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Stratigraphy, sedimentology and paleontology of Upper Cretaceous deposits of Day Nunatak, Snow Hill Island, Antarctica

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ABSTRACT

Day Nunatak exposes an actively emergent stratigraphic section located on Snow Hill Island to the east of the Antarctic Peninsula. Strata exposed on Snow Hill Island were deposited in the James Ross Basin, which includes marine units of Cretaceous–Paleogene (K–Pg) age. Here we provide the first report of the sedimentology and paleontology of Day Nunatak, and place it into the broader stratigraphic context of the basin. Day Nunatak was previously unexplored due to difficulties accessing the site, and the historically poor exposure which has recently improved due to warming of the Antarctic Peninsula. Deposits exposed at Day Nunatak are assigned to the Karlsen Cliffs Member (KCM) of the Snow Hill Island Formation, and are better preserved than deposits at the type section of the KCM at Karlsen Cliffs, which has been altered by cross-cutting basaltic dikes. Correlation of lithostratigraphic and biostratigraphic data from Day Nunatak with other outcrops in the basin allows the section to be placed within a previously developed stratigraphic framework, and assigned an early Maastrichtian age. Our observations, and previous descriptions of the KCM, are consistent with a middle- to inner-shelf depositional environment below storm-wave base. Ammonites of the genus *Gunnarites* are very common, with other ammonite genera and benthic mollusks an order of magnitude less common. Stable carbon and oxygen isotope values obtained from bivalve shells are similar to values previously reported from Seymour Island, and suggest seawater temperatures of ~7 °C. Measured bedding orientations suggest the presence of a structural offset between Day Nunatak and other sections exposed further north on Snow Hill Island. Day Nunatak preserves a similar depositional environment to deposits reported from the uppermost Maastrichtian on Seymour Island, and is the deeper-water equivalent of contemporaneous proximal sections reported from Vega Island.

1. Introduction

The Late Cretaceous record from Antarctica is represented primarily by sedimentary rocks deposited in the James Ross Basin (JRB). These rocks crop out throughout the James Ross Island archipelago, which is located on the eastern side of the Antarctic Peninsula (Fig. 1). JRB sediments are only exposed in areas where snow and/or ice cover does not persist over the austral summer, which limits exposure in many areas of the archipelago. There are several continuous stratigraphic exposures located on the comparatively well-studied James Ross Island (Crame et al., 1991; Olivero, 1992; Strelin et al., 1992) and Seymour Island (Macellari, 1988; Zinsmeister, 2001; Olivero et al., 2007; Tobin et al., 2012; Witts et al., 2016; Tobin, 2017) which contain abundant and well-preserved invertebrate fossils and a well exposed Cretaceous–Paleogene (K–Pg) boundary. The smaller islands of the archipelago, including Vega, Snow Hill, Cockburn, and Humps, as well as geographically-isolated smaller exposures on the eastern and southern shores of James Ross Island, are either more difficult to access, limited in areal extent, or both. As a consequence, these locations are not as well studied and their stratigraphic positions relative to the rest of the basin are not as well-constrained (Olivero, 2012; Roberts et al., 2014).

Here we report the first paleontological and sedimentological description of the Cretaceous sediments exposed at Day Nunatak, Snow Hill Island, based on our observations made during

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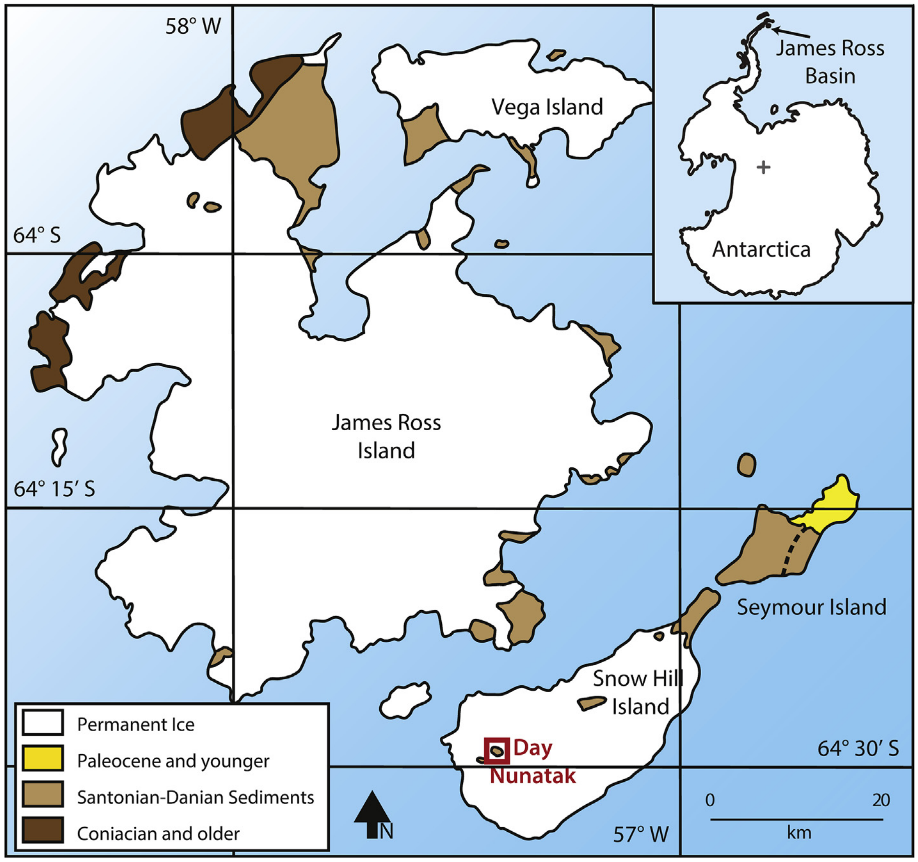

Fig. 1. Map of the James Ross archipelago showing its location relative to the Antarctic continent (inset). The red box indicates the location of Day Nunatak (see Fig. 2). After Crame et al. (2004). (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

exploration in March 2016. Day Nunatak was named in 1995 by the United Kingdom Antarctic Place Names Committee and was first mentioned in the geologic literature by Pirrie et al. (1997). The minimal prior investigation of this locality is a consequence of both the inaccessibility and relatively recent exposure. Day Nunatak is surrounded by heavily crevassed glacial ice, restricting access to helicopter flights. The outcrop was exposed recently, probably as a result of warming during the last 50 years. Fig. 2 shows Landsat imagery of the area from 1975 to present, where the earliest available satellite imagery, though low resolution, shows minimal exposure. Fig. 3 documents the increase in the exposed area of Day Nunatak as measured from nine Landsat images spanning the years 1975–2017. Increased exposure due to receding ice has created landing sites for helicopters, unvisited sedimentary outcrops, and extensive fossils weathered from the poorly lithified sediment. This report describes the sedimentology and paleontology of Day Nunatak, places the section within the sequence stratigraphic context of the JRB, and presents a three-dimensional model of the locality using structure from motion computational techniques applied to low-altitude imagery (Fig. S1).

2. Geologic setting

The JRB is composed primarily of sediments dated from the Aptian (~125 Ma) through the Eocene (~34 Ma) (Crame et al., 2006; Ivany et al., 2006; Marenssi et al., 2002; Olivero, 1992, 2012), locally capped Neogene volcanics and Quaternary glacial sediments (Smellie et al., 2008). JRB sediments were deposited in the rapidly subsiding back arc associated with Cretaceous uplift of the Antarctic Peninsula. Minimal metamorphism, alteration, and tectonic movement or deformation has occurred since deposition. Most of the stratigraphic thickness of the basin consists of Santonian–Danian (~85–65 Ma) deposits of the Marambio Group, which has been the focus of most previous work. Olivero (2012) presented a detailed sequence stratigraphic model for the JRB wherein the Marambio Group is divided into three sequences, with the proximal basin deposits to the west (closer to the Antarctic Peninsula) and the distal basin deposits to the east. The Marambio Group is typically interpreted as prograding shelf facies, with a shoreline and center of deposition migrating toward the east.

