

# Dating 'Zebra': A subaerial to ultra-shallow marine Lomonosov Ridge at the end of the Oligocene?<sup>☆</sup>

Francesca Sangiorgi<sup>a,\*</sup>, Evi Wubben<sup>a</sup>, Suning Hou<sup>a</sup>, Henk Brinkhuis<sup>a,b</sup>

<sup>a</sup> Department of Earth Sciences, Utrecht University, the Netherlands

<sup>b</sup> Royal Netherlands Institute for Sea Research, the Netherlands

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## ABSTRACT

Twenty years after the pioneering IODP Expedition 302 (ACEX) to the Lomonosov Ridge, central Arctic Ocean, a robust age model was still lacking. This was foremost due to the overall poor core recovery, and frequent lack of age diagnostic features including (micro)fossils, notably in the likely Neogene succession. Interestingly, one of the few intervals that were relatively well-recovered was interpreted to span the Paleogene-Neogene transition. On board and follow up marine palynological studies indicated that within this interval, a potential ~26 Myr long hiatus separated the local top of the Paleogene (~44 Ma) from the Neogene (~18 Ma), occurring between local lithological subunits 1/6 and 1/5. The latter was informally also referred to as the 'Zebra' interval, owing to its characteristic black/white alternations in the colour of the sediments. This hiatus would possibly imply a subaerial or ultra-shallow marine Lomonosov Ridge during late Oligocene to early Miocene times. A Neogene, (late) Early Miocene age for the base of 'Zebra' subunit 1/5 was tentatively provided by the finding of a new, later formally described, organic walled dinoflagellate cyst (dinocyst) genus we named *Arcticacysta*, which included two species, *A. backmanii* and *A. moraniae*. Subsequent work challenged the presence of a hiatus and the age of the 'Zebra' subunit.

Here we present recent palynological (dinocyst) findings from Miocene sediments retrieved from the Pennell Basin during IODP Expedition 374 (Ross Sea, Antarctica) that contain the first appearance at 17.7 Ma of specimens of the same dinocyst genus, *Arcticacysta*, and species, and a more continuous presence between 17.0 and 15.9 Ma. Providing that the (first) occurrence of this dinocyst genus is synchronous in both (polar) records, these findings confirm the assignment of the Arctic Ocean 'Zebra' interval to the (late) Early Miocene, adding evidence for a large hiatus characterizing the Paleogene/Neogene transition on the Lomonosov Ridge.

## 1. Introduction

Even well into the 21st century, the tectonic, oceanographic, and climate history of the central Arctic Ocean during the Cenozoic remains enigmatic. In 2004, Integrated Ocean Drilling Program (IODP) Expedition 302 (aka the Arctic Coring Expedition, ACEX) retrieved sediments with partial recovery from few drillholes close to the North Pole (Backman et al., 2006; Moran et al., 2006), in water depths of ~1300 m at the central part of the Lomonosov Ridge. ACEX drilled to about 428 m below seafloor (mbsf), to the top of the local 'basement' (deformed sediments of late Cretaceous age), and was the first-ever, and so far, single attempt of deep coring in the central Arctic. It partially recovered Paleogene and Neogene sediments and provided the first stratigraphic

and environmental picture of the Cenozoic history of the Arctic Ocean (Moran et al., 2006). Backman and Moran (2009) presented a synthetic, but comprehensive summary of the results obtained from this expedition.

The presence of a rather thick package of lower Paleogene sediments (Backman et al., 2006) came however somewhat as a surprise to many, as pre-expedition models anticipated a thick Neogene cover overlying Cretaceous basement of the Lomonosov Ridge (e.g., Jokat et al., 1992). Initial shipboard marine palynological studies implied a large hiatus separating the rather complete upper Paleocene to middle Eocene succession from overlying units, assigned to a 'likely late Early Miocene age'. The overall age span of the sediment section was greater than predicted by a few million years. In the earliest reports, it was decided to

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\* Corresponding author.

E-mail address: [f.sangiorgi@uu.nl](mailto:f.sangiorgi@uu.nl) (F. Sangiorgi).

report that “stratigraphically, the ACEX sites show a major hiatus spanning the transition from the Neogene to the Paleogene” (Expedition 302 Scientists, 2005) and later, it was chosen to characterize this specific interval encompassing lithologic Units 2 and 1 (Fig. 1) as “a presumably condensed and possibly partially missing section from ~ 45 to 14 Ma” (Moran et al., 2006), leaving doubt on the precise age and nature of the contact between the two local lithological units. This interval was one of the very few rather completely cored sections, a rarity when compared to the overall poor recovery during ACEX, and included a sharp, and distinct lithological change.

### 1.1. Post-expedition constraints for the ACEX age model: the age of local lithological subunit 1/5, also known as ‘Zebra’

In the years following the expedition, biostratigraphic, cosmogenic isotope, magnetostratigraphic, and cyclostratigraphic data were merged into a coherent age model (Backman et al., 2008).

