R. Given the biostratigraphic correlation to the Rabot Formation described above, this date is consistent with biostratigraphic evidence if Ammonite Assemblage 7 is actually near the upper half of C33N, though this would require unusual sedimentation patterns in the Rabot Formation. The sandstone sample was collected at roughly the same stratigraphic level as many of the relevant ammonite fossils, though clearly below the recovered inoceramid fragments. The discrepancy between this depositional age constraint and the age implied by biostratigraphic correlation to the JRI area is further explored below.

6.2.3. Magnetostratigraphic age implications

Although all biostratigraphically-relevant fossils and the sample for U–Pb detrital zircon dating were recovered from sections B–B'

(likely equivalent) and C–C' (Figs. 1, 2) of del Valle and Medina (1985), they help inform interpretation of the magnetostratigraphic results from Section A–A'. Ammonite Assemblage 7 has recently been assigned to C33N from magnetostratigraphic study of the Rabot Formation in the JRB, whereas the underlying Ammonite Assemblage 6 is largely within C33R (Milanese et al., 2018, 2017). Whereas there are some issues with reconciling the maximum depositional age with the biostratigraphic assignments (see below), both techniques imply a placement of the Cape Marsh strata within C33N. If deposition at Cape Marsh was fairly continuous, then it is most likely that the normal polarity recorded in Section A–A' also falls within C33N. There is no clear field evidence for a long hiatus between Section A–A' and the overlying sections, but this interval does represent a break in observable outcrop, and if there is an unrecognized unconformity, the normal polarity of Section A–A' could instead represent C34N (i.e., older than 83.6 Ma; Ogg, 2012). These correlations rely on the fossil data and biostratigraphic correlations from the JRI area; if these data are ignored and the youngest age constraint from the detrital zircons is used, the magnetic directions from Section A–A' could represent one of the many normal polarity subchrons of C32 (e.g., C32R.1N at 74 Ma or C32N at younger than 73.6 Ma). Alternatively, it is possible that the observed normal polarity is not primary, but instead is a modern overprint, in which case the age of Section A–A' would not be well-constrained.

6.2.4. Resolution of age inconsistencies

Whereas all data are consistent with a Campanian age, there are some probable inconsistencies, specifically between the maximum depositional age and the age implied by biostratigraphic correlations to other dated sections. In short, biostratigraphic correlation places the B–B' and C–C' sections within Ammonite Assemblage 7, which is most likely within the lower half of C33N (~80–77 Ma). In contrast, the maximum depositional age obtained from strata at or below the biostratigraphic constraints has a younger estimated age (74.2 ± 1.1 Ma). The magnetostratigraphic data are plausibly consistent with either model. There are several potential resolutions for this problem:

1. If a lengthy (~5 Ma) hiatus exists between ammonite assemblages 6 and 7 in the Rabot Formation, then Ammonite Assemblage 7 could also represent the later part of C33N, and be consistent with the maximum depositional age obtained here. A hiatus, or possibly a significant change in depositional rate, would be necessary, because Ammonite Assemblage 6 is observed to be C33R (Milanese et al., 2019) and is therefore 80 Ma at the youngest. We consider this scenario unlikely because the transition from Ammonite Assemblage 6 to 7 does not show any major hiatuses in the JRB when Ammonite Assemblage 7 is not reworked – in fact, observed hiatuses separate assemblages 7 and 8 (Olivero, 2012a). It is also theoretically possible that the occurrences of these genera are not coeval across the JRB. However, given the length of time and the relatively small geographic distance represented, we do not think that true diachroneity in the distribution of the Ammonite Assemblage 7 organisms is a likely explanation, though we cannot completely exclude it.
2. Given the fragmentary nature of the fossil material recovered from Cape Marsh, it is possible that many of these fossils are reworked, similar to the situation observed for Ammonite Assemblage 7 in the Santa Marta Formation (Olivero, 2012b). We favor this scenario because of the correlation with a similar sequence boundary on JRI and its consistency with both published and our new age constraints. This interpretation would constrain the age of deposition of sections B–B' and