The Marambio Group is composed (oldest to youngest) of the Santa Marta, Snow Hill Island, López de Bertodano, and Sobral formations, although this stratigraphic nomenclature has been used inconsistently. In particular, the Haslum Crag Sandstone has sometimes been elevated to a formation (adopted here) between the Snow Hill Island and López de Bertodano formations (Olivero et al., 2008; Olivero, 2012) or demoted to the uppermost member of the Snow Hill Island Formation (SHIF) (Crame et al., 2004; Roberts et al., 2014). In the southern and eastern parts of the JRB, the SHIF is composed (oldest to youngest) of the Hamilton Point, Sanctuary Cliffs, and Karlsen Cliffs members (KCM), as well as (in some descriptions) the Haslum Crag Member. In the more proximal part of the basin to the west, the SHIF is comprised of the Upper and Lower Cape Lamb members, which are age equivalent to the members on Snow Hill Island (Roberts et al., 2014). Based on the evidence presented below, we suggest the Cretaceous deposits of Day Nunatak should be considered part of the KCM (Fig. 4).

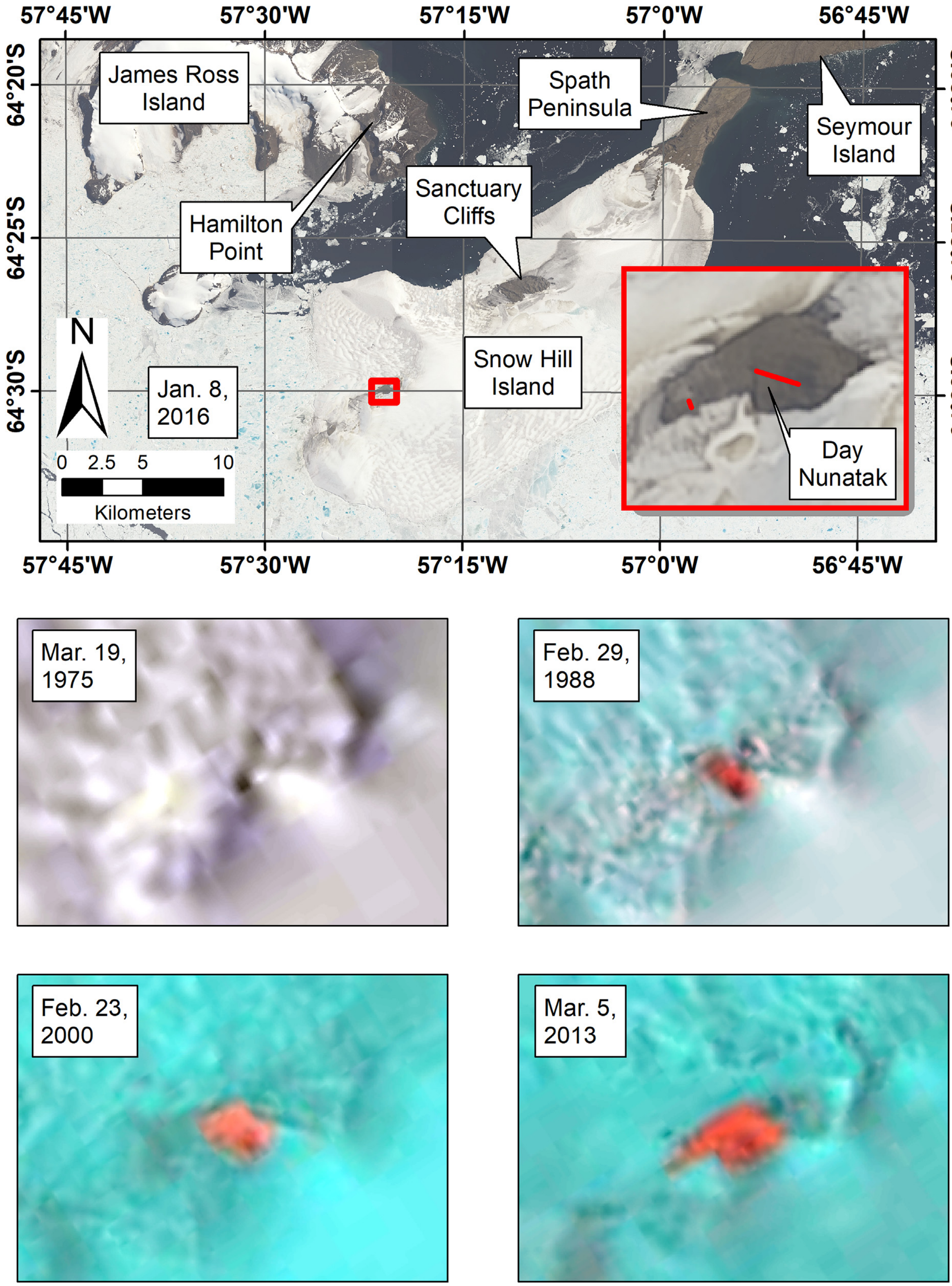

Fig. 2. Satellite photos of the Day Nunatak area on Snow Hill Island through time. The upper figure shows a 2016 satellite photo, with red box indicating location of inset figure of Day Nunatak. Red lines in inset indicate section traces, for detailed section traces see Fig. S2. Sea ice obscures channels surrounding Snow Hill Island to the W through SE. Bottom four images are satellite photos of the same inset area showing melt progression through time. (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

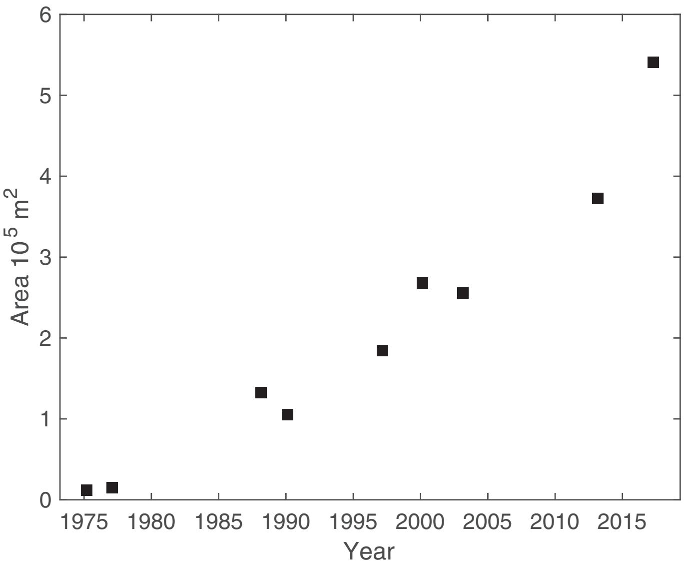

Fig. 3. Changes in areal extent of exposed rock through time at Day Nunatak based on satellite imagery.

3. Methods

3.1. Field work

Field work was completed in March 2016 by a team based on the R/V Nathanial B. Palmer, which was equipped with helicopters. Stratigraphic sections were measured using a Jacob staff and Abney level, and sedimentological samples were collected from trenches where lithologic changes were observed. In some cases sedimentological samples were collected as loose sediment due to the unconsolidated nature of the outcrop. Fossils were collected both from the surface (most commonly), or *in situ* when possible. Field observations, including striations in soils (Fig. S2), indicate active retreat of the glacial ice surrounding Day Nunatak, and suggest that further deglaciation in future years will continue to significantly broaden the extent of accessible outcrop.