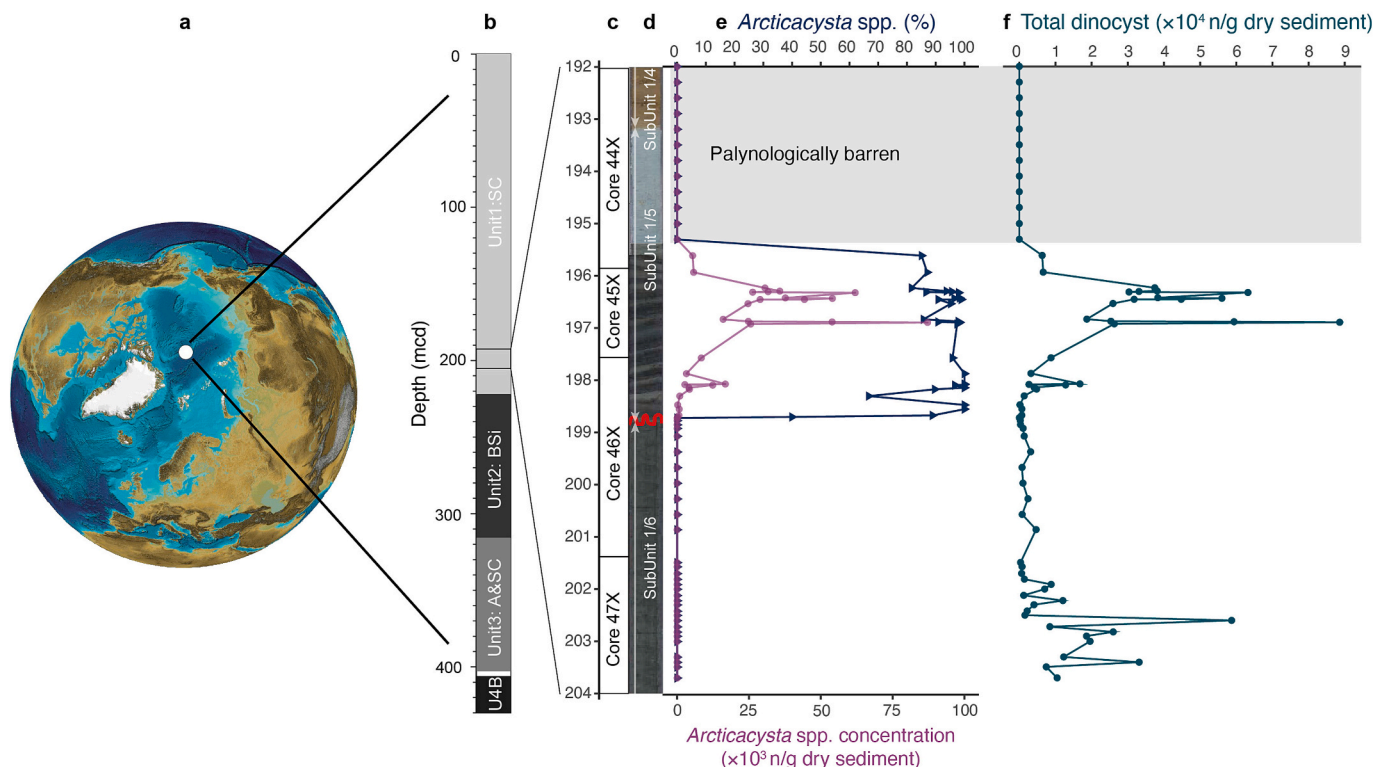
The hiatus appeared to occur between the ACEX local lithological subunits 1/5 and 1/6 (at 198.70 m composite depths, mcd, Fig. 1, Suppl. file 1), and to reflect two very different sedimentary regimes. Subunit 1/6 sediments are dark, partly laminated, compacted, siliciclastic claystone, rich in organic carbon (TOC up to 5 %), pyrite, and (nothing but) mid Eocene microfossils (e.g., Backman et al., 2008; Sangiorgi et al., 2008, 2009). The overlying, with a sharp contact, perhaps Neogene sediments of subunit 1/5, are cross-bedded silty muds and clays, and, in the basal parts, strongly alternating in organic carbon content, and therefore also alternating black and white in colour (coined ‘Zebra’ as a catchy name for this portion of subunit 1/5 already during the expedition). Moreover, also dropstones and sand lenses were recorded within subunit 1/5 (Backman et al., 2006; Moran et al., 2006; Sangiorgi et al.,

2008; März et al., 2011). Slightly up section, the typical black and white alternations give way to grey-blue, bright blue, and eventually to the red silty claystones of subunit 1/4 (Fig. 1, Backman et al., 2006, Moran et al., 2006), which was interpreted as representative of the transition from relatively restricted, estuary-like to a fully ventilated Arctic Ocean following the complete opening and deepening of the Fram Strait in the late middle Miocene (Jakobsson et al., 2007).