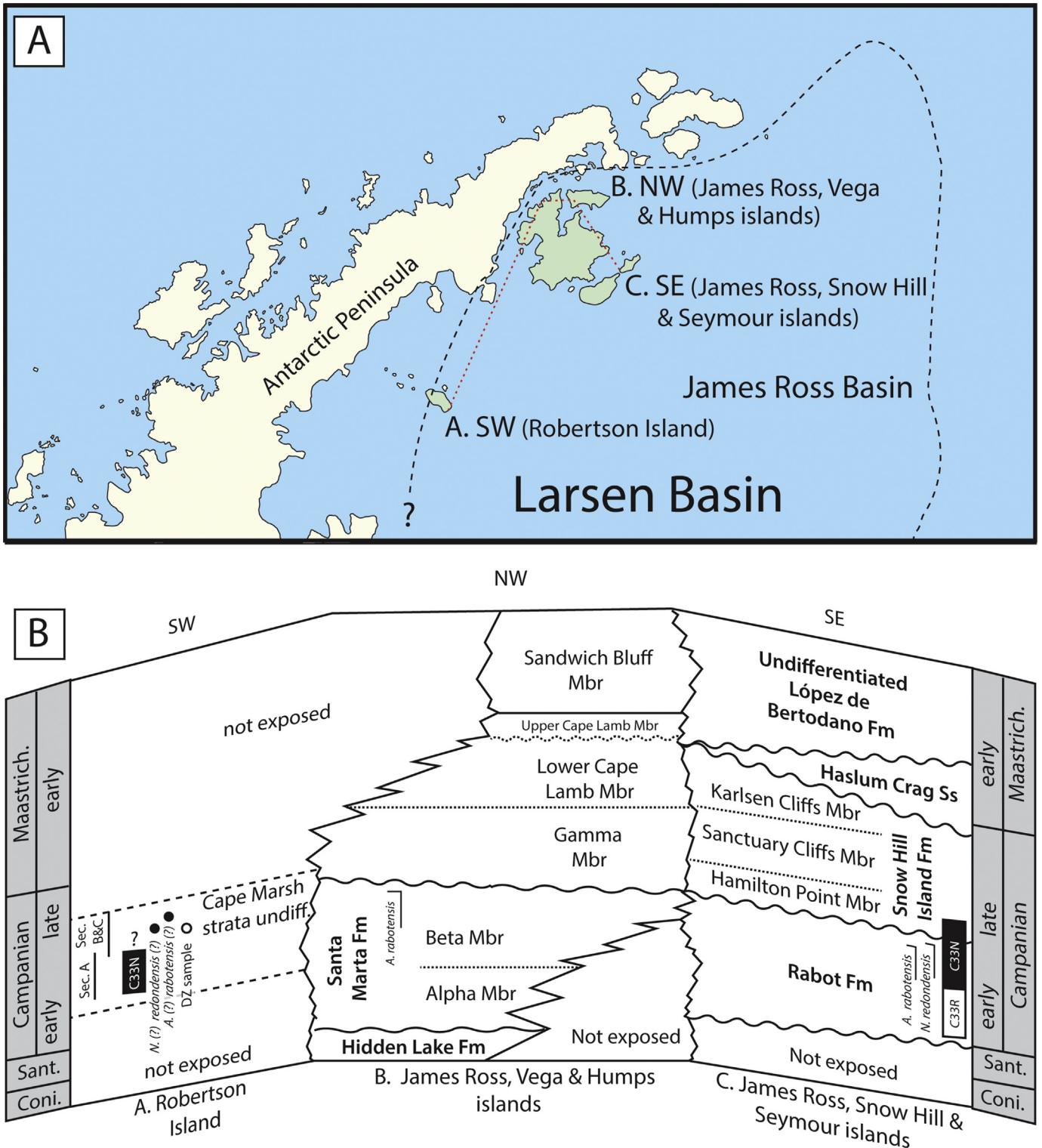


Fig. 9. (A) map including the northern end of the Antarctic Peninsula (yellow) and the islands with Cretaceous-aged exposures of the James Ross Basin (green). Red dashed line indicates cross section trace for fence diagram; black dashed line indicates hypothesized margins of Larsen Basin (which includes the James Ross Basin) (del Valle et al., 1992); (B) simplified fence diagram of deposition within the James Ross Basin, modified after Roberts et al. (2014) with location of detrital zircon (DZ) sample indicated and relevant biostratigraphic markers and magnetostratigraphy added from Olivero (2012a) and Milanese et al. (2017), respectively. Formation and member names follow Olivero (2012a), though the Alpha and Beta members of the Santa Marta Formation are roughly equivalent to the Lachman Crags Member of Pirrie et al. (1997) and the Gamma Member of the Snow Hill Island Formation is roughly equivalent to the Herbert Sound Member of Crame et al. (1991). (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

C–C' only by the detrital zircon maximum depositional age, i.e., younger than 75.3 Ma (accounting for uncertainty), though probably not much younger. This interpretation would also allow temporal correlation with the lower part of the Snow Hill Island Formation instead of the upper part of the Santa Marta or Rabot formations (Fig. 9). Testing this hypothesis would require an extended future field campaign on Cape Marsh.

- For the sake of completeness, it is also possible that there are sampling or analytical errors in published work, or in our interpretations. For example, our biostratigraphic identifications could be confounded by poor preservation and therefore be incorrect, our U–Pb age may be incorrect, or the magnetostratigraphic interpretations from the Rabot Formation on JRI could be in error. It is also possible that unrecognized localized slumping within the section where the detrital zircon sample was collected could have contributed to the age inconsistency. We stress that we find no evidence for any such explanation, but it does remain plausible.

7. Conclusions