3.2. Structure from motion

Helicopters were used to complete an aerial photographic survey to allow the generation of a georeferenced three-dimensional model of Day Nunatak using structure from motion computational techniques (e.g. Fonstad et al., 2013). We reconstructed a high-resolution digital elevation model (20 cm resolution) and photo-realistic digital surface model that allows for both visualization of the field area and digital measurements after returning from the field (see Fig. S1). Images were acquired using two digital single lens reflex cameras shooting from open helicopter windows. Cameras were aimed at various inclinations, and images were acquired along several passes at different altitudes and distances from the outcrop. Workflow for digital reconstruction followed standard structure from motion procedures in the AgiSoft, Inc. Photoscan Pro software package.

3.3. XRD analysis

Powder X-ray diffraction patterns were obtained using a Bruker AXS D8 Discover X-ray diffractometer and a General Area Detector Diffraction System at the Jet Propulsion Laboratory. The radiation

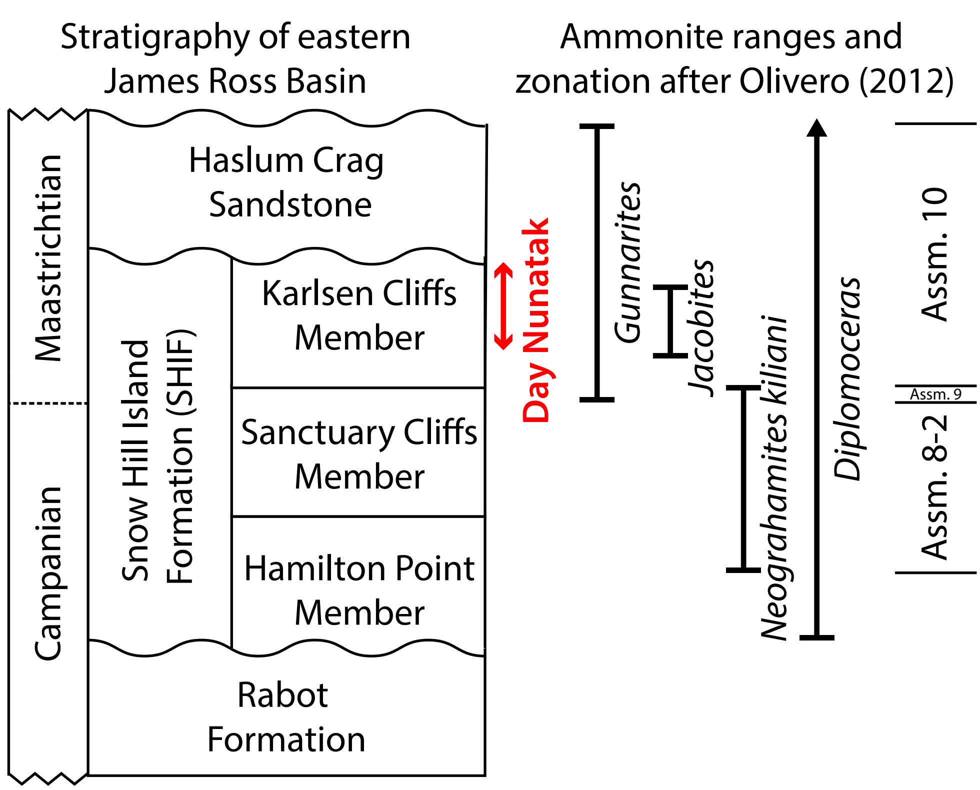

Fig. 4. Stratigraphic relationship of the Snow Hill Island Formation (SHIF) members and over/underlying formations in the eastern part of the basin. Day Nunatak likely represents the upper part of the Karlsen Cliffs Member (see text). The range of ammonites used for biostratigraphy, and the assemblage zones from Olivero (2012) in this interval are depicted at right. Note: The SHIF is comprised of different members in the western part of the basin.

applied was a CuKα (λ = 1.5404 Å) source operated at 40 kV and 20 mA. Phase identification was accomplished by comparing the 13–75° 2θ-range with standard powder diffraction files from the International Centre for Diffraction Data (ICDD) (2000) using the DIFFRACplus EVA 13 Evaluation Package from Bruker AXS (2007). The relative abundance of each phase present was determined using the reference intensity ratio (RIR) method (Chung, 1974), employing RIR values available in the literature.

3.4. Petrological analysis

Light and electron microscopy was performed at the Jet Propulsion Laboratory. Petrographic thin sections of standard (30 μm) thickness were prepared from hand samples and imaged in reflected, transmitted, cross-polarized and reflected UV light using a Leica DM6000 microscope fitted with automated stages and software allowing for large area, high-resolution mosaicking. Scanning electron microscopy and energy dispersive spectroscopy (SEM-EDS) were performed using a Hitachi SU-3500 variable pressure SEM in secondary electron (SE) and backscattered electron (BSE) modes.

3.5. Stable isotope analyses

Six examples of *Pycnodonte* were drilled with a hand drill in a single spot near the umbo of the shell to generate powder for isotopic analysis. Similarly, several concretionary burrows from meter 142 in the measured section (Fig. 5) were drilled, both on the interior and exterior of the burrow. Powdered material was analyzed using GasBench II connected via continuous flow to a Delta V+ isotope ratio mass spectrometer housed at the Alabama Stable Isotope Laboratory at the University of Alabama. Samples were interspersed with, and corrected using, NBS-19 standards during analysis.

4. Observations

4.1. Paleontology

Like most of the Marambio Group, fossils on Day Nunatak are well-preserved and abundant, particularly so in this case due to the lack of any previous collection at the site. Fig. 5 shows the approximate stratigraphic position of fossils collected throughout the section, most of which were not *in situ* due to the steep nature of the poorly-consolidated outcrop. A series of bedding planes near the top of the current exposure preserve the greatest abundance of fossils. These fossils are currently housed at the University of Alabama for study (assigned provisional James Ross Basin 2016 collection numbers – JRB-16-XXX), but will be accessioned into the Burke Museum of Natural History in Seattle, Washington when analyses are complete.

The mode of preservation of fossils is very different from that on the Spath Peninsula of Snow Hill Island (Fig. 1), which preserves the greatest extent of the KCM. On the Spath Peninsula, most fossils are preserved in molds within calcareous, well-cemented, red-colored concretions, and preservation in non-concretionary intervals is poor to absent (Pirrie et al., 1997). Such concretions are characteristic of the Spath Peninsula, but are largely absent from our Day Nunatak section. Body fossils, both isolated and in paler-colored concretions, are more common on Day Nunatak. We tentatively attribute this difference to the presence of basaltic dikes that cut the Spath Peninsula and harden the concretionary layers through chemical alteration, and which may have destroyed fossils that would otherwise have been preserved within unconsolidated sediments.

4.1.1. Cephalopods

The ammonite assemblage is dominated by specimens of the *Gunnarites*, with an estimated greater than 90% of ammonites recovered belonging to this genus. More than 100 specimens were collected, and hundreds more samples were uncollected from horizons of high abundance. In contrast, fewer than ten examples of any other individual taxon were collected. *Gunnarites* samples show substantial variation in ribbing density and shape, presence and preservation of crenulation and tubercules, and to some extent, cross-sectional shape. Spath (1953) separated over a dozen species and/or morphotypes of *Gunnarites* from the JRB based on these variations, but in lieu of careful morphometric work it is currently unclear which of these specific designations are valid. A typical *Gunnarites* specimen is shown in Fig. 6B.