Onboard age-assessment of ‘Zebra’ was solely based on marine palynological analysis, since the samples did not yield any other microfossil groups. Yet, while subunit 1/6 did yield abundant organic and siliceous microfossils allowing a good mid Eocene age-assessment (Backman et al., 2008), the age of subunit 1/5 could not be based on well-calibrated bioevents. The palynologically-rich samples from Zebra portion of the 1/5 are dominated by organic-walled dinoflagellate cyst (dinocyst) assemblages, most of them belonging to a then unknown genus. We later described this taxon as *Arcticacysta* from the same material, massively occurring together with sparse dinocysts of the genera *Lejeunecysta*, *Operculodinium*, *Selenopemphix* and *Spiniferites* (Sangiorgi et al., 2009 and Suppl. file 1). Interestingly, samples from the Zebra interval were also larded with typically reworked palynomorphs (dinocysts and pollen), notably from Paleozoic, Mesozoic and early Paleogene to middle Eocene times, including dinocysts from strata not recovered in the ACEX record (e.g., from the Late Eocene to Early Oligocene), all scattered in no particular order or pattern.

Based on these findings the age-assessment allowed two options: 1) based on the ‘youngest of likely reworked palynomorphs, in this case dinocyst taxa like *Wetzeliella gochtii* and *Svalbardella* spp. (early to mid-Oligocene), 2) a much more likely one, with a much younger age, based on the ominous presence of the new genus *Arcticacysta*, and its peculiar morphology and distinctive 3A3I archeopyle, unknown in Paleogene

### IODP 302, ACEX Arctic record



**Fig. 1.** (a) Location of IODP 302 ACEX Expedition drillsite (white dot) in the central Arctic Ocean, on the Lomonosov Ridge. (b) Lithological units of the ACEX core. SC = Silty Clay, BSi = Biosilica, A&SC = Authigenic and Silty Clay. B=Basement. (c) Core numbers. (d) Core photos of the studied interval (including subunits 1/4 to 1/6). (e) Relative abundances (blue triangles) and concentrations (dark purple dots,  $\times 10^3$  number of cysts/g sediment) of *Arcticacysta* spp. (f) Concentration of total dinocysts ( $\times 10^4$  number dinocysts/g sediment). Grey rectangle indicates the palynologically barren interval (Sangiorgi et al., 2008). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

dinocysts (Sangiorgi et al., 2008, 2009). Eventually, the option two was preferred (Backman et al., 2008). Meanwhile, it was noted that a Miocene age assessment for the subunit 1/5 was somewhat supported by the recovery of (albeit long ranging) early Miocene agglutinated foraminifera at the base of overlying subunit 1/4 (Kaminski, 2007), where samples are palynologically barren. Using the mid-point of the Burdigalian as an approximate age, the oldest sediments above the presumed hiatus and onset of the subunit 1/5 (at 198.70 mcd, Fig. 1 and Suppl. file 1) were assigned an age of 18.2 Ma (Backman et al., 2008).

Later, Poirier and Hillaire-Marcel (2009, 2011) performed high-end elemental stable isotope geochemistry on samples from the ACEX Arctic record. They reported Rhenium-Osmium (Re—Os) isochron ages and complementary Os-isotope measurements in the ACEX sediments including samples from the *Zebra* interval that challenged the existence of any hiatus between subunits 1/6 and 1/5 and instead pointed to the option of a condensed, low sedimentation rate interval, and a rather complete Paleogene/Neogene transition. Briefly, the Poirier and Hillaire-Marcel (2009) data to them indicated a minor relative sea-level change, a smooth tectonic history of Lomonosov Ridge subsidence, and ingress of marine waters in the Late Eocene (~ 36 Ma). Sangiorgi et al. (2008, 2009) instead suggested a shallow water setting both before and after the hiatus, which would imply that the Lomonosov Ridge remained near sea level for the duration of the gap in the sedimentary record. Subsidence of the Lomonosov Ridge and the full ingress of marine waters only occurred in the (late) Early Miocene (Jakobsson et al., 2007). According to Sangiorgi et al. (2008), some interaction of paleoclimatic and paleoceanographic changes and/or tectonic activity (possibly uplift) were to be invoked as possible causes for such a major hiatus.

In summary, the age of *Zebra* and marine ingress to the Arctic Ocean was still debated, and so was the intrinsically related Cenozoic history of this climatologically and tectonically important region. It all hinged on calibrating the chronostratigraphic range of *Arcticacysta*, of which no further occurrences were recorded, or published.