New biostratigraphic, magnetostratigraphic, and detrital zircon U–Pb constraints have refined the correlation between Cretaceous sediments at Cape Marsh of Robertson Island and their better-studied counterparts situated further northeast in the JRB (Fig. 9). Cape Marsh has clearly undergone a significantly different post-depositional diagenetic history than most other material in the JRB, but it records generally similar depositional conditions and a comparable invertebrate fauna. The fauna are difficult to positively identify in some cases, but recovered specimens are generally referable to those from various localities in the JRI area, and specifically the upper parts of the Santa Marta and Rabot formations. Whereas some inconsistencies exist between these biostratigraphic constraints and the maximum depositional age derived from U–Pb analysis of detrital zircons, together they likely require a true depositional age of the Cape Marsh outcrop in the late Campanian, approximately 74 Ma. This model requires that many of the invertebrate fossils are reworked, which is consistent with their pre-cementation fragmentation, but would require further evidence to confirm. Our observations were likely facilitated by increased melting of ice cover on Robertson Island that has increased the surface exposure of these strata. As this process continues into the future, Cape Marsh may prove to be an even more useful point of comparison to contemporaneous exposures elsewhere in the JRB.

Acknowledgments

We acknowledge support from NSF grants ANT-1142129 (to MCL), ANT-1142104 (to PMO), ANT-1141820 (to JAC), ANT-1142052 (to Ross MacPhee), and ANT-1341729 (to JLK) that funded our 2016 fieldwork on Robertson Island. We are grateful to Albert Kollar (CM) and Ron Eng (UWBM) for their assistance. We thank the crew of *R/V Nathaniel B. Palmer*, the NSF science support staff on board, and the crew from Air Center Helicopters for transportation to the site and assistance in the field. U–Pb detrital zircon data is available in the data repository. Paleomagnetic data are available in the MagIC database (<https://www.earthref.org/MagIC/doi/10.1016/j.cretres.2019.104313>). Rock magnetic and U–Pb zircon raw data are available at <http://doi.org/10.5281/zenodo.3464591>. Finally, we thank two anonymous reviewers, whose comments greatly improved the manuscript.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at <https://doi.org/10.1016/j.cretres.2019.104313>.