Fragments of *Diplomoceras* are also common, which we here assign to *D. cylindraceum* after Witts et al. (2015) who argue for *Diplomoceras* as a monospecific genus, though this classification is disputed (Machalski, 2012). Previous distinctions between *D. lambi* and *D. maximum* based on cross sectional shape and ribbing density are argued to be the result of intraspecific variability and diagenetic processes. Five samples had sufficient preservation to measure rib index (number of ribs over a distance equal to the whorl height at that location), which varied from 9 to 17 (20 mm/9 ribs; 23.2 mm/11 ribs; 26 mm/11 ribs; 29 mm/12 ribs; 61 mm/17 ribs) with an ontogenetic trend towards a greater rib index at larger whorl heights. While the sample number is small, these specimens do not support the stratigraphic separation on *Diplomoceras* into *D. lambi* and *D. maximum* as recorded by Olivero and Zinsmeister (1989), as these rib index values span the range of both species. This finding implies that the treatment of *Diplomoceras* as a variable monospecific genus is correct (Witts et al., 2015; Dochev and Metodiev, 2016), or that the studied interval captures a transitional period between the two species. All samples from Day Nunatak are fragmentary; typical preservation can be seen in Fig. 6C.

Several examples of *Jacobites crofti* were recovered, though they are much rarer than most of the other ammonites and complete fossils were not preserved. A few small, likely juvenile, ammonites possibly represent a species of *Maorites*, but distinction between juvenile *Maorites* and *Jacobites* is very challenging due to the lack of pronounced ventral tubercules that define *Jacobites* at larger sizes (Spath, 1953). Tubercule preservation on the external whorl is poor in all examples, but impressions of the inner whorls on the dorsum of the subsequent whorl often show the tubercules clearly on incomplete fossils (Fig. 6D). Also present on Day Nunatak are several examples of an unornamented depressed to round whorled form that is classified as *Pseudophyllites loryi* (Fig. 6A). Most of the examples are small (<5 cm in diameter), though one specimen preserves a body chamber mold of almost 15 cm. A number of nautiloid fragments are present that are likely examples of *Eutrephoceras* though their poor preservation and lack of ornamentation make this identification tentative.

4.1.2. Benthic mollusks

No new species were identified, and all recovered benthic mollusks are referable to species previously identified from either Seymour Island or Snow Hill Island, though few are found in abundance. At the generic level, all identified benthic mollusks from Day Nunatak are also found on Seymour Island, with many of the same species present in both locations. *Pinna, Oistotrigonia,* and *Struthiochenopus*, are represented by different species (*frenexiae, pygoscelium*, and *hurleyi*, respectively) on Seymour Island, while the rest of the species are found on Seymour Island. While we do not attempt a comprehensive review of the fauna here, this difference may be the result of the preference for different taxonomists in subdivision of genera and species.

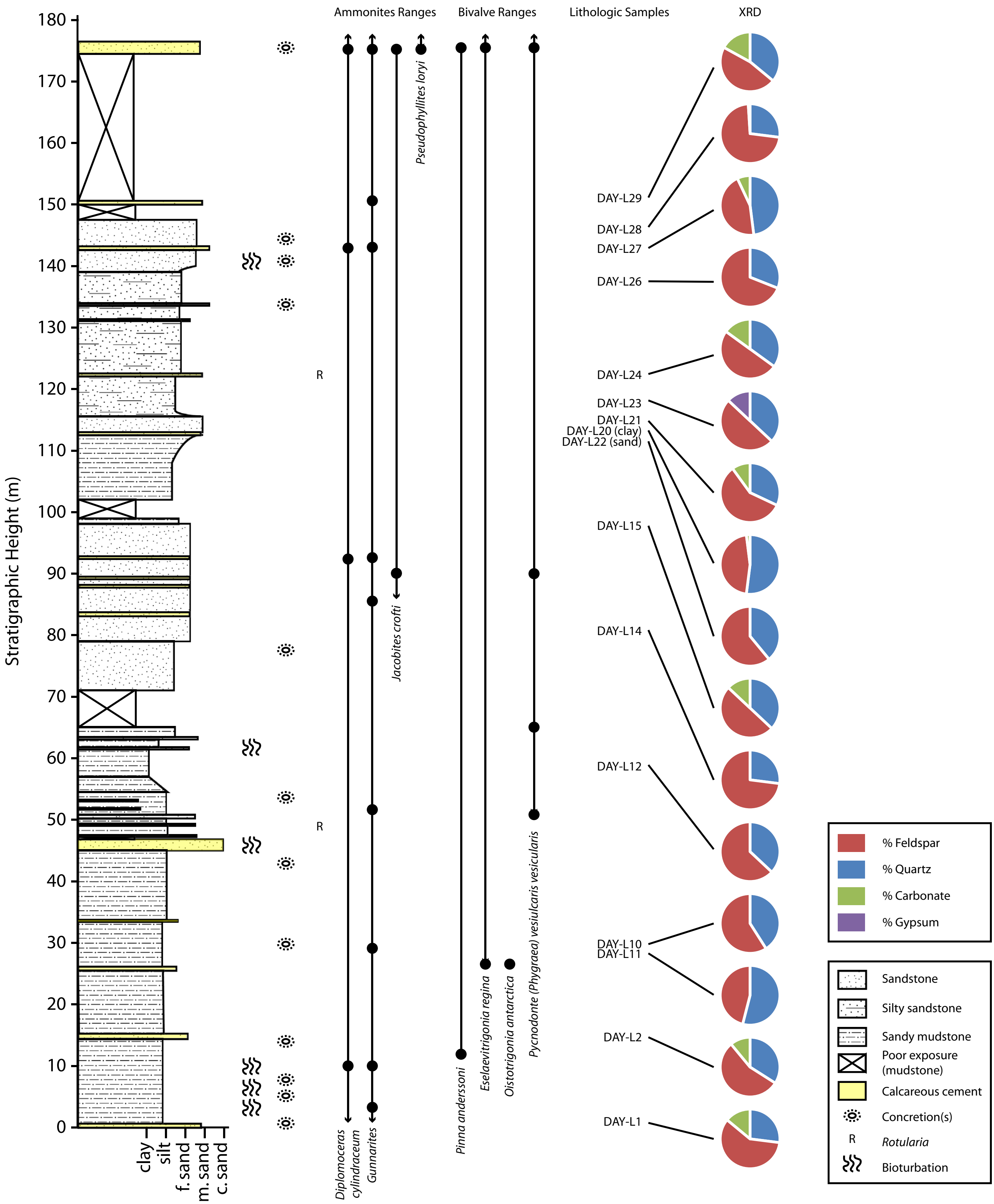

Fig. 5. At left, a lithologic log of Day Nunatak, with ranges and locations of ammonites and bivalves depicted in the middle. Arrows are included on ranges when the taxon is known to range into an overlying or underlying formation. Gastropods are not included as all were collected from the 175 m horizon. Lithologic sample names are placed at the height of collection, and the pie diagrams indicate the prevalence of quartz, feldspar, and carbonate in the samples.