## 1.2. Preliminary finding during IODP Expedition 374, Ross Sea (Antarctica)

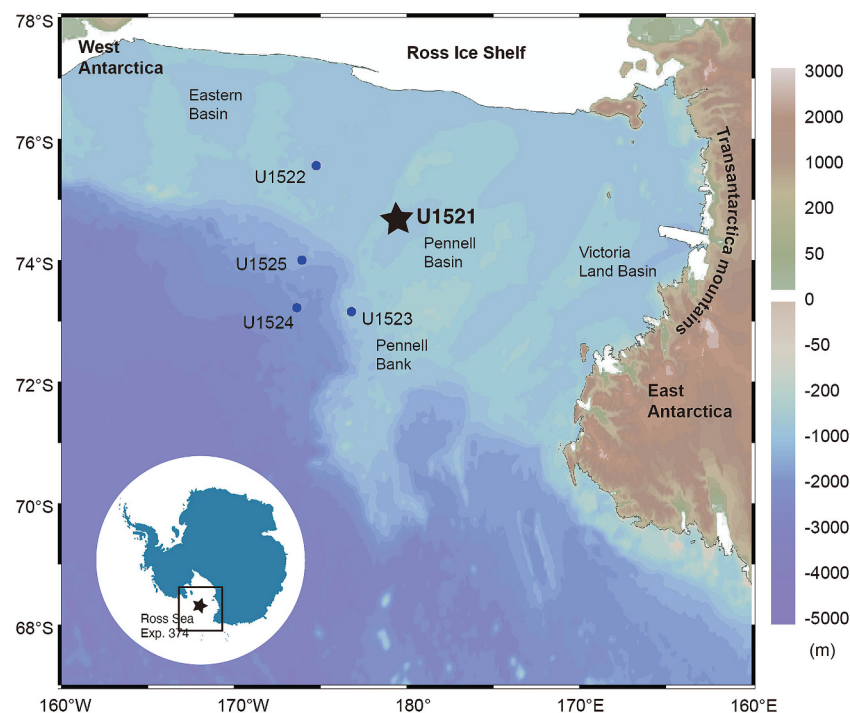
In 2018, International Ocean Discovery Program (IODP) Expedition 374 drilled sediments in the Ross Sea (Fig. 2) with the aim of unraveling the Neogene and Quaternary history of the West Antarctic Ice Sheet (McKay et al., 2019).

During the expedition, the core catchers of the 71 cores retrieved from Site U1521 (Fig. 2) Hole A were analyzed for micropaleontology and palynology and a preliminary age model was built mostly based on biostratigraphy (radiolarian and diatoms) and magnetostratigraphy (McKay et al., 2019). Specimens of *Arcticacysta*, belonging to the same two species *A. backmanii* and *A. moraniae* found in the Arctic record were found in some of the core catchers (Hole U1521A-52R and higher, above ~470 mbsf, Figs. 3 and 4 and Suppl. file 2), and low-quality pictures were taken on board. This discovery merited further investigation after proper palynological processing of the sediments of the entire record.

This study aims at documenting the presence of *Arcticacysta* in the sediments of Site U1521 (IODP Expedition 374, Ross Sea, Antarctica) and constraining the timing of its first occurrence and continuous presence in this well-dated record. Pinpointing the age of the first *Arcticacysta* occurrence helps improving the age model of the IODP 302 ACEX Arctic record, assuming that the first occurrence is (approximately) synchronous at these two locations. This finding will then confirm (or reject) the hypothesis of the presence of a hiatus between the Paleogene and the Neogene of the Lomonosov Ridge (central Arctic) record, with consequences for the tectonic history and Neogene climate of the Arctic Ocean.

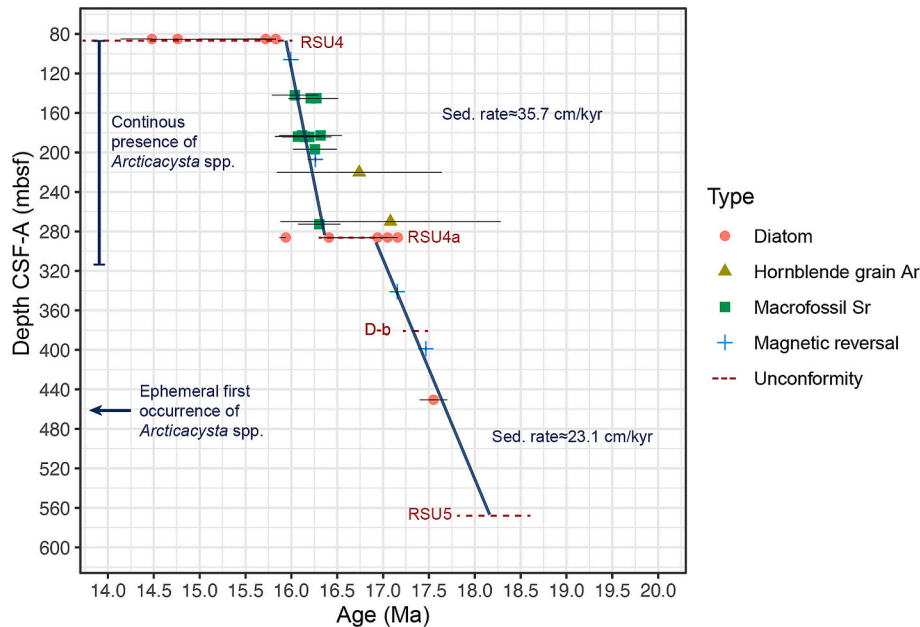
## 2. Materials and methods

During IODP Expedition 374 to the Ross Sea (2018), Site U1521 was drilled in the Pennell Basin (75°41.0351'S, 179°40.3108'W at 562 m of water depth, Fig. 2). The site is on the mid- to outer continental shelf near a northeast–southwest-oriented Miocene paleo-trough identified by mapping regional unconformities in seismic-reflection profiles. In total,



**Fig. 2.** Location map of IODP Expedition 374 Site U1521 (star) drilled in the Pennell Basin (central Ross Sea, Antarctica). Other Sites drilled during the Expedition 374 (U1522, U1523, U1524 and U1525) are also shown (McKay et al., 2019). The figure is made using Ocean Data View (Schlitzer, 2022).

