Limited freshwater cap in the Eocene Arctic Ocean

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Remains of the freshwater fern Azolla, found in Eocene (~50 Ma ago) sediments in the modern central Arctic Ocean, have been used to suggest that seasonal freshwater caps covered the entire Arctic Ocean during that time, with significant impact on global ocean circulation and climate. However, these records are located on the Lomonosov Ridge, which during the Eocene was a continental fragment barely rifted from Eurasia, separating the smaller Eurasian Basin from the much larger Amerasian Basin to the west. As such, the Lomonosov Ridge does not necessarily record environmental conditions of the broader Arctic Ocean. We tested the hypothesis of freshwater caps by examining sediment records from the western Amerasian Basin. Here we show that in the larger Amerasian Basin the Azolla event is associated with marine microfauna along with allochthonous (terrestrially sourced) organic matter. We propose that Azolla events are related to an increased hydrologic cycle washing terrestrially sourced Azolla, and other organics, into the Arctic Ocean. If freshwater caps did occur, then they were at best restricted to the small Eurasian Basin and would have had a limited impact on Eocene global climate, contrary to current models.

The late Paleocene and early Eocene (47.8 to 59.2 Ma time period) provides an analogue to understand impacts of modern climate warming, particularly at high latitudes. During this time the Arctic experienced extremely warm conditions, including rainforests inhabited by alligators and giant tortoises1–3 with mean annual air temperatures reaching ~15 °C3–5. However, the palaeoenvironment of the Eocene Arctic Ocean has been largely inferred from only one locality, the ACEX cores from the Lomonosov Ridge6–8. At this location the 'Azolla event' was defined by thousands of Azolla containing laminae observed in mid Eocene sediments over ~800 kyr6. The large numbers of the free-floating freshwater Azolla fern found at the ridge are suggested to be a product of fern growth on surface freshwater layers, with floating mats covering the entire Arctic Ocean6. The co-occurrence of marine dinocysts, diatoms, silicoflagellates and ebridians was explained by Arctic Ocean surface waters being only seasonally fresh6. These Eocene sediments of the Lomonosov Ridge are purported to reflect mid-Artic Ocean conditions. This, however, is not consistent with plate tectonic models. The Lomonosov Ridge from which the ACEX cores were collected is a seafloor feature more than 1500 km long and 30–80 km wide, rising 3 km above the abyssal plains10. The ridge rifted from Eurasia ~55 Ma, opening the Eurasia Basin11,12. Rifting formed a shallow sill8,10 separating the older and much larger Amerasian Basin from the younger, smaller and shallower Eurasian basin12 (Fig. 1). Micropaleontological data indicate that marine sediments on the Lomonosov Ridge had an epipelagic depth (0–200 m) throughout the Paleogene13. This is thought to relate to heat flow from the Nansen-Gakkel seafloor spreading centre, and voluminous magmatism14, as well as far-field in-plane stress that kept the Lomonosov Ridge shallow, if not elevated above sea level in places, until the Miocene1,15,16. An exposed ridge has even been suggested to have acted as a temporary land bridge during the Eocene that stimulated the movement of plants and animals1. Thus it remains unclear if the marine sediments from the ACEX core of the Lomonosov Ridge truly represent open Arctic Ocean conditions, or did the ridge itself act as a sill that formed a restricted Eurasian sub-basin. To test the palaeoceanographic model of the entire Arctic Ocean containing fresh surface waters, with extensive floating Azolla mats, we examined coeval records from the dominant Amerasian Basin, from a well drilled in the Beaufort Mackenzie Basin (BMB) – western Arctic.

Results

Azolla event in the western Arctic. The late Cretaceous–Cenozoic BMB contains 14 km of sediment infill in a rapidly subsiding deltaic and marine environment. We examined the sediment record from a well named ‘Dome Pacific et al. PEX Natsek E-56’ (herein Natsek E-56) (Fig. 1) located in the southwestern part of the BMB (69°45′21.46″N; 139°44′3458″W, Northwest Territories, Canada). Natsek E-56 preserves the early to mid Eocene
Taglu Sequence (including the *Azolla* event; Fig. 2)\textsuperscript{16,17} that consists of weakly consolidated silty to pebbly mudstone. The well represents an expanded section characterized by rapid rates of sedimentation that is at least 9 times greater than the Lomonosov Ridge, with 2 km of deposition during the Eocene\textsuperscript{17} (Fig. 2). The depositional environment changed significantly across an intra-Taglu unconformity, from outer shelf (mesohaline marine micropalaeontological character) to slope/shelf (with marine dinoflagellate cysts and *Azolla* present)\textsuperscript{18,19} (Table 1, Figs 2 and 3).