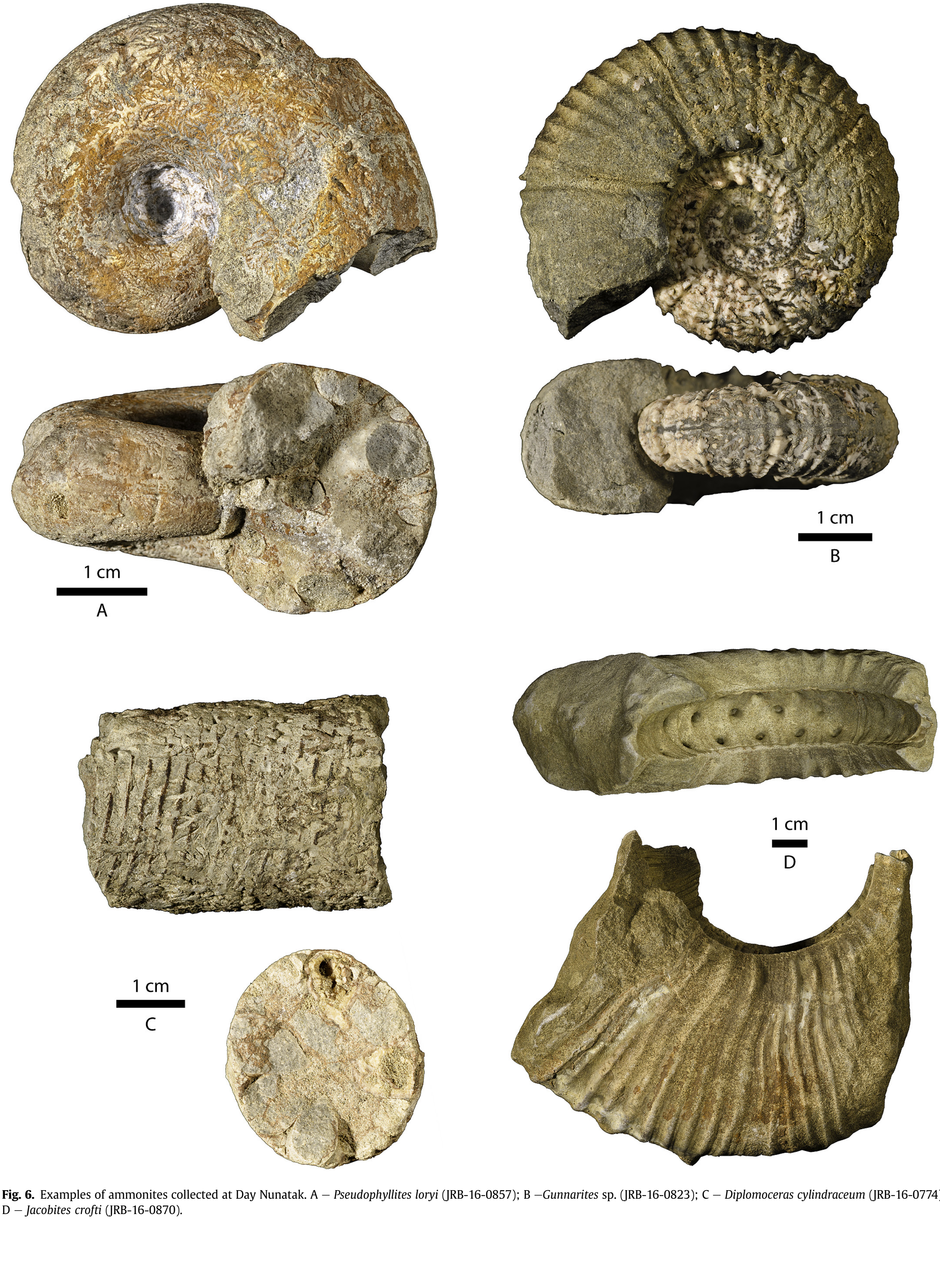

Fig. 6. Examples of ammonites collected at Day Nunatak. A – *Pseudophyllites loryi* (JRB-16-0857); B –*Gunnarites* sp. (JRB-16-0823); C – *Diplomoceras cylindraceum* (JRB-16-0774); D – *Jacobites crofti* (JRB-16-0870).

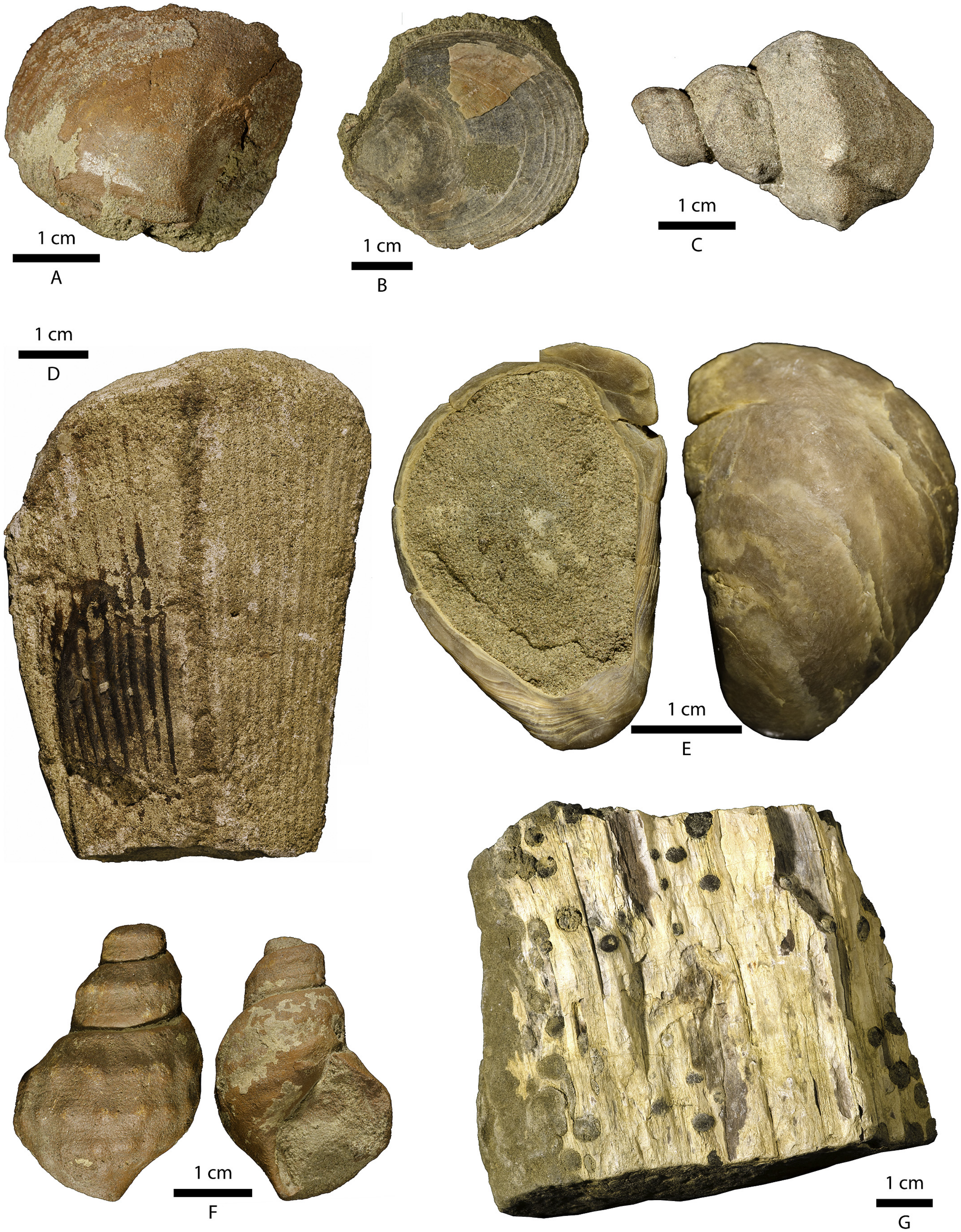

Fig. 7. Examples of non-ammonite mollusks from Day Nunatak, all of which are relatively uncommon compared to the abundance of *Gunnarites*. A – *Eslaevitrigonia regina* (JRB-16-0278); B – *Entolium seymouriensis* (JRB-16-0870); C – *Struthiochenopus nordenskjoldi*(?) (JRB-16-780); D – *Pinna anderssoni* (JRB-16-0769); E – *Pycnodonte* (*Phygraea*) *vesicularis vesicularis* (JRB-16-0011); F – *Cassidaria mirabilis* (JRB-16-0643); G – *Teredolites* bored wood (JRB-16-0661).