### Age model of IODP 374 (Ross Sea, Antarctica), Hole U1521A



**Fig. 3.** Age model of IODP Expedition 374 Hole U1521A (modified from Marschalek et al., 2021). Black lines indicate errors in age; dashed red lines indicate regional unconformities (Pérez et al., 2022). Purple lines present linear regressions for 80–280 mbsf and 280–560 mbsf intervals, with calculated sedimentation rates. Lithological log of Hole U1521A for the interval considered in this study is also presented (McKay et al., 2019). The first temporary appearance and more continuous presence of *Arcticacysta* spp. is also reported next to the depth axis. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

drilling penetrated ~650 below seafloor and ~411 m sediments were recovered from just one hole (Hole U1521A), with average 63 % recovery. Seven lithological Units were identified at first on board (McKay et al., 2019). The record contains a very expanded Early to Middle Miocene sequence, with hiatuses which correspond to well-known Ross Sea Unconformities (RSU, e.g., Brancolini et al., 1995; De Santis et al., 1995; Pérez et al., 2022).

#### 2.1. An update age model for IODP 374 Hole U1521A

The preliminary age model published shipboard (McKay et al., 2019) was revisited and an updated age model based on magnetostratigraphy, astrochronology, biostratigraphy and Sr dating was published in Marschalek et al. (2021) and Pérez et al. (2022). Fig. 3 reports the tie-points used and the age model of Hole U1521A for the interval relevant for this study (paleomagnetic correlations to GPTS 2020, Ogg, 2020). Age model constraints for the entire Hole U1521A are reported in McKay et al. (2024).

#### 2.2. Palynological processing

About 15 g of freeze-dried sediment from Hole U1521A Cores 9R to 66R (~75 to ~595 mbsf, 66 samples in total) were processed at the Geolab facility of the Geosciences Faculty, Utrecht University for palynology using standard palynology procedure, without oxidation. A tablet containing a known amount of *Lycopodium clavatum* was added to each sample before processing for the quantification of palynomorph abundances, following the method of Wood et al. (1996). Cold 10 % hydrochloric acid (HCl) and cold 40 % hydrofluoric acid (HF) were added in subsequent steps to remove carbonates and silicates, respectively. The remaining organic material was then sieved through a 250 µm and a 10 µm sieve in combination with ultrasonic bath to aid breakup of the organic material. Eventually, the residues were mounted on microscopic slides with glycerin jelly and sealed. The palynomorphs including dinoflagellate cyst (dinocysts) in situ and reworked,

freshwater and brackish water algae (*Cymatiosphaera* spp., *Pediastrum* spp.), acritarchs, and pollen and spores (in situ and reworked) were identified and counted using a microscope with 400× magnification. A selection of palynology data in 21 samples from Cores 25R to 65R (220–600 mbsf) were previously published and data reported in the supplementary information (Marschalek et al., 2021).

For the purpose of this paper, only *Arcticacysta* spp. will be discussed and the results of the complete palynological assemblages will be presented in another publication to be submitted soon (Hou et al., in prep). The complete dataset is provided as Supplementary file here (Suppl. file 2).