The lower Taglu Sequence contains a well-developed circum-Arctic early Eocene benthic agglutinated foraminiferal assemblage assigned to the *Portatrochammina tagluensis* Zone (Fig. 2). Foraminifera disappear entirely above the unconformity in the mid Taglu Sequence, replaced by a diverse assemblage of pollen, remains of the freshwater fern *Azolla* (preserved as megaspores and massulae (Fig. S1)), as well as dinocysts and other microfossils. The *Azolla* occurrences consist of two major peaks, one in the upper slope sediments and the other in the outer shelf (Fig. 2). The *Azolla* acmes in Natsek E-56 are coeval with the *Azolla* event on the Lomonosov Ridge in the earliest mid Eocene (onset 50 Ma)\textsuperscript{6}, with similar peaks displayed between both localities. However, our measured average abundance of *Azolla* plant parts (85 remains per 100 g of dry sediment; maximum 460 remains/100 g of dry sediment at 521 m) (Fig. 3) is significantly lower than the 5–30 × 10\textsuperscript{6} remains per 100 g of
dry sediment observed in ACEX. Our Rockeval data also show that the Azolla event laminae in Natsek E-56 have low organic content (Total Organic Carbon (TOC) = 1.17 wt.%). Rockeval parameters that indicate organic matter type (i.e. marine algae versus terrestrial organics) show high RC, S3, and OI indices (RC = 1.02 wt.%, S3 = 428.70 mgCO2/g, OI = 108.15 mgCO2/TOC).

Table 1. Summary results for Natsek E-56 of Rock-Eval analyses (pyrolyzed carbon (PC); residual carbon (RC); total organic carbon (TOC); hydrogen index (HI); oxygen index (OI); mineral carbon (MinC)) and carbon isotope organic carbon ($\delta^{13}C_{org}$). The results are further subdivided at the intra-Taglu unconformity separating the lower from mid Taglu Sequence. The average of the results for the entire sequence are in bold. The full Rock-Eval data set for Natsek E-56 are reported elsewhere. HI = Hydrogen index (S2 × 100/TOC), OI = Oxygen index (S3 × 100/TOC).

| Sequence | Depth m | S2 mgHC/g | S3 mgCO2/g | Tmax °C | PC wt.% | RC wt.% | TOCwt.% | HI mgHC/TOC | OI mgCO2/TOC | MinC wt.% | $\delta^{13}C_{org}$ ‰ |
|----------|---------|------------|-------------|---------|---------|---------|---------|-------------|--------------|-----------|-----------------|
| Taglu    | 1950-229| 0.80       | 2.19        | 417.47  | 0.18    | 1.15    | 1.33    | 57.03       | 161.03       | 0.34      | -28.61          |
| Azolla event – mid Taglu | 1226-229 | 0.57 | 1.72 | 411.67 | 0.15 | 1.02 | 1.17 | 47.92 | 148.32 | 0.34 | -28.55 |
| Lower Taglu | 1226–1950 | 1.22 | 3.05 | 428.17 | 0.23 | 1.39 | 1.62 | 73.85 | 184.50 | 0.35 | -28.71 |
| Aklak    | 1950–2226| 10.00      | 5.49        | 428.70  | 1.12    | 7.02    | 8.14    | 108.15      | 93.93        | 0.82      | -27.12          |

Figure 3. Micropalaeontological and rock-eval data for the Natsek E-56 well. TOC = total organic carbon, RC = residual carbon, OI = oxygen index. Depth represents true vertical depth. (kelly bushing, true vertical depth). Horizontal grey box represents the Azolla acme (counts tabulated from megaspores and massulae).
genera such as environment) character 22. Similar marine dinocyst assemblages were also observed with the Cordosphaeridium, Hystrichosphaeridium, Glaphyrocysta normal marine shelf conditions (Figs 3, S2, Table S1). Dinocysts included the prevalence of Phthanoperidinium, Cordosphaeridium, Hystrichosphaeridium, Glaphyrocysta, and wetzelielloids, along with the sparsity of offshore genera such as Operculodinium and Nematosphaeropsis, suggesting an inner to outer neritic (shallow marine environment) character22. Similar marine dinocyst assemblages were also observed with the Azolla event in the Labrador-Baffin Seaway23. At the Lomonosov Ridge, however, only Phthanoperidinium and Senegalinium, low-salinity tolerant genera, were associated with Azolla blooms23. In our samples, the co-occurrence of Azolla, which cannot tolerate salinities higher than 1–1.6‰, and marine dinocysts in Natsek E-56 is consistent with ACEX core observations of a mixed fresh/saline water fauna. However, organic matter that co-occurs with both marine fauna and Azolla in Natsek E-56 has an allochthonous origin. We argue then that this is more consistent with terrestrial material (organic matter and Azolla) being washed into a marine environment, rather than the model of Azolla blooming in situ in seasonal freshwater caps7. This simpler interpretation is consistent with the lack of evidence for a strongly stratified anoxic water body and alleviates the physical and biological constraints of forming and maintaining seasonal freshwater caps with floating Azolla mats on the Arctic Ocean surface7 as discussed below.