In general, preservational quality of the benthic mollusks is poor, making some identifications challenging, and most samples are found as float with poor stratigraphic control (stratigraphic locations of bivalve samples are reported in Fig. 5). The exception to this rule is *Pycnodonte,* which is the most common bivalve genus found with examples of morphologies consistent with both *P. seymouriensis* and *P. vesiculosa* described from Seymour Island (Zinsmeister and Macellari, 1988) present (Fig. 7E). These two species were originally described as variable in morphology, and given this variability, we agree with Witts et al. (2016) that they represent variability within a single species, *Pycnodonte* (*Phygraea*) *vesicularis vesicularis*. Their more common preservation is likely due to their calcitic shells, which are more resistant to alteration than the originally aragonitic shells of the other mollusks in the assemblage. Several examples of *Pinna anderssoni* are preserved as internal molds, and represent a similar morphology to *Pinna frenexiae* described from Seymour Island (Zinsmeister and Macellari, 1988), differing only in ribbing density (Fig. 7D).

Other bivalves recovered from Day Nunatak are represented by one or two specimens, and identification is in some cases incomplete. *Eselaevitrigonia regina* is present and morphologically similar to examples from Seymour Island, though the low quality preservation may disguise differences in shell ornamentation (Fig. 7A). Another trigonid, *Oistotrigonia antarctica* is present, and differs from *Oistotrigonia pygoscelium* from Seymour Island in ribbing definition. *Entolium seymouriensis* is represented by a reasonably well preserved specimen that appears similar to examples from Seymour Island. There is also evidence for *Teredolites* borings in fossil wood samples, though the shells are generally not preserved (Fig. 7G).

Gastropods from Day Nunatak exhibit similar preservational characteristics to the bivalves in their rarity and overall middling preservation. *Taioma charcotianus*, *Cassidaria mirabilis*, and *Struthiochenopus nordenskjoldi* are each represented by two specimens, and a poorly preserved internal mold is classified as *Cryptorhytis philippiana* (Fig. 7C), all from 175 m in the section (not pictured on Fig. 5). To the extent possible given the preservation issues, all gastropod species are indistinguishable from examples on Seymour Island with the possible exception of *S. nordenskjoldi*. Stilwell et al. (2004) classify the upper Maastrichtian examples a *S. hurleyi*, including by their description all examples from Units 9 to 10 of the López de Bertodano formation. Whether this includes examples what was at the time classified as *Perissoptera nordenskjoldi* from Unit 8 (Macellari, 1988) is unclear.

4.1.3. Other fossils

While the fossil assemblage is dominated by mollusks, as is typical for the Marambio group, there are numerous other fossils present that have limited biostratigraphic value, but provide some useful information in interpreting the depositional environment. *Teredolites* bored wood fragments are common, as are small twig fossils that are reported from elsewhere on Snow Hill Island (Pirrie et al., 1997). *Rotularia* (serpulid worms) are present, and most closely resemble *R. tenuilaevis*, though *R. fallax* is the most common *Rotularia* previously reported from Snow Hill Island (Macellari, 1984). Like most other places in the basin, *Rotularia* are abundant and concentrated in certain beds on Day Nunatak, which may represent intervals where bottom water conditions are unfavorable to benthic mollusks. Small solitary corals are found in transported concentrations and as isolated examples. A single crinoid stem fragment with star shaped ossicles was also collected. Finally, arthropod fragments, mostly claws, are reasonably common from concretions. While signs of bioturbation were evident in a few places, particularly in the well cemented sandstone layers, distinct ichnofossils were uncommon. In addition to *Teredolites*, only a single example of *Rhizocorallium* was identified (Fig. 8C).

4.2. Sedimentology/Petrography

The section is comprised of discrete beds of quartz and arkosic wackes and intervals of cm-dm bedded siltstone and mudstone with the overall grain size coarsening upwards over the measured section (Figs. 8A,B and 9A). Quartz and feldspar grains are sub-angular to sub-rounded. Rounded and partially-replaced glauconite grains are common in sandstone, with abundances ranging up to 15% (Fig. 9C,D). Mica, bioclasts, lithic grains, zircon and 5–50 μm framboidal pyrite grains (Fig. 9B) are the most common minor components. Small amounts of gypsum may be the result of oxidative pyrite weathering or later gypsum (selenite) veins observed crosscutting some beds in the middle of the section. Sandy siltstone is typically cemented by micrite, which also cements spherical concretions that often host fossils such as ammonites. The deflection of fine-grained laminae around concretions, and the presence of uncompacted fossils within concretions, suggests an early-diagenetic, pre-compaction origin for these features.

4.3. Isotopic results

Isotopic analyses were performed on a small number of *Pycnodonte* specimens as well as calcite cements in the burrows preserved near meter 142 of our stratigraphic section. The *Pycnodonte* values were fairly consistent (Table 1), with average $\delta^{13}C$ of 2.1 ± (σ) 0.5‰ (VPDB) and $\delta^{18}O$ of 0.5 ± (σ) 0.3‰ (VPDB). Assuming *Pycnodonte* secrete their shells in equilibrium (Kim and O'Neil, 1997) and a Cretaceous seawater $\delta^{18}O$ value of −1.0‰ (VSMOW) (Shackleton and Kennett, 1975), this $\delta^{18}O$ value would translate to a seawater temperature value of 7.2 ± (σ)1.5 °C, similar to most of the temperatures observed from Seymour Island (Tobin et al., 2012; Tobin and Ward, 2015; Petersen et al., 2016). The isotopic values for the Day Nunatak *Pycnodonte* (average 0.50‰) are indistinguishable from two *Pycondonte* specimens (average 0.43‰) previously analyzed from Seymour Island (Tobin et al., 2012). There is also no significant difference in the isotopic values of the Day Nunatak samples when comparing those collected lower in the section and those collected at the top of the section.

Ditchfield et al. (1994) recorded $\delta^{18}O$ values for a suite of *Pycnodonte* from what they described as the López de Bertodano Formation, which would overly the SHIF. While their samples lack differentiation within the formation, their locality designations indicate that the samples were from the Cape Lamb area of Vega Island, or the Naze peninsula on James Ross Island, both of which are now placed within the SHIF (Pirrie et al., 1997; Crame et al., 2004; Olivero, 2012), as the Lower Cape Lamb Member, which is the more proximal equivalent of the Hamilton Point, Sanctuary Cliffs, and Karlsen Cliffs Members (inclusive). The $\delta^{18}O$ values from Ditchfield et al. Table 2 ($\bar{x}$ = −0.1‰, σ = 0.4‰, max = 0.5‰, min = −0.9‰, n = 29) are universally lower than, or equal to, the average recorded from Day Nunatak (0.5‰). Their average value (−0.1‰) equates to a temperature 2.4 °C higher (9.6 °C) than at Day Nunatak, which could reflect shallower water conditions in a more proximal depositional area. The age difference between the samples could also explain the isotopic difference; the Cape Lamb samples range from the Campanian to the Maastrichtian (Roberts et al., 2014), while the Day Nunatak samples are Maastrichtian only. Globally, there is a known cooling event across the Campanian–Maastrichtian boundary (Barrera and Savin, 1999), and the cooler temperatures of the Day Nunatak samples could also be the result of a climatic shift, though analysis of samples that are