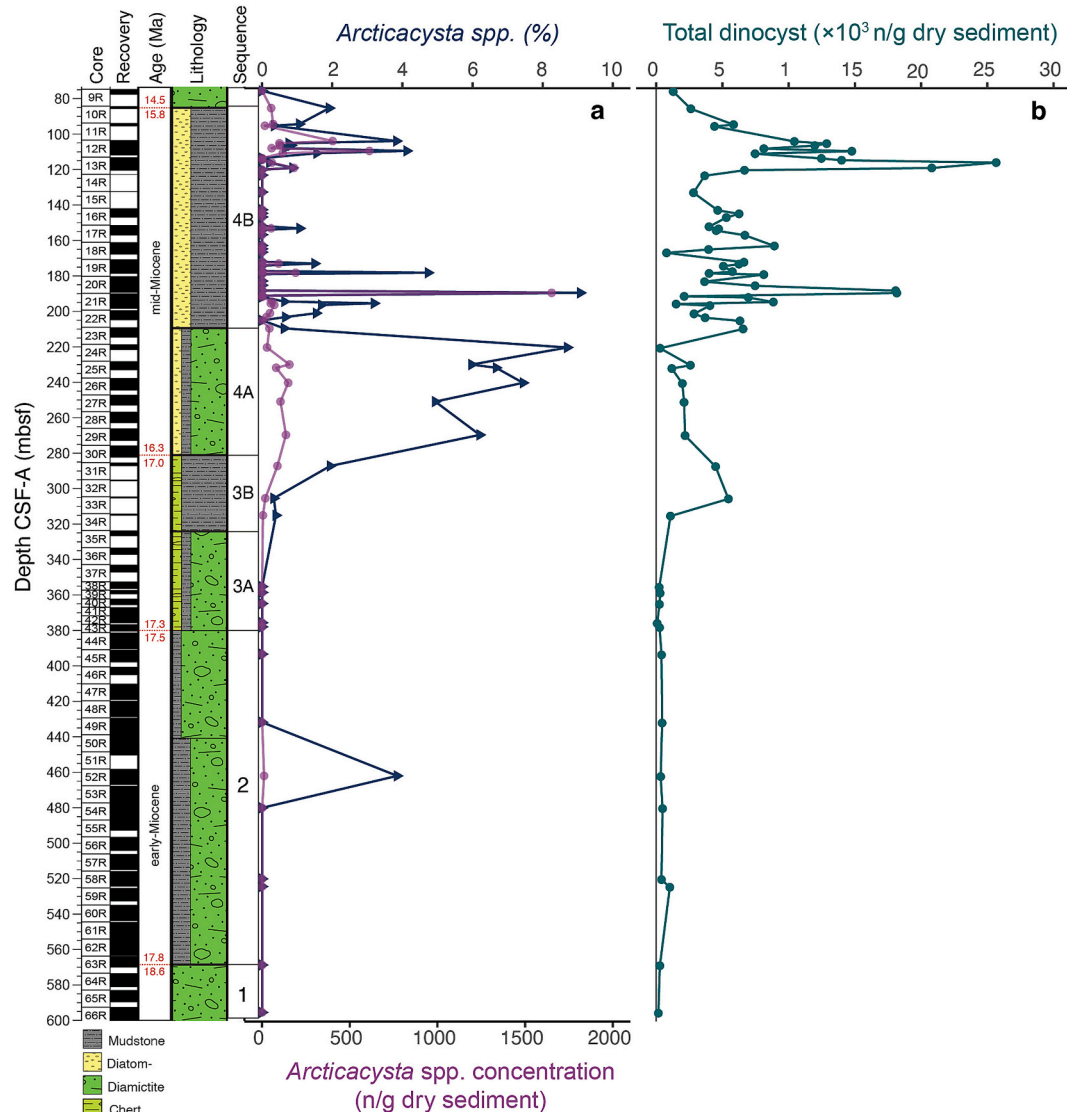
### 3. Results and discussion

#### 3.1. A late Early Miocene age of *Arcticacysta* from IODP 374 Site U1521 (Ross Sea)

Palynomorphs in Site U1521 Hole A are generally well-preserved though not always very abundant. They consist of dinocysts (in situ and reworked), fresh-brackish water algae like *Cymatiosphaera* and *Pediastrum*, acritarchs like *Leiosphaeridia*, pollen and spores, both in situ and reworked (Suppl. file 2). While samples below ~315 mbsf (cores 34R and lower) contain few in situ dinocysts (max ~1000 dinocysts/g), samples above are generally rich in dinocysts (Fig. 4). One sample at ~460 mbsf (core 52R, 3 W, 23–26 cm) contains a first and isolated occurrence of *Arcticacysta* spp. (~4 %), which then becomes more regularly – albeit not continuously – present in samples above 341 mbsf and up to 85 mbsf, with varying but generally low percentage (max 9 %) and concentrations up to 1650 cysts/g.

Based on the updated age model (Marschalek et al., 2021; Pérez et al., 2022; McKay et al., 2024) and using linear sedimentation rates between tie points, the first appearance of *Arcticacysta* spp. can be dated ~17.7 Ma. The same two species *A. backmanii* and *A. moraniae* found in the Arctic were also found in the Ross Sea record (Plate 1) with *A. backmanii* being more abundant than *A. moraniae* (as it was in the