Constraints on forming a freshwater lens and floating mats. Modern Azolla ferns only float freely on the surface of quiescent freshwater, such as ponds and canals in tropical, subtropical, and warm temperate regions24,25. They are not found on larger water bodies exposed to significant wave action that breaks up mats; it would thus be particularly challenging for a floating fern to cover the ~11.4 × 106 km2 Arctic Ocean25. Given the size and annual modern freshwater flux (~8500 km3)26 the Arctic Ocean could only develop a seasonal freshwater cap of ~0.75 m. Even if increased Eocene cyclone activity27 led to river flow that was a maximum of twice as high as modern (based on estimates of doubling rainfall24, but not accounting for increased evapotranspiration) the annual freshwater cap would not exceed 1.5 m, well within the fair-weather mixing zone and storm wave base down to 5 m28. The same increased frequency and intensity of cyclones in the Eocene Arctic and northward shift in storm tracks would have further exacerbated mixing26,28, making formation and maintenance of a freshwater cap in the central Arctic Ocean highly improbable. After annual die-off, due to lack of winter sunlight, Arctic Ocean mats would require entirely vegetative reproduction in tolerable bottom water salinities not found in marine environments. Thus, even with a freshwater cap, Azolla would not have germinated in the Arctic Ocean.

Discussion
We do not attempt here to re-interpret ACEX data, and allow that the interpretation of a seasonal freshwater lens from that location may still be valid. However, based on the differences between the BMB and Lomonosov Ridge records, it is possible that a subaerial ridge, or submerged sill, separated the Arctic Ocean into two distinctive bodies of water creating differing depositional environments. The high Azolla accumulation observed in the ACEX core could at best be a localized phenomenon restricted to the newly formed Eurasia Basin, that did not represent overall dominant Arctic Ocean conditions. The presence of Azolla along with marine microfauna and terrestrial organic matter in the BMB more likely reflects the change to warmer Eocene temperatures and an increased hydrological system leading to enhanced mass transport of terrestrial material, including freshwater fern debris, from freshwater bodies surrounding the Amerasian Basin. If correct, our alternative interpretation has significant implications for models of the transition from a global greenhouse climate towards the modern icehouse being triggered by Arctic Ocean wide growth of Azolla23. Factoring the size of the basin, it was suggested that atmospheric carbon dioxide as high as 2500 to 3500 ppm was reduced by half after the growth was significantly more limited than these models and do not support such levels of CO2 drawdown. Other mechanisms should be explored to explain amelioration of Eocene hothouse conditions.

Methods
Cuttings and duplicate samples (n = 195 and n = 5, respectively) were collected from the Natsek E-56 well between 229–2226 m and prepared for analysis at the Geological Survey of Canada (Calgary). The handpicked samples were washed lightly with tap water to remove drilling mud then oven dried at ~35 °C for ~24 hours before being powdered. Aliquots of the powdered samples were subjected to the below analysis. Additional details are published elsewhere21.

Rock-Eval 6 pyrolysis was conducted at the Geological Survey of Canada (Calgary) on a Rock-Eval 6 Turbo device following the Basic Method23,24. Total organic carbon (TOC) content and Rock-Eval parameters were determined on bulk ground samples to provide information on organic carbon source, hydrocarbon source-rock potential, presence of hydrocarbons, and thermal maturity. Detailed data are presented elsewhere22.
Samples were prepared, processed and analyzed for micropalaeontological content at the Geological Survey of Canada (Calgary), following the standard methods for breaking down samples\(^2\). The processed residues were picked for all microfossils and the microslides are stored in the collections of the Geological Survey of Canada, Calgary (GSCC). Foraminifera were identified using standard taxonomy\(^3\). Palynological data was obtained from Dolby (2011)\(^2\) and interpreted by Dr. R.A. Fensome (Geological Survey of Canada – Atlantic).

**Data Availability**

Data used in this study are available for download in Geological Survey of Canada. Open File Report 7949 as well as published data in Dolby (2011)\(^2\).

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Author Contributions
L. Neville and D. McNeil conducted microfauna analyses, S. Grasby provided geochemical interpretation. All authors contributed to manuscript preparation.

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