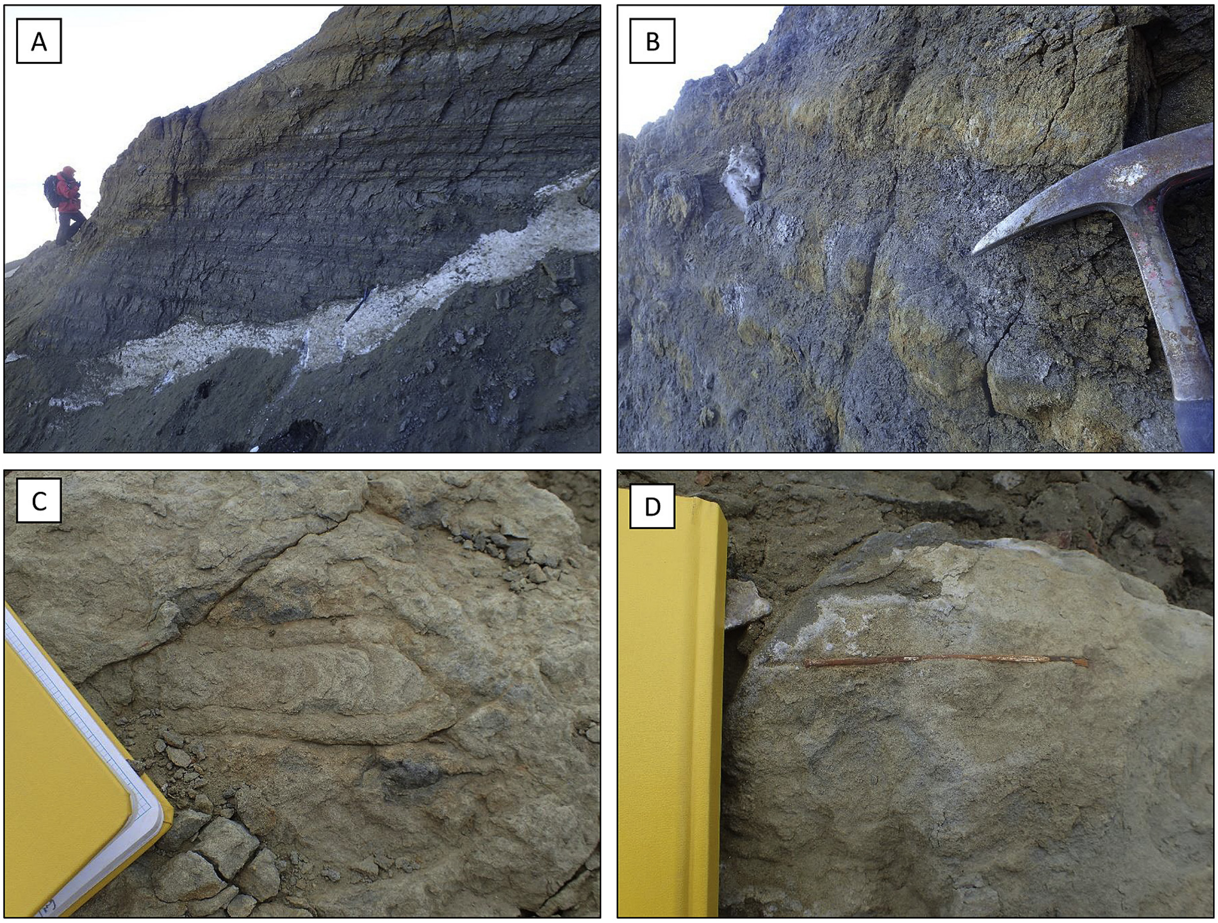

Fig. 8. Distinctive "rusty-orange" banded mudstone/siltstone (A,B), and carbonate-cemented sandstone preserving rhizocorallium (C) and twigs (D). (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

stratigraphically better constrained within the Cape Lamb Member would be necessary to test this hypothesis, specifically separating Maastrichtian and Campanian samples.

The exterior and interior of concretionary burrows were also analyzed, though no important differences were observed between the sampling positions (Table 1). These burrows are similar in appearance to those figured (5b) from Seymour Island by Little et al. (2015), who interpreted them as methane seep related on the basis of very low $\delta^{13}C$ values (less than −40‰ VPDB). Samples from Day Nunatak were notably low (−27.2‰) but not within the range typically associated with methane presence. As such these isotopic values are likely to represent carbonate deposition and cementation by later stage diagenetic fluids instead of early diagenetic cementation, and interpretation which is consistent with the lower $\delta^{18}O$ values as well, which are all lower than those observed anywhere by Little et al. (2015). This does not preclude the presence of cold seep activity on Day Nunatak, but no unambiguous seep indicators such as diagnostic seep bivalve taxa were observed.

5. Discussion

5.1. Depositional interpretation

The Day Nunatak succession likely represents deposition on a shallow to middle (50–200 m) marine shelf below storm wave base, with some variation in depth. This interpretation fits well with the placement of the KCM in the sequence stratigraphic framework of Olivero (2012), likely during an overall shallowing upwards trend. There is substantial faunal overlap with the benthic molluscan fauna on Seymour Island at the generic level (*Pinna, Oistotrigonia, Struthiochenopus*) and species level (*P. vesicularis, E. regina, C. mirabilis, T. charcotianus, C. philippiana, E. seymouriensis*) (see 4.1.2 Benthic Mollusks), which suggests a similar depositional environment. No major changes in the QLF percentages of samples within the section were observed, and the values that were observed (large feldspathic component) are consistent with a relatively short transport history from the nearby uplifting Antarctic Peninsula.

Observations of well-preserved horizontal bedding with minimal bioturbation (Fig. 8A,B) and abundant pyrite framboids suggests the basin may have experienced periods of euxinia or anoxia that prevented burrowing to substantial depths. These conditions are similar to those suggested by results of trace element analyses of sediments from Seymour Island (Schoepfer et al., 2017), implying that the marine conditions of the JRB may not have been well-mixed throughout the entire Maastrichtian. As on Seymour Island, there are intervals where bioturbation is prevalent, generally in comparatively well-cemented sands (Fig. 8C,D), suggesting the low oxygen conditions may have been intermittent or perhaps seasonal. The similarity between the lithological, biological and redox conditions of Day Nunatak and the molluscan units of Seymour Island could be useful for future studies to compare early and late Maastrichtian conditions within the JRB.

5.2. Stratigraphic placement

From the ammonites recovered it is clear that the sedimentary succession at Day Nunatak belongs within early Maastrichtian