## IODP 374 (Ross Sea, Antarctica), Hole U1521A record

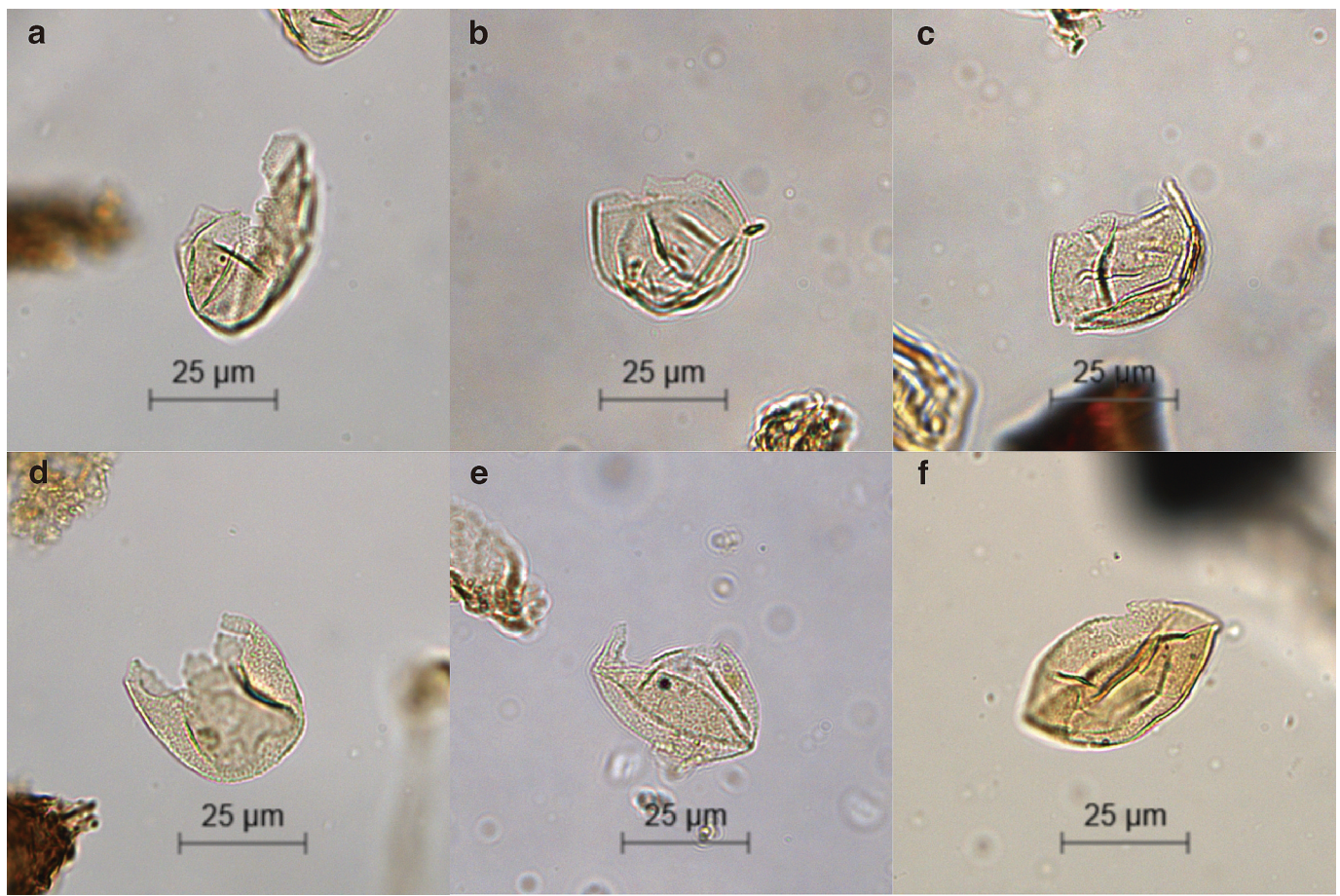


**Fig. 4.** Depth (mbsf), core numbers, core recovery, age, lithological log and palynological results of Site U1521 (Hole A). Relative abundances (blue triangles) and concentrations (purple dots,  $\times 10^3$  number cysts/g) of *Arcticacysta* spp. are presented next to the concentration of total dinocysts ( $\times 10^3$  number cysts/g sediment). Red dashed lines and associated numbers indicate the approximate age of regional unconformities. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

Arctic record, Sangiorgi et al., 2009). Because the two species appear synchronously, we decided to group them as *Arcticacysta* spp. and make no further distinction. Their mostly continuous presence in the sediments recovered from Hole U1521A between  $\sim 17.0$  and  $15.9$  Ma provides a (late) early Miocene to early Middle Miocene age. Ross Sea Unconformity (RSU) 4a and 4 (17–16.3 Ma and 15.8–14.5 Ma, respectively, Marschalek et al., 2021; Pérez et al., 2022) truncated the Ross Sea record at the relatively shallow Site U1521, located in much shallower conditions during the Miocene than at present (Bombard et al., 2024). Given the timing of *Arcticacysta*'s occurrence in the Ross Sea and its more frequent presence and higher abundance during the recovered portions of the Miocene Climatic Optimum ( $\sim 17$ – $\sim 15.9$  Ma), it seems likely that this genus found both the Antarctic and Arctic records typically includes polar/high latitude species and is early to middle Miocene in age.

### 3.2. A subaerial to ultra-shallow marine Lomonosov Ridge at the end of the Oligocene?

The first appearance of *Arcticacysta* species at  $\sim 17.7$  Ma in the Ross Sea (Figs. 3 and 4) and its range now seems to provide a strong confirmation of the earlier age-assessment for the Zebra subunit 1/5 of the central Arctic Lomonosov Ridge to the late early Miocene (Fig. 1), assuming an approximately synchronous (first) occurrence of this dinocyst genus at both locations. This would imply that the existence of a hiatus on the Lomonosov Ridge at the Paleogene/Neogene transition. This finding has several important consequences for the tectonic and paleoclimatic history of the Central Arctic Ocean, and the Lomonosov Ridge. Moreover, the (sparse) reworked dinocysts of all ages in the Zebra subunit 1/5 (Fig. 1, Suppl. file 1), including dinocysts of late Eocene and early Oligocene age (*Wetzelia gochtii* and *Svalbardella* spp., Sangiorgi et al., 2009), implies that sediments with ages as young as the early Oligocene that did not directly deposit in the ACEX record were eroded from regions around and redeposited at drill location during the late



**Plate 1.** Images of *Arcticacysta* spp. found in sediments from Hole U1521A. (a-d) U1521A 13R1W 10–15 cm. (e) U1521A 20R6W 18–20 cm. (f) U1521A 26R2W 80–82 cm. (a, b, c, e) *Arcticacysta backmanii* (d) *Arcticacysta moraniae*; (f) *Arcticacysta* sp.

Early Miocene. This could also mean that part of the organic matter in this *Zebra* subunit is reworked, potentially explaining the anomalous results of the associated Rhenium-Osmium measurements of Poirier and Hillaire-Marcel (2009, 2011).