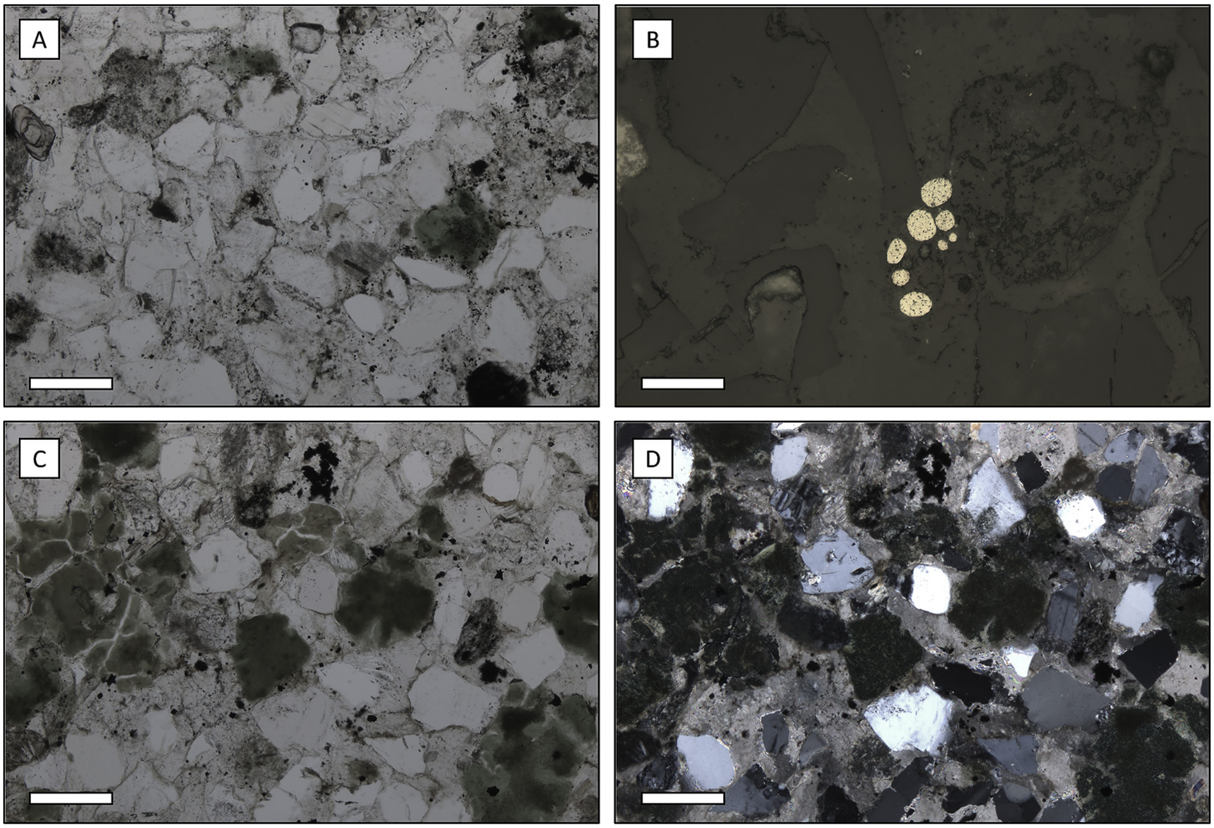

Fig. 9. Thin section photomicrographs showing carbonate cemented quartzofeldspathic sandstone in transmitted light (A), framboidal pyrite in carbonate-cemented quartzofeldspathic sandstone in reflected light (B), and glauconitic sandstone in transmitted (C) and cross-polarized transmitted light (D). Scale bars for A, C, D = 200 μm. Scale bar for B = 50 μm.

Table 1
Table of *Pycnodonte* samples analyzed for carbonate stable isotope values. Averages and standard deviation errors are located at bottom.

Specimen	Type	Stratigraphic level (m)	δ^{13}C (‰ VPDB)	δ^{18}O (‰ VPDB)	Reconstructed temp. (°C)
JRB-16-0003	*Pycnodonte*	~175	1.8	0.4	7.6
JRB-16-0009	*Pycnodonte*	~175	2.2	0.6	6.7
JRB-16-0669	*Pycnodonte*	~52	2.7	0.1	8.9
JRB-16-0670	*Pycnodonte*	~52	1.5	0.3	8.0
JRB-16-0691	*Pycnodonte*	~65	1.8	0.7	6.3
JRB-16-0845	*Pycnodonte*	~175	2.5	0.9	5.4
Average	*Pycnodonte*		2.1 ± 0.5	0.5 ± 0.3	7.2 ± 1.5
DF71-INT2A	Burrow interior	142	−27.4	−9.6	N/A
DF71-INT2C	Burrow interior	142	−27.4	−9.9	N/A
DF71-EXT2B	Burrow exterior	142	−27.8	−10.9	N/A
DF71-EXT2D	Burrow exterior	142	−27.8	−10.9	N/A
Average	Burrow (all)		−27.2 ± 0.2	−10.3 ± 0.7	N/A

Ammonite Assemblage 10 of Olivero (2012), as defined by both the notable abundance of *Gunnarites* and presence of *Jacobites*. The other ammonites collected (*Diplomoceras*, *Pseudophyllites*) are known from this assemblage, but are long ranging and provide lower resolution biostratigraphic constraints, though *Diplomoceras* is consistent with an age assignment from the late Campanian through Maastrichtian (e.g. Macellari, 1986; Remin et al., 2015). Notably, no examples of *Neograhamites* were recovered, which likely excludes Assemblage 9, the only other ammonite assemblage where *Gunnarites* is present. The benthic fauna represent no new taxa when compared with previously described collections from elsewhere in the JRB, and for the most part these taxa have not been employed in biostratigraphy.

From a lithostratigraphic perspective, the section described from Day Nunatak corresponds well with the KCM of the SHIF as described by Pirrie et al. (1997). The majority of the stratigraphy at Day Nunatak consists of sandy-siltstone hosting carbonate concretions, the distinctive “rusty-orange” cm-dm bedded mudstone/siltstone, and heavily bioturbated and well-cemented sandstone. The *Thyasira*-associated facies identified by Pirrie et al. (1997) is not present, but this facies has been determined to represent a methane seep deposit (Little et al., 2015) and is recognized as having limited lateral extent even in the original section described from the Spath Peninsula. The fossil assemblage from Day Nunatak also matches closely with that described from the KCM, including the observations of *Teredolites* bored wood and isolated small twigs, the latter of which appear to be unique to the KCM, strengthening our confidence in this lithostratigraphic assignment. Given the prevalence of sandier horizons in the Day Nunatak stratigraphy, particularly in the upper part of our section, Day Nunatak outcrop likely represents the upper part of the KCM, but not the contact with overlying Haslum Crag Sandstone.

The KCM has been correlated to Lower Cape Lamb Member from Vega Island using both biostratigraphic and sequence stratigraphic arguments (Olivero, 2012). Our lithostratigraphic and biostratigraphic observations are consistent with the integrated framework developed by Olivero (2012) and the work of Crame et al. (2004). The Campanian–Maastrichtian boundary was assigned to be very near the first occurrence of *Gunnarites* on Vega Island (Crame et al., 1999; McArthur et al., 2000). The *Gunnarites* recovered at Day Nunatak do not represent the first occurrence of the genus, as Assemblage 9 where *Gunnarites* first appears is missing. Given these constraints, the succession exposed at Day Nunatak is almost certainly early Maastrichtian in age.

5.3. Structural implications

We measured the attitude of bedding at Day Nunatak as striking 40° and dipping 10° E, comparable to the variable dips recorded elsewhere on Snow Hill Island (Pirrie et al., 1997). Simple projection of bedding along strike, while accounting for elevation differences, between Day Nunatak and other sites described on Snow Hill Island would predict that the strata at Day Nunatak should be overlain by the exposures at both Sanctuary and Karlsen Cliffs, which is inconsistent with the interpreted stratigraphy. As such, it is necessary to invoke either a fold or a fault to explain the observed bedding. No large scale folds have been observed in the JRB, but several researchers have proposed ENE-WSW trending faults in the southeastern parts of James Ross Island (Crame et al., 1991; Olivero et al., 1992; Pirrie et al., 1997) and WNW-ESE trending faults separating Snow Hill Island from Seymour Island through Picnic Passage (Pirrie et al., 1997), though a erosional/depositional explanation has been invoked as alternative hypothesis in the case of the latter set of faults (Olivero et al., 2007). We hypothesize that faulting from one or both of these groups separates Sanctuary Cliffs from Day Nunatak, but recognize that current outcrop on SHI is insufficient to fully constrain the nature of this structure(s).

6. Conclusion

The currently exposed section at Day Nunatak represents an exposure of the Karlsen Cliffs Member (KCM) of the Snow Hill Island Formation that is arguably better preserved than the section at Karlsen Cliffs due to the lack of igneous intrusions. However, the geographic isolation of Day Nunatak precludes precise placement of the section relative to the previously described KCM. In terms of abundance, *Gunnarites* dominates the molluscan fossil assemblage, though benthic organisms were also collected and identified. The benthic organisms are all represented at the generic level in the late Maastrichtian on Seymour Island, indicating a fairly stable benthic community. Ultimately, this section fits well into the sequence stratigraphic and biostratigraphic frameworks developed by Olivero (2012). For future workers, this site may provide an interesting temporal contrast with the Molluscan Units of Seymour Island, as it represents an earlier time but a similar depositional environment. Alternatively, it provides an onshore-offshore contrast with the Cape Lamb Member on Vega Island. As climate on the Antarctic Peninsula continues to warm (Mulvaney et al., 2012), it is likely that the area of exposed rock at Day Nunatak will continue to expand, allowing more detailed correlations to be drawn.

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Appendix A. Supplementary data

Supplementary data related to this article can be found at https://doi.org/10.1016/j.cretres.2017.12.006.