The finding of a hiatus in the Lomonosov Ridge contrast with pre-drilling seismic predictions and an initial postcruise assessment of its subsidence history that ‘assumed smooth thermally controlled subsidence following late Paleocene rifting’ (review in O’Regan et al., 2008). These authors, reviewing potential Cenozoic tectonic processes affecting the geodynamic evolution of the wider Arctic Ocean, opened the idea of a prolonged phase of basin-wide compression that ended in the Early Miocene that may have kept the Lomonosov Ridge at very shallow depth or even subaerial. The conspicuous coincidence in timing between the end of compression and the start of the sediment deposition on the Lomonosov Ridge aged late Early Miocene (*Zebra* subunit 1/5), provides a compelling link between our data and these observations.

Moreover, the hiatus in the central Arctic Lomonosov Ridge sediment record conspicuously occurs across the Greenhouse – Icehouse transition and the Eocene – Oligocene junction, paleoclimatic mechanisms including (land) ice-formation and sea-level changes may potentially have had influence as well on the topography and paleodepth of the Lomonosov Ridge at the location where the sediments were cored.

### 3.3. Environmental preferences of *Arcticacysta*

Interestingly, *Arcticacysta* has so far only been found in these two high latitude records, although it may have been overlooked due to its similarity with species of the genus *Batiacasphaera* (Sangiorgi et al., 2009 and Plate 1). The quantitative marine palynological analysis of the

Arctic record presented in Sangiorgi et al. (2008) carries strong evidence that the depositional settings of both the mid Eocene subunit 1/6, as well as the late Early Miocene interval of subunit 1/5 (Fig. 1) were similar in that they are both reflecting very marginal, ultra shallow marine conditions. Such marginal, relatively shallow environment with freshwater presence is also confirmed by the palynological assemblages of Site U1521 record in the Ross Sea, where brackish water palynomorphs such as the algae *Cymatiosphaera* are abundant concomitantly with *Arcticacysta* (Hou et al., in prep; Suppl. file 2). However, and even convincingly stronger, the entire palynological associations retrieved from the Arctic *Zebra* subunit 1/5 are typical for extremely restricted marine, freshwater-rich environment, given the near dominance of one taxon, and the abundance of pollen and spores from higher plants (Sangiorgi et al., 2008).

*Arcticacysta* in the Ross Sea is only a minor component of the assemblage (Fig. 4), but it also occurs in sediments representing shallow water setting conditions where fresh-brackish algae are common (Hou et al., in prep, Suppl. file 2) and is most abundant during the Miocene Climatic Optimum. It may be concluded that this genus has a strong tolerance for restricted settings likely influenced by freshwater. The freshwater may originate from the melting of land and/or sea-ice. There is evidence of ice expansion at 17.7 Ma in the central Ross Sea Site U1521 (Marschalek et al., 2021) and western Ross Sea ANDRILL-2A marginal record at ~17.7 Ma (Passchier et al., 2011; Hauptvogel and Passchier, 2012), which then retreated during the Miocene Climatic Optimum (e.g., Levy et al., 2016).

#### 4. Concluding remarks

This paper presents indirect but compelling evidence for a major hiatus in the Central Arctic, mid Lomonosov Ridge, Cenozoic record between the Paleogene and the Neogene, with all its consequences. The first (temporary) appearance of the dinoflagellate cyst genus *Arcticacysta* in the sediment record of Site U1521 in the central Ross Sea (Antarctica) in the late early Miocene (~17.7 Ma), and its almost continuous occurrence between ~17.0 and 15.9 Ma confirm that *Arcticacysta* is of late early Miocene age. Assuming that the (first appearance and) occurrence of *Arcticacysta* in both the Ross Sea (Antarctic) record and the Lomonosov Ridge (Arctic) record is synchronous, a late early Miocene age for the Arctic regional subunit 1/5 (*Zebra*) earlier used to assign the youngest age to a major hiatus in the central Arctic sediment record of Expedition 302 (Sangiorgi et al., 2008) is confirmed. The existence of a hiatus in the sediments of the Lomonosov Ridge implies that the tectonic history of the rifting and subsidence of the Arctic Ocean is complex and different from a smooth thermally controlled subsidence of the Lomonosov Ridge following early Paleocene rifting proposed by other studies (Poirier and Hillaire-Marcel, 2009, 2011). Hopefully, future ocean drilling will provide further insights into this intriguing issue. Finally, palynological assemblages where *Arcticacysta* occurs seem to indicate that this genus thrives in marine environments with (high) freshwater input. Whether freshwaters originate from river input, and/or sea/land ice melting remains elusive as *Arcticacysta* has so far only been found in two high latitude records.

#### CRediT authorship contribution statement

**Francesca Sangiorgi:** Writing – review & editing, Writing – original draft, Investigation, Funding acquisition, Formal analysis, Conceptualization. **Evi Wubben:** Writing – review & editing, Formal analysis. **Suning Hou:** Writing – review & editing, Formal analysis. **Henk Brinkhuis:** Writing – review & editing, Conceptualization.

#### Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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#### Appendix A. Supplementary data

Supplementary data to this article can be found online at <https://doi.org/10.1016/j.margeo.2025.107618>.

#### Data availability

Data are available at DOI <https://doi.org/10.5281/zenodo.15852294>. Data are also provided as supplementary information files